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# **BIOENERGETICS**

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Edited by **Kevin Clark**

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## Preface

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All living matter, from the conventional basic unit of life, the cell, to a higher-order integrated manifestation of cells, an organism, exists as an open dynamical system requiring capabilities for extracting energy from respective interstitial, host, or ambient environments, for converting that same energy to biologically useful forms, and for employing biologically useful energy to drive energetically expensive life processes. In a most general sense, the scope of the scientific discipline now called *bioenergetics* extends to all of biophysics and biochemistry as they concern the study and description of energy transformations that occur during thousands of organic chemical reactions in living soft matter. As one should expect, the definition and scope of bioenergetics have changed with time. Landmark transitions, such as the discoveries of photosynthesis, of glycolysis and oxidative phosphorylation, of adenosine triphosphate (ATP) and creatine phosphate and their roles in working muscle, of cytochromes and the respiratory chain, and of membrane-dependent electron transport and chemiosmotic coupling, accompany technological and conceptual innovations. Over the past thirty-or-so years, traditions in study at the level of membrane-bound energy-transducing catalysts have switched to an emphasis on the deeper molecular nature of bioenergetics, including the gene expression, biosynthesis, and membrane assembly of catalysts, the production and neutralization of harmful reactive oxygen species known as free radicals, the quantum efficiency of energy-harvesting protein complexes, and the effect these and other events have on the state of cells and organisms. This transition from the science of membrane physiology to molecular biology comes with advancing instrumentation and methods which allow researchers to probe the biological function and impact of macromolecules and substrate at smaller physical scales. As readers of this three-sectioned collected volume will find, however, these trends in bioenergetics theory and research often complement, rather than replace, more established interests in membrane physiology and will lead to progress in such endeavors as preventing mitochondrial diseases, improving physical performance, and slowing aging.

Even in the midst of conceptual and technical revolutions, bioenergeticists typically take for granted that their discipline broadly entails studying the transformation of biological fuels by cells. Yet, despite many textbooks and peer-review articles published in scientific journals devoted to the subject of bioenergetics, no fixed origin for this field of study is objectively identifiable. A few words here placing

contemporary scientific trends within the context of past and anticipated achievements might be therefore instructive to readers. Popular experts on bioenergetics assign its beginnings as far back as the mid-18<sup>th</sup> century (e.g., Ernster, 1984) and as recently as the mid-20<sup>th</sup> century (e.g., Nicholls, 1982). Discrepancies between authorities on this matter chiefly result from how one defines bioenergetics and from what historic scientific milestones one measures as being crucial to the field's development. Modernists have several convincing reasons for affixing the initial date of bioenergetics to circa 1950, such as mounting evidence at that time indicating mechanisms of respiratory chain catalysis and ATP synthesis were located in the inner mitochondrial membrane of animals, in the thylakoid membrane of plant chloroplasts, and in the chromatophore or plasma membrane of photosynthetic bacteria. However, this perspective ignores the enormous significance of roughly 200 years of preceding research. Ernster (1984), utilizing a general characterization of bioenergetics as the biological process of acquiring energy from oxidative reactions, cites the independent experimental discoveries of oxygen by Joseph Priestly, Antoine Lavoisier, and Carl Scheele during the 1770s as the birth of bioenergetics. Each of these pioneering figures in chemistry tested the properties of their newly found gas through its influence on living organisms. Priestly, for example, proposed a functional relationship between oxygen and blood, verified vertebrates consume purified oxygen with improvements in health, and showed green plants produce oxygen. While Lavoisier, dispelling George Stahl's phlogiston theory of combustible materials, demonstrated respiring guinea pigs emit heat. Also instrumental in Ernster's scholarly dating of bioenergetics was Scheele's subsequent isolation of organic compounds, such as citric acid, lactic acid, and glycerol, from living tissue: Jan Ingenhousz, Jean Senebier, and Nicolas-Théodore de Saussure's initial observations of photosynthesis and cellular respiration by green plants: and Julius von Mayer's formulation of the First Law of Thermodynamics, which relates energy conservation through concepts of a system's internal energy, heat exchange, and work.

Undoubtedly, these and other early contributions by skillful and conscientious scientists provided the foundation for our contemporary notions and understandings of bioenergetics. They established that oxygen was among the essential nutritional requirements for organisms to grow and fend-off infection and, perhaps more importantly, that cellular life derived energy and other substrate for life-sustaining work from their environments. But bioenergetics, as a discipline and a definition, started to take on its current identity only after the persistent ideology of vitalism, a belief that life was reducible to a natural or vital force, largely ceased to plague the natural sciences (cf. Ernster, 1984; Racker, 1980). In a cruder technological era, when determination of biomechanisms underlying many of life's processes often evaded physicochemical scrutiny, even clever scientists, such as Louis Pasteur, resorted to imprecise and invalid depictions of biological processes and substrates as vital forces. The early 19<sup>th</sup> century research of Friedrich Wöhler on synthesizing urea helped usher in the realization that organic substances were not alone the products of living organisms, but could be created by laboratory chemists using inorganic starting

materials. Soon after, Jöns Berzelius' hypothesis that organisms synthesize their own organic compounds via catalysts instead of vital forces took hold among some leading authorities. Nevertheless, vitalism continued to find its way into the description of life processes. For instance, Pasteur writing about his discovery of the importance of oxygen availability for sugar fermentation by yeast, to be later known as the Pasteur effect, argued for the exclusive dependency of intact cell structure, a variant of cell theory postulated by Matthias Schleiden, Theodor Schwann, and their predecessors, and "ferments", a set of biocatalysts represented as vital forces. Adherence to vitalism ironically retarded progress in studying energy transfer in living matter because it demanded that physicochemical processes mediating bioenergetics only reside in live media. Such an axiom enabled the false conclusion that more easily replicable and less resource-intensive test-tube chemistry techniques were unsuitable for investigating the chemistry of life.

The last vestiges of vitalism stubbornly disappeared by the early 20<sup>th</sup> century largely because of Eduard Büchner's Nobel-prize-winning research. Büchner's demonstration that the Pasteur effect was reproducible from a cell-free extract of pressed brewer's yeast reinforced the opinion of Justus von Liebig that the bioproducts, if not the composition and operation, of metabolic pathways were accessible to bench science. A rapid succession of central findings ensued during the first part of the 1900s (cf. Ernster, 1984; Racker, 1980), such as the observation that inorganic phosphate and soluble cofactors or coenzymes, including a key pyridine substance first named cozymase by discoverers Arthur Harden and William Young (and later renamed nicotinamide adenine dinucleotide (NAD)), were needed for cellular energy metabolism. Further identification of enzymatic reactions and chemical intermediates of glycolysis, the catabolic modification of monosaccharide sugars to pyruvate fated for oxidation in the citric acid cycle, also served as important stages in the development of bioenergetics. Prime examples include the finding by Otto Warburg that cozymase helps oxidize glyceraldehyde-3-phosphate and that this process is associated with ATP synthesis, Carl Neuberg's discovery of carboxylase, an enzyme that catalyzes the decarboxylation of pyruvate, and the work of Gustav Embden, Nobel laureate Otto Meyerhof, and Jakub Parnas which explicated the cycle responsible for lactic acid generation from glucose during muscle contraction. Using preparations of working muscle, Karl Lohmann, Yellapragada Subbarow, and Cyrus Fiske also made giant contributions when they isolated and bioassayed creatine phosphate and ATP, showing ATP phosphorylates creatine after cleavage of creatine phosphate. Around the same period, David Keilin united the disparate views debated by Nobel laureates Otto Warburg and Heinrich Wieland on the role played by oxygen, hydrogen, iron-possessing enzymes, and insoluble cytostructures in respiratory activity. Keilin rediscovered the heme proteins or cytochromes, previously reported by Charles MacMunn in the 1880s, in the flight muscles of insects and perceptively conjectured their involvement as electron carriers between biological fuels and molecular oxygen. Later studies on mammalian heart muscle performed with his colleague E.F. Hartree inspired the eventual description of cellular respiration as a

chain of electron-transporting redox catalysts that begins with NADH dehydrogenase and ends with cytochrome *a<sub>3</sub>*. Kreilin's advancements in understanding aerobic respiration were followed by Nobel laureates Albert Szent-Györgi and Hans Krebs' elaboration of the amphibolic citric acid cycle, which creates usable energy from the catabolism of carbohydrates, fats, and proteins.

But not until the 1940s and 1950s, as acknowledged by Peter Mitchell in his Nobel lecture, was much of Keilin's ideas on aerobic respiration largely brought to completion. Nobelist Fritz Lipmann a decade following the discovery of ATP suggested ATP was the main molecule for cellular energy transport, with hydrolysis at one of two phosphodiester bonds liberating stored energy for biological work at distant cell sites. Lipmann also developed the idea that respiration occurred through phosphorylation of an oxidized electron donor. In part, this model found support from thiol ester mechanisms of glycolytic phosphorylation and from results of V.A. Belitser and E.T. Tsybakova that confirmed at least two ATP molecules arise from each atom of oxygen consumed. The growing belief of many researchers was that if respiration drives ATP synthesis, then phosphorylation must be coupled to a series of mostly exergonic reactions that culminate in the reduction of O<sub>2</sub> to H<sub>2</sub>O. Morris Friedkin and Albert Lehninger took a big step toward proving this hypothesis in the late 1940s when they confirmed respiration was a chain of events involving phosphorylation. Several years afterwards, experiments performed by Nobelist Albert Claude and collaborators B.H. Hogeboom and R.D. Hotchkiss and by Eugene Kennedy and Lehninger revealed that mitochondria are the sites of cellular respiration and of oxidative phosphorylation, the citric acid cycle, and fatty acid oxidation. Together, these and additional ultrastructural findings brought about through improved use of tissue-fractionation and microscopy techniques, anaerobiosis, and respiratory inhibitors and uncouplers paved the path for redefining and localizing what Keilin termed a "colloidal surface" for animal cell respiration to the folded inner mitochondrial membrane (cf. Ernster & Schatz, 1981; Slater, 1981).

Throughout the mid-20<sup>th</sup> century, concerted efforts of innumerable scientists were aimed at uncovering the details of respiratory-chain constituents, operation, and localization. Much of the research of this era, such as that conducted by Fritz Lipmann, Albert Lehninger, Paul Boyer, David Green, Efraim Racker, Bill Slater, Henry Lardy, and Britton Chance, supported the concept of respiration as the processes of electron transport and ATP synthesis coupled to energy-rich nonphosphorylated intermediates (cf. Ernster, 1984; Ernster & Schatz, 1981; Racker, 1980). This "chemical" model, first proffered by Slater in 1953, diverged from Lipmann's earlier suggested mechanism. Slater's conceptualization benefited from publication of new evidence, some of which were reported from Lipmann's group, implicating thiol esters and coenzyme A in phosphorylations linked to  $\alpha$ -ketoglutarate and pyruvate oxidation. Later research would show this model of individual catalysts, each thought directly capable of ATP synthesis, was an over-simplification. Furthermore, the introduction of sensitive experimental methods for analysis of mitochondrial electron transport, such as combined use of dual-wavelength spectrophotometry and oxygen electrodes and

better resolution and reconstitution protocols, allowed studies into respiratory chain kinetics and metabolic states in intact and subparticulate mitochondrial preparations. With such methodology, Chance and coworkers, for instance, demonstrated sites of respiratory chain phosphorylation, the concentration of electron-transport catalysts, the reversibility of oxidative phosphorylation, and the energy-linked uptake of divalent cations. Additional work carried out in the laboratory of Nobel laureate Paul Boyer exposed partial reactions involving the association of H<sub>2</sub>O and ATP to inorganic phosphate. Boyer subsequently speculated that the mechanism for ATP synthesis primarily required energy for phosphate binding and ATP release. Three identical circularly arranged catalytic sites of a single enzyme were thought to perform sequential changes in binding driven by rotation of an internal catalytic subunit. Confirmation of membrane-associated ATPases, electron transport complexes, and the involvement of ubiquinone, nonheme iron proteins, and metalloflavoproteins as redox carriers in the respiratory chain helped to refine these concepts. For example, Efraim Racker and his colleagues Anima Datta, Maynard Pullmand, and Harvey Penefsky identified and purified an important enzyme, called Factor 1 or F<sub>1</sub>, needed to create the proton gradient for ATP synthesis. Racker's research team showed Factor 1 was part of the ATP synthase Complex V, a peripheral membrane protein required for oxidative phosphorylation. By 1960, cumulative findings involving the nature of membrane-dependent energy transport and synthesis in animal tissues led to Mitchell's groundbreaking chemiosmotic hypothesis of oxidative phosphorylation, where a mitochondrial transmembrane proton gradient enables energy transfer between electron transport and ATP synthesis. A few years later, Mitchell generalized his model to photosynthesis. Another decade would pass until critics of the chemiosmotic hypothesis relented to mounting experimental findings against earlier arguments in favor of energy transfer by individual respiratory-chain catalysts.

Meanwhile, trends in photosynthesis and origins of life research commensurate with developments in the study of mitochondrial physiology encouraged a more comprehensive view of cell metabolism across phylogeny and presumptive protolife (cf. Ernster & Schatz, 1981; Fuller, 1999; Jagendorf, 1998; San Pietro, 2008; Orgel, 2004). From the 1930s to the 1970s, researchers, including Cornelis Van Niel, Robert Emerson, Robin Hill, Daniel Arnon, Anthony San Pietro, Horst Witt, André Jagendorf, Mordhay Avron, Achim Trebst, and Nobel laureates Melvin Calvin, Johann Deisenhoffer, Robert Huber, and Rudolph Marcus, made substantial progress toward elaborating the roles of, among other substrate, chloroplasts, chromatophores, photosystems, and photopigments in the light harvesting and energy conversion of photosynthesis. 19<sup>th</sup> century scientists knew chloroplasts as the site of carbon dioxide assimilation and sugar and starch formation in plants. Studying photosynthetic microbes, Van Niel and Emerson made respective significant contributions in the photochemistry of bacteria, algae, and diatoms, such as identifying H<sub>2</sub> as the reducing agent of CO<sub>2</sub> in anoxygenic photosynthesis and identifying two separate photosystems, described decades later by Louis Duysens as PSI and PSII, containing photopigments of different spectral absorption. Employing artificial reducing agents, including iron oxalate and

ferricyanide, Hill first showed chloroplasts evolve oxygen, an intermediate-mediated photo-ionization process now known as the Hill reaction. Martin Kamen and Samuel Rueben using algal preparations next revealed that O<sub>2</sub> liberation during the Hill reaction originates from H<sub>2</sub>O. In contrast to energy-capturing and -storing light reactions, Calvin, Andrew Benson, and James Bassham explained the pathway for CO<sub>2</sub> fixation and carbohydrate generation via dark reactions, oftentimes referred to as the Calvin or Calvin-Benson cycle. Without fully characterizing the photosynthetic apparatus and pathways of photoautotrophs, similarities to mitochondrial bioenergetics were emerging for light-dependent ATP synthesis and photophosphorylation. In the 1950s, Arnon, Frenkel, Jagendorf, Marcus and others began to build upon Van Niel's demonstration that photosynthesis is a redox reaction. These scientists ascertained the sites and kinetics of light and dark reactions. Among the first findings were the localization of light-induced electron-transport-coupled ATP synthesis and photophosphorylation to plant thylakoid membranes and bacterial plasma membranes. Exciting achievements in distinguishing the subunits, cofactors, and catalytic sequence of photosynthesis shortly followed for light-harvesting complexes and reaction centers (cf. Barber, 2004; Fuller, 1999). In addition, a surprising happening in this period of science directed the field of bioenergetics in a new bearing marked by 100-year-old synthetic chemistry. Stanley Miller's 1953 report of amino acid synthesis in an electric discharge commenced the search for prebiotic chemistry capable of sustaining the emergence and evolution of life. Miller's findings, reminiscent of the contentious exchanges between organic and inorganic chemists over the validity of vitalism, require atmospheric conditions now considered unlikely for early Earth. However, his research stimulated discussion and study into the advent of cellular life from putative antecedent evolutionary states, endeavors that continue today.

The possibility that polymerization and even template-directed synthesis of sugars, purines, pyrimidines, and nucleosides could arise in a prebiotic microenvironment caused debate between supporters of protein- and lipid-first hypotheses (cf. Fox, 1988). In a moderately reducing atmosphere or hydrothermal environment believed common to prebiotic Earth, nucleotide starting materials could have been produced by aqueous or solvent-less reactions, such as sugar synthesis from formose or synthesis of amino acids and proteins from CO<sub>2</sub> reduction over ferrous sulfide. By the late 1960s, such conditions were independently proposed by Leslie Orgel, Francis Crick, and C. Woese to evolve naked protoreplicators made of macromolecular nucleotides, now typically labeled the RNA- and DNA-world hypotheses. Simple self-replicating molecules were largely thought to unreliably code, synthesize, select, and propagate metabolic enzymes without semipermeable shells. An appealing aspect on variations of this promising model for early metabolism defended by evolutionists Orgel, Sidney Fox, and others is that membrane-like shells initially served to encapsulate the contents of protocells then evolved to compartmentalize cell structures and functions to regulate cell energetics and other processes under ambient ecological pressure. That bioprocesses of comparatively sophisticated mitochondria and chloroplasts entail operation of membrane-associated components partly indicated eukaryotic cell

energetics evolved from primitive bacteria-like symbiots incorporated into hosts. Prior to being expressed as cellular organelles, these symbiots likely adapted to unstable host environments, where specialized energy-transformation and –transport mechanisms were advantageous for progressively increasing mutualism.

Interests in the study of membrane bioenergetics transitioned to study of molecular bioenergetics during the closing decades of the last millennium. This paradigm shift primarily resulted from development and wide availability of new experimental and computational technologies useful for examination of the static and dynamic structure of molecules as well as their biological functions. In the late 1950s and early 1960s, X-ray crystallography, liquid scintillation, zone-sedimentation-velocity and equilibrium-gradient centrifugation, polyacrylamide gel electrophoresis, and high-performance liquid chromatography were cutting-edge methods for extracting information about the structure of tissue-isolated proteins. People, such as Racker, Chance, Lehninger, and J.B. Chappell, exploited these tools to discover, for example, ionophores, anion translocators, coupling factors, and proton pumps involved in mitochondrial energetics. Similar results were obtained from those researching photosynthesis (cf. Barber, 2004; Fuller, 1999). While these and derivative methods still play an important role in biochemistry research, intervening years of improving technologies gave rise to, among other advances, restriction cleavage mapping, Southern blotting, gene cloning, site-directed mutagenesis, DNA and protein sequencing, DNA amplification, *in situ* hybridization labeling, scanning and tunneling microscopy, and nuclear magnetic resonance. The bioenergeticist's toolbox brims with powerful techniques to competently practice his/her trade and to satisfy his/her curiosities. Now researchers may track phosphotransfer networks, such as chains of sequential rapidly equilibrating reactions catalyzed by creatine kinase and adenylate kinase, for distant intracellular delivery of ATP and removal of ATPase byproducts in living cells (cf. Dzeja & Terzic, 2003). Or, one may evaluate the transcriptional responses of photorespiratory genes (cf. Foyer et al., 2009). Even physicians exploit new technologies involving dietary restrictions, antioxidants, and combinations of uncoupling agents and electron-transport inhibitors to effectively treat energetically ravenous neoplasms, degenerative diseases, and apoptotic tissue damage and aging due to mitochondrial free radical production (cf. Adam-Vizi & Chinopoulos, 2006; Demetrius et al., 2010; Wallace, 2005; Wallace & Starkov, 2000). Yet, despite modern technological innovations, a surprising lack of knowledge pervades the discipline of bioenergetics, ranging from the exact structure and conformational changes of mitochondrial ion channels (O'Rourke, 2007) to how mutations and epigenetic control over bioenergetics genes directly and reciprocally affect the evolution of life forms, their social groups, and inhabited ecological niches (cf. Wallace, 2010).

Certain of these problems in molecular bioenergetics will be undeniably solved by applying the computational framework imparted by quantum mechanics (and by perhaps more unifying extradimensional and holographic physics). At the edge between macroscopic and microscopic scales, classical Newtonian mechanics, which dominated the fundamental principles of bioenergetics almost since the field's

inception, begin to acquiesce to the trickiness of quantum phenomena. Hints of the power that quantum mechanics would give bioenergeticists to explain cell energetics appeared in the early 1960s, with, for instance, the perceptive forays of collaborators Britton Chance and Don DeVault into the effects of quantum tunneling on cytochrome oxidation rates. Present-day bioenergeticists must also confront problems in both classical and quantum physicochemistry to gain a fuller appreciation of life processes. As a result, the discipline of bioenergetics is being infused by the start of a new revolution in science -- *quantum biology*. Leaders in this area of research, such as Koichiro Matsuno, Klaus Schulten, Peter Wolynes, Lloyd Demetrius, Johnjoe McFadden, and other individuals, have discovered quantum influences that govern energy transformation in different biological systems, including light capture and energy transduction by bacterial photosynthetic apparatus (cf. Trevors & Masson, 2010), allometric scaling of metabolic rates across phylogeny (Demetrius, 2003, 2006; Demetrius & Tuszyński, 2010), regulation of oxidative phosphorylation and glycolysis in cancer cells (Demetrius et al., 2010), engine-like properties of the citric acid cycle under hydrothermal flow (Matsuno, 2006), adaptive mutation of lactose-fermenting bacteria (McFadden & Al-Khalili, 1999), and learned changes in the kinetics of autocatalytic  $\text{Ca}^{2+}$  reactions that tune behavioral output and metabolic expenditures in microbes and possibly plants and animals (Clark, 2010a-e, 2011a-c, 2012, in press a, b).

Although far from being exhaustive, the preceding historical survey illustrates that bioenergetics has become a very fertile and diverse research field in the span of a few centuries. Its accepted importance for chemistry and biology is underscored by the respectable number of Noble prizes awarded to scientists investigating aspects of bioenergetics (cf. Govindjee & Krogmann, 2002). I confidently expect this honored tradition to continue. As this century progresses, many significant unanswered questions of bygone and of incipient scientific generations will be tackled with fresh approaches toward bioenergetics and the life sciences. Indeed, a better understanding of bioenergetics at all levels of physical structure and function will become critical to resolving some of the most pressing concerns and ambitions of humanity, including, but not limited to, manned deep space travel, adaptation to increasingly extreme environments and habitat destruction, development of cures for cancer and metabolic pathologies, the search for extraterrestrial life, improving physical performance, creation of alternative green technologies, perfecting yield and health of aqua- and agricultural products, and management of parasitism and infectious disease. I hope the contents of this book on bioenergetics will help inspire contemporary and future scientists to meet and overcome the above and additional challenges.

Finally, I thank InTech for inviting me to edit this volume. I wish to acknowledge the indispensable contributions of many individuals in preparing *Bioenergetics*. Foremost among this group of people is the chapter authors. Without their labor, insights, and openness to editorial suggestion, our undertaking would have resulted in a poorer quality publication, if not downright failure. The work of Ms. Maja Jukic, InTech's Publishing Process Manager for *Bioenergetics*, was also exemplary in her diligence to accommodate author needs and for assisting me with InTech publishing procedures



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# **Part 1**

## **Reviews of Bioenergetics Applied to Life Span and Disease**



# Antioxidant Action of Mobile Electron Carriers of the Respiratory Chain

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## 1. Introduction

### 1.1 Evolutionary aspects

Both oxidative photophosphorylation and oxidative phosphorylation are dependent on electron transport chains sharing similarities that are suggestive of evolution of a chemolithotrophy-based common ancestor (conversion hypothesis). Therefore, an early form of electron transport chain with oxidative phosphorylation that is known as prerespiration was able of donating electrons to terminal acceptors available in the primitive reducing biosphere. In the evolutionary pathway this apparatus was supplemented by a photocatalyst capable of a redox reaction. Therefore, oxygenic photosynthesis was a late event during evolution that was preceded by anoxygenic photosynthesis. The development of the manganese complex able to promote water oxidation was a key event in developing oxygenic photosynthesis (Xiong & Bauer, 2002; Bennown, 1982; Castresanal et al., 1994).

The development of oxygenic photosynthesis was one of the most important events in the biological evolution because it changed the redox balance on Earth and created conditions for the biological evolution to more complex life forms. Molecular data showing cytochrome oxidase in the common ancestor of Archaea and Bacteria and an existing cytochrome oxidase in nitrogen-fixing bacteria living in an environment where the level of oxygen was very low are indicia that aerobic metabolism could be present in an ancient organism, prior to the appearance of eubacterial oxygenic photosynthetic organisms. Although the hypothesis that aerobic metabolism arose several times in evolution after oxygenic photosynthesis is not sustained by the above mentioned data, the widespread use of molecular oxygen as final acceptor of electrons resulting from the oxidation of biological fuels was an evolutionary acquisition subsequent to the oxygen photosynthesis. The use of molecular oxygen as final acceptor of electrons removed from biological fuels resulted in a significant improvement of energy yield, a crucial event for the rise of complex heterotrophic organisms. According to the endosymbiotic theory, the respiratory chain present in prokaryotes was transferred to eukaryotes and resulted in cells bearing mitochondria. At the present step of the biological evolution, the aerobic oxidation of biological fuels occurs in the respiratory chain apparatus of the cell membrane of

prokaryotes and in the inner mitochondrial membrane of eukaryotes (Xiong & Bauer, 2002; Bennnawn, 1982; Castresanal et al., 1994).

Figure 1 illustrates the more recent view of the evolution pathway of electron chain transport correlated to the arising of more complex living organisms.

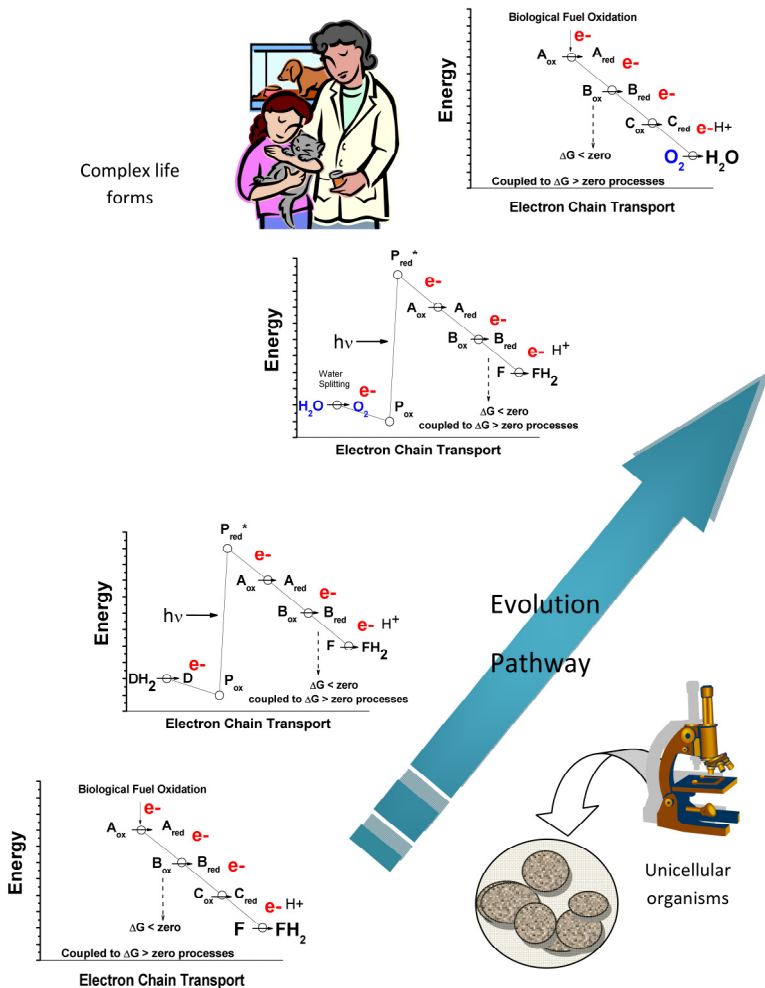


Fig. 1. Evolution pathway of electron transport chain that created conditions for the arising of more complex life forms. A, B and C are representative intermediates in a generic electron transport chain. F represents an electron final acceptor that made feasible the electron chain transport in the primitive reductive atmosphere. P represents a photocatalyst pigment responsible for light harvesting in non-oxygenic and oxygenic photophosphorylation. D represents the electron donor in the non-oxygenic photophosphorylation. The oxygenic photophosphorylation was not represented as Z scheme for clarity. The energy scale is arbitrary. ATP synthesis (phosphorylation) are among the  $\Delta G > \text{zero}$  processes coupled to electron transport chains.



## 1.2 Respiratory chain

The oxidation of biological fuels such as glucose, lipids and amino acids proceeds by the electron transfer to coenzymes  $\text{NAD}^+$  and  $\text{FAD}$ . These metabolic pathways such as glycolysis, citric acid cycle and  $\beta$ -oxidation of fatty acids are totally dependent on the continuous recycling of  $\text{NADH}$  and  $\text{FADH}_2$  coenzymes to the oxidized forms. In aerobic organisms, the recycling of  $\text{NADH}$  and  $\text{FADH}_2$  was done by the electron transfer to respiratory protein complexes I and II, respectively. In the following, electrons are transported through a sequence of redox centers, most of them composed by heme proteins that are known as respiratory cytochromes (Hatefi, 1985; Nantes & Mugnol, 2008). Similarly to the mechanism operating in the photosynthetic apparatus, spontaneous electron transfer through respiratory chain complexes is coupled to proton ejection from the matrix to the intermembrane space resulting in the protomotive force (Eq. 1).

$$\Delta p = \Delta \psi - 60 \Delta pH \quad (1)$$

$\Delta p$  supports ATP synthesis and other energy requiring processes in mitochondria such as ion transport and transhydrogenation. ATP synthesis is done by the enzyme ATP synthase that encloses a membrane extrinsic  $\text{F}_1$  and a transmembrane  $\text{F}_0$  subunits (Solaini et al, 2002; Zanzami et al, 2007).

As described above, the respiratory chain comprises proteins assembled as supramolecular complexes; most of them are composed by integral proteins inserted in the inner mitochondrial membrane. This redox system encompasses four complexes:  $\text{NADH:ubiquinone oxidoreductase}$  (complex I),  $\text{succinate:ubiquinone oxidoreductase}$  (complex II),  $\text{ubiquinol:ferricytochrome c oxidoreductase}$  (complex III),  $\text{ferrocytochrome c: oxygen oxidoreductase}$  (complex IV) that assembled with ATP synthase constitute the so-called respirasome (Hatefi, 1985; Nantes & Mugnol, 2008; Duchen, 1999; O'Reilly, 2003; Wittig et al, 2006; Fernandez-Vizarra et al, 2009 and Dudkina et al, 2008), (Fig. 2). However, the electron transport among the respiratory complexes is mediated by two mobile electrons carriers: coenzyme Q (CoQ) and cytochrome c.

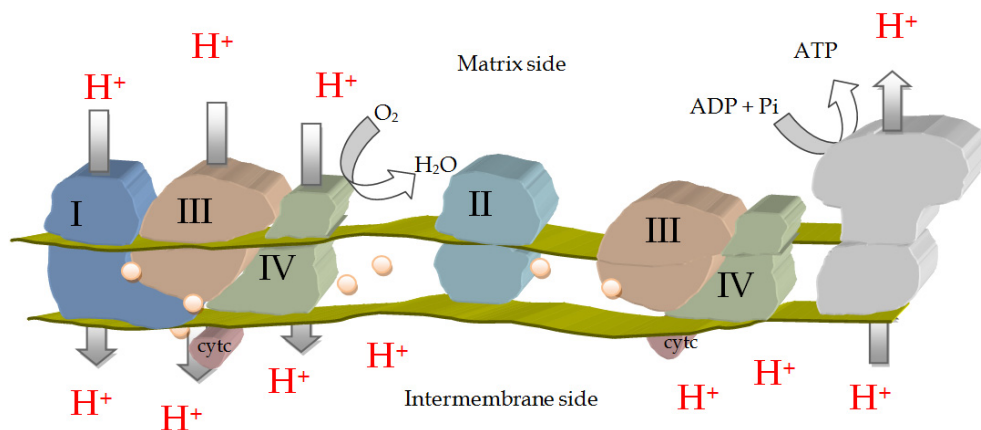


Fig. 2. Pictorial representation of a coupled respiratory chain with respiratory components assembled as respirasomes. CoQ is represented as yellow shadowed spheres.

### 1.2.1 Fundamental concepts about CoQ

The structure of CoQ was determined by Wolf et al. in 1958. The compound is a 2,3-dimethoxy-5-methylbenzoquinone with the redox active benzoquinone ring connected to a long isoprenoid side chain. According to the isoprenoid chain, five quinones are designated as members of a coenzyme Q group, i.e., CoQ6, CoQ7, CoQ8, CoQ9 and CoQ10 (Fig. 3). Ubiquinol is the product of two-electron reduction of ubiquinone with an ubisemiquinone intermediary form (Fig. 3). The predominant form of ubiquinone in humans presents 10 isoprenoid units in the side chain and it is referred as coenzyme Q<sub>10</sub> (CoQ<sub>10</sub>) or ubiquinone-10. The first studies about coenzyme Q were published in the end 50's with the isolation of a beef heart quinone (Crane et al., 1957) and sequential studies on its redox properties (Moore, 1959; Gale et al, 1963).

The hydrophobicity of this coenzyme results in its partition into the lipid bilayer (Littarru & Tiano, 2007).

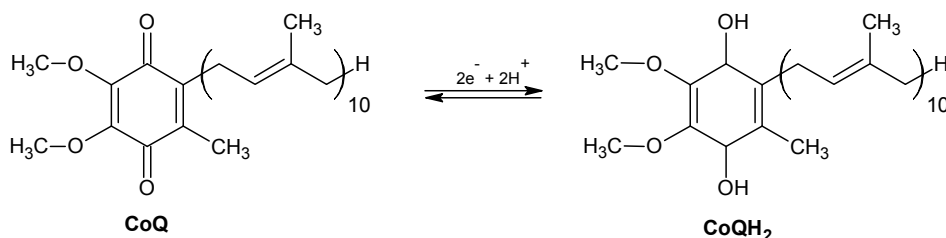


Fig. 3. Chemical structure coenzyme Q in its oxidized (CoQ) and reduced (CoQH<sub>2</sub>) forms.

CoQ<sub>10</sub> is found in almost all cellular membranes as those of Golgi apparatus and lysosomes. In the inner mitochondrial membrane, CoQ carries electrons from complexes I and II to *bc*1 complex but its participation in the respiratory chain involves a redox cycle that also contributes to the generation of the proton motive force. The CoQ redox cycle involves the interaction of the coenzyme with of the *bc*1 complex. Several studies are concerned about the mechanism of proton translocation through the cytochrome *bc*1 complex related to CoQ cycle and the function of individual subunits of the enzyme in the energy transduction process. Unlike the electron transfer pathway through the *bc*1 complex, there is not a consensus on the mechanism that couples the electron transfer to a transmembrane proton electrochemical potential. Two mechanisms of proton translocation by respiratory complexes have been described: the redox loop and the proton pump mechanism. The redox loop mechanism was the mechanism proposed by Mitchell, (1966). This mechanism requires concomitant acceptance of protons from the matrix side followed by proton release at the intermembrane space associated to the redox changes of some respiratory redox centers. The proton pump mechanism requires that the reduction and re-oxidation of protein redox centers would be accompanied by changes in the conformation of proteins with consequent alterations of the pK<sub>a</sub> of amino acid side chains and leading to the exposure of these residues alternately at the internal and external side of the membrane (Erecinska, 1982; Trumpower, 1990; Boyer, 1993). Considering exclusively a redox loop mechanism, the CoQ molecules solved inside the membrane lipid fraction are converted to the completely reduced form (CoQH<sub>2</sub>) by Complex I or II and the high potential *b*<sub>562</sub> of Complex III. This process is accompanied by the uptake of two protons from the mitochondrial matrix. The reduction occurs in two steps and consequently semiquinone is generated as intermediate. The

reoxidation of CoQH<sub>2</sub> results from one electron transfer to cytochrome *c*1 via the iron sulfur protein (ISP) and one electron transfer to heme *b*566 that recycles it to heme *b*562 that reinitiates the cycle by transferring one electron to oxidized CoQ. The oxidation of CoQH<sub>2</sub> releases two protons in the intermembrane space. The ratio H<sup>+</sup>/electron transferred to cytochrome *c*1 and consequently to molecular oxygen is 2/1 (Figure 4).

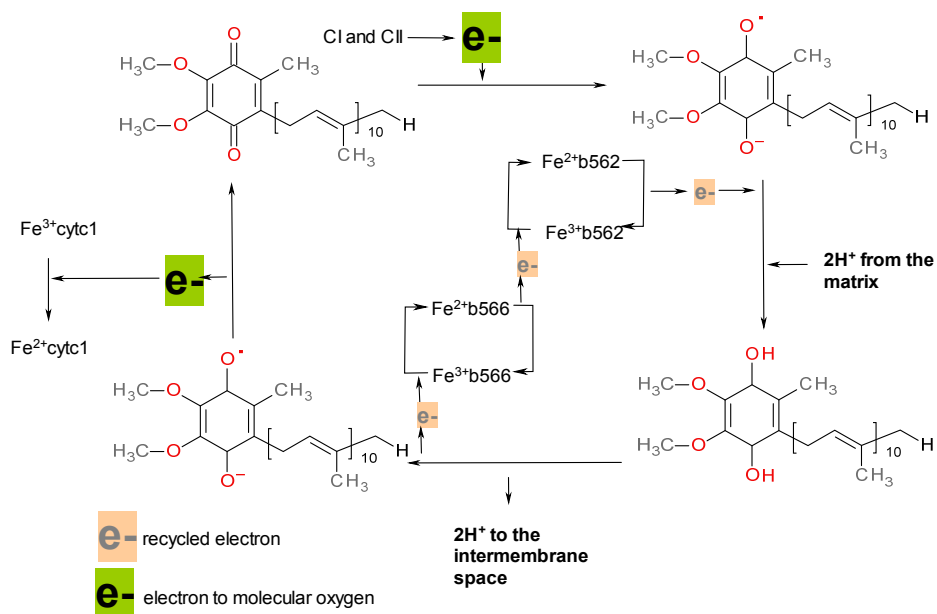


Fig. 4. Coenzyme Q cycle.

Besides the participation in the respiratory chain, literature data has reported, several other important functions of CoQ. The functions include participation in the uncoupling of oxidative phosphorylation and production of heat (Echtay et al., 2001), signaling for gene expression (Doring et al., 2007, Chew et al., 2007) and antioxidant activity (Gomez-Diaz et al., 1997, Papucci et al., 2003). This latter role is the focus of the present chapter and it will be discussed herein.

### 1.2.2 Fundamental concepts about cytochrome *c*

Respiratory cytochrome *c* is a nuclear-encoded protein located at the external side of the inner mitochondrial membrane. In mammals this protein contains 104 amino acids and a single heme group covalently bound to the protein and with a reduction potential of +260 mV. Unlike the other respiratory cytochromes that assembled in large and membrane bound complexes, cytochrome *c* is a small peripheral protein located at the external side of the inner mitochondrial membrane. Thus, cytochrome *c* is considered a diffusible carrier with pool function in the aqueous phase.

Cytochrome *c* is a basic protein bearing 19 lysine and 5 arginine residues giving a highly positively charged with pI = 9.6 and conferring to this protein a high affinity to acidic phospholipids such as cardiolipin, a lipid component of the inner mitochondrial membrane.

The electrostatic interaction is an important factor for the association of cytochrome *c* with phospholipid membranes and has been focus of several studies. (Rytömaa, 1995, Tuominen, 2002 Zucchi, 2003). The interaction of cytochrome *c* with acidic phospholipids involves both electrostatic and lipid extended interactions, the latter resulting from the insertion of one phospholipid chain in a hydrophobic channel, present in the cytochrome *c* structure, in the region of the heme crevice. Other important aspect about the interaction of cytochrome *c* with the inner mitochondrial membrane is the existence of two membrane binding sites in the cytochrome *c* structure (Kawai et al, 2005, Kawai, 2009).

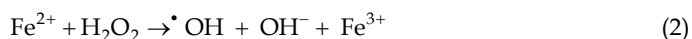
The biological role of cytochrome is beyond the cell respiration and involves also apoptosis and redox cell balance (Yong-Ling et al, 2008, Huttemann et al, 2011). Cytochrome *c* participates in the mitochondrial electron-transport chain as a mobile electron carrier that shuttles electrons between cytochrome *c*1 of Complex III and cytochrome *c* oxidase. The reduction of molecular oxygen to water catalyzed by cytochrome *c* via complex IV has a  $\Delta G^{\circ} = -100$  kJ/mol that is around twice higher as compared to the redox reactions catalyzed by complexes I and III (Hinkle et al., 1991)

Besides the participation in the respiratory chain, cytochrome *c* is a key protein for the intrinsic pathway of apoptosis triggered by some stimulus such as DNA damage, metabolic stress or the presence of unfolded proteins (Yong-Ling et al., 2008; Huttemann et al., 2011). The participation of cytochrome *c* in apoptosis is dependent on its detachment from the inner mitochondrial membrane followed by its translocation through the outer mitochondrial membrane to attain the cytosol. In the cytosol, cytochrome *c* engages the Apoptotic protease-activating factor-1 (APAF1), and composes the apoptosome (Liu et al., 1996; Kluck et al., 1996; Kluck et al., 1997, Yang et al., 1997).

## 2. Generation of reactive species in mitochondria

The use of molecular oxygen as final acceptor of electrons removed from the biological fuels was an evolutionary acquisition that resulted in a significant improvement of the energy yield, a crucial event for the rise of complex organisms. However, a low percentage of molecular oxygen consumed in mitochondrial respiratory chain is not completely reduced to water generating reactive oxygen species (ROS). Mitochondria clearly represent a primary source of ROS in most aerobic mammalian cells (Turrens et al., 1985). The mitochondrial generation of ROS occurs at electron transport chain as a secondary product of mitochondrial respiratory chain (Murphy, 2009). The primary ROS produced in this process is the superoxide anion ( $O_2^{\cdot-}$ ) resulted from a single electron reduction of molecular oxygen by the electrons leaked from the substrate of respiratory chain. In the mitochondrial matrix a superoxide dismutase (MnSOD) transforms superoxide into a more stable form: hydrogen peroxide ( $H_2O_2$ ). The rate of  $H_2O_2$  production in isolated mitochondria when in state 4 of respiration is 0.6–1.0 nmol/mg mitochondrial protein/min. (Turrens et al., 1985) but this range was considered over estimated and the superoxide production in normal respiring mitochondria could be around 0.1 nM  $H_2O_2$ /mg mitochondrial protein/min. Besides the components of the respiratory chain, other mitochondrial complexes also can generate superoxide, such as: dihydrolipoamide dehydrogenase-containing FAD-linked pyruvate,  $\alpha$ -ketoglutarate dehydrogenase complexes (Starkov et al., 2004), as well as the flavoenzymes  $\alpha$ -glycerophosphate dehydrogenase. In the respiratory chain, two sites have been found to be responsible for the vectorial generation of  $O_2^{\cdot-}$ . Mitochondria respiring with complex I/III substrates release superoxide anion into the matrix while complex II/III

substrates release superoxide anion into the intermembrane space. In complex I the production of  $O_2^{\bullet-}$  probably occurs via autooxidation of the reduced flavin mononucleotide (Turrens & Boveris, 1980) and in complex III the partial reduction of molecular oxygen to  $O_2^{\bullet-}$  occurs in the Q-cycle via the semiquinone intermediate (Zhang et al., 1998). The vectorial synthesis of superoxide anion indicates that the resultant  $H_2O_2$  formed can act as a mitochondrial second messenger for both nuclear and mitochondrial genomes. This signaling system could be a requirement for appropriate nuclear and mitochondrial gene expression and metabolome modulation. By this point view, the prooxidant formation of the  $O_2^{\bullet-}/H_2O_2$  second messenger system is essential for the normal physiological function of the metabolome and the random molecular damage promoted by  $O_2^{\bullet-}/H_2O_2$  has been rebutted. However, the physiological function of reactive species is dependent of a fine regulation mechanism warranted by the balance between the generation and decomposition of ROS. Oxidative stress occurs when cells have an imbalance of production and decomposition of ROS that results in damages of biomolecules such as lipids, DNA and proteins. Therefore,  $H_2O_2$  may generate the hydroxyl radical ( $HO^{\bullet}$ ), the most reactive and damaging oxygen species, through the Fenton reaction catalyzed by transition metals (Halliwell & Gutteridge, 1990, Eq. 2).



Hydroxyl radical can also be generated in the Haber-Weiss reaction with the superoxide radical as shown in Eq. 3 (Valko et al., 2004)



Superoxide ion can also contribute for the generation of hydroxyl radical by recycling  $Fe^{3+}$  to  $Fe^{2+}$  (Eq. 4)



Mitochondria is also a source of reactive nitrogen species (RNS) derived also from a signaling molecule, the nitric oxide ( $NO^{\bullet}$ ) (Moncada & Higgs, 1993; Denninger, 1999, Radi et al., 2002). Nitric oxide is generated by the family of nitric oxide synthases (NOS). The NOS family synthesizes  $NO^{\bullet}$  using L-arginine as a substrate and NADPH as reducing agent and the reaction is favored by the presence of  $Ca^{2+}$  ions and sulfhydryl groups.

Cells of the immune system produce both the superoxide anion and nitric oxide during the oxidative burst triggered by inflammation processes.

Under these conditions, nitric oxide and the superoxide anion may react to produce significant amounts of a highly oxidative molecule, peroxynitrite anion ( $ONOO^-$ ), able to promote DNA fragmentation, lipid oxidation and protein nitrosylation (Valko et al., 2007; Ghafourifar & Cadenas, 2005). Reaction (5) has one of the highest rate constants known for reactions of  $NO^{\bullet}$ . Thus,  $NO^{\bullet}$  toxicity is linked to its ability to combine with superoxide anion.



To assure the cell redox balance, the evolutionary acquisition of aerobic  $O_2$ -dependent metabolism was accompanied by a highly conserved antioxidant enzymatic apparatus that works in a concerted way to promote decomposition of  $O_2^{\bullet-}$  (Cu-Zn/Mn superoxide

dismutase and cytochrome *c*) and H<sub>2</sub>O<sub>2</sub> (catalase and glutathione peroxidase) as well as to repair oxidative damage of proteins (thioredoxine, glutaredoxine, thioredoxine reductase and others). In addition to the enzymatic apparatus, low molecular molecules contribute also to the redox cell balance by acting as free radical trapping. CoQ is included among these antioxidant molecules and, unlike cytochrome *c*, its action is not restricted to the mitochondria.

The present chapter is concerned with the state of art of the more recent findings about the antioxidant role played by the two mobile electron carriers present in the mitochondrial respiratory chain of higher organism cells: CoQ and cytochrome *c* and these findings are described herein.

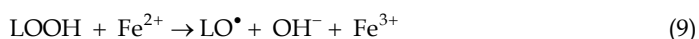
### 3. Antioxidant properties of CoQ and cytochrome *c*

#### 3.1 CoQ

Antioxidants are molecules able to inhibit the oxidation of other molecules by eliminating free radicals or by decreasing their formation. In biological systems the high effectiveness of antioxidant system is fundamental due to the constant generation of free radicals inside the organism at several sites that potentially may cause oxidative damage and consequently loss of function of protein, lipids and nucleic acids (Halliwell & Gutteridge, 2007). The effectiveness of antioxidants against oxidative damage in biological environments is directly related to their chemical structure.

The role of CoQ<sub>10</sub> in biological energy conversions as a redox component of the mitochondrial electron transport chain is well-described. Despite its ability to generate free radicals acting as pro-oxidant, as discussed before, Mellors & Tappel (1966) proposed an antioxidant role for CoQ showing that the reduced and oxidized forms of CoQ were able to prevent heme-catalyzed lipid peroxidation. Up today an increasing number of works has been conducted to understand the mechanisms of CoQ antioxidant action and the *in vivo* situations in which this property is achieved.

Due to the relatively high hydrophobicity, CoQ is partitioned into the lipid bilayers and can play the antioxidant role toward the impairment of lipid oxidation. Impairment of lipid oxidation is biologically important to the maintenance of the membrane integrity and to prevent the oxidation of lipoproteins (Ingold et al, 1993). Lipid oxidation is an oxidative chain reaction that is triggered by the abstraction of a hydrogen atom (H<sup>•</sup>) from allylic carbon of an unsaturated chain of a phospholipid (LH) by reactive species such as hydroxyl radical (<sup>•</sup>OH) resulting in a carbon centered free radical (L<sup>•</sup>). After intramolecular rearrangement L<sup>•</sup> may react with another LH or with molecular oxygen generating peroxy radicals (LOO<sup>•</sup>) that react with another LH resulting in lipid hydroperoxides (LOOH). Such lipid-derived peroxides suffer homolytic cleavage in the presence of metals in Fenton type reactions. The reactions involved in the initiation and propagation of the lipid peroxidation are summarized below.



Molecules that are able to react with these intermediate radical species to form less reactive radicals are considered chain breaking antioxidants, such as vitamin E. One of the mechanisms by which coenzyme Q exerts its antioxidant action inhibiting the lipid oxidation of membranes is by reacting directly with lipid-derived radicals transferring H<sup>•</sup> and generating the ubisemiquinone radical (CoQH<sup>•</sup>) as shown in Eq. 10.



Besides the inhibition of the lipid oxidation of membranes, CoQ also protects DNA from oxidation induced by H<sub>2</sub>O<sub>2</sub> plus metal ions. This process seems to be important especially for mitochondrial DNA oxidation since such damage is not easily repaired (Bentinger, 2010). It was demonstrated in human lymphocytes that incubation with CoQ results in increase of resistance to H<sub>2</sub>O<sub>2</sub> damage and less damage by exposure to oxygen (Litarru & Tiano, 2007). Endogenous CoQ also plays an important role in the protection of protein oxidation. The sensitivity of different proteins to oxidative stress varies to a great extent, depending on their structure, composition and localization (Bentinger et al, 2007) but the protective effect of CoQ is probably mediated by a direct scavenger mechanism. Also, the reactive ferrylmyoglobin formed by the reaction of myoglobin with H<sub>2</sub>O<sub>2</sub> can use CoQH<sub>2</sub> to be converted to metmyoglobin and oxymyoglobin in a mechanism that allows the heme protein to neutralize peroxides that can be harmful to cells (Mordente et al, 1993; Guo et al, 2002; Litarru & Tiano, 2007).

Although several studies have compared the antioxidant efficiency of vitamin E *versus* CoQ, there is no other biological function described for vitamin E differently of CoQ that participates in the energetic metabolism. This raises some evolutionary questions addressed by Beyer (1994) whether the antioxidant role of CoQ is merely a coincidence of its structure or it was selected on the basis of the advantage to organism against oxidative stress. Furthermore, there is more CoQ than vitamin E in tissues and in mitochondria (Joshi et al, 1963; Mellors & Tappel, 1966; Ingold et al, 1993). Due to its hydrophobicity, the antioxidant efficiency of CoQH<sub>2</sub> is influenced by the polarity of the environment and it is dependent on the accessibility to the free radicals. In aqueous media, ubiquinol is only about 10% as effective as a chain breaking antioxidant like Vitamin E, possibly because the intramolecular hydrogen bonding between the hydroxyl and methoxy groups in CoQ, and also to the electron withdrawing inductive effects of the methoxy groups that stabilize the phenolate relative to the phenoxyl radical (Ingold et al, 1993). These considerations are important to the interpretation of the *in vitro* analysis of the antioxidant activity of CoQ in aqueous systems and apolar environments, such as liposomes and membranes of organelles and cells. In aqueous media, the reactivity of a free radical generated by oxidant agents is modulated by the proton concentration as a function of the pK<sub>a</sub> of the radical group. Thus, the reactivity of CoQH<sup>•</sup> radicals generated by the reaction with lipid derived free radicals is lower within the phospholipid bilayer.

By using liposomes as membrane model, Frei et al (1990) showed that CoQH<sub>2</sub>, but not its oxidized form CoQ, scavenged free radicals and inhibited lipid peroxidation with similar efficiency than vitamin E. Also, the simultaneous addition of CoQH<sub>2</sub> and vitamin E resulted in oxidation of the quinone sparing vitamin E. In this *in vitro* system, ascorbate or GSH were not able to recycle the oxidized CoQ (Frei et al, 1990). The antioxidant activity of the reduced form CoQH<sub>2</sub> is due to its behavior as a phenolic antioxidant inhibiting not only the lipid

peroxidation but also regenerating vitamin E, preventing DNA and protein oxidation, and reducing ferrylmyoglobin (James et al, 2004; Littarru & Tiano, 2007; Roginsky et al, 2009). Several groups have been concerned to study the mechanisms of the antioxidant action of CoQ. It was proposed that CoQH<sub>2</sub> inhibits lipid peroxidation by decreasing the production of lipid peroxy radicals (LOO•) and reducing perferryl radicals. CoQH<sub>2</sub> could eliminate LOO• directly acting as a primary scavenger of free radicals (Crane, 2001). Thus, CoQH<sub>2</sub> can exert its antioxidant action inhibiting lipid peroxidation directly by acting as a chain breaking antioxidant and indirectly by recycling vitamin E (James et al, 2004; Cuddihy et al, 2008). It was showed that α-tocopherol recycling in mitochondrial membranes is directly dependent on the CoQ/α-tocopherol molar ratio (Lass & Sohal, 2000) and that such recycle process also occurs in vivo (Lass et al, 1999).



CoQ significantly increases the rate of vitamin E regeneration in membranes a process also observed in low density lipoproteins, presumably by CoQ content present in the blood (Crane, 2001). Alternatively, reduced coenzyme Q could react directly with superoxide and hydroxyl radicals as a free radical scavenger and interfere with the initiation of lipid peroxidation (Beyer, 1990). Differently of others antioxidant compounds, CoQ inhibits both the initiation and propagation of lipid and protein oxidation. (Bentinger et al, 2010). In fact, it is probable that this antioxidant is considerably more efficient than that exhibited by vitamin E (Turunen et al, 2003). The reactivity of CoQ and vitamin E with different radicals, including the reaction rate constants, was reviewed by James et al (2004).

In mitochondria it is proposed that the respiratory chain enzymes and other dehydrogenases are able to recycle CoQ to the reduced form able to protect membranes against oxidation. There are at least three enzymes responsible to maintain CoQ<sub>10</sub> in its reduced form: NADH cytochrome b5 reductase, NADH/NADPH oxidoreductase (also called DT-diaphorase) and NADPH coenzyme Q reductase (Turunen et al, 2004). Mitochondrial DT-diaphorase, a two-electron quinone reductase, seems to have a crucial participation in the antioxidant action of CoQ due to its maintenance in the reduced form CoQH<sub>2</sub> (Cadenas, 1995). Differently from NADH and succinate dehydrogenases, which are able to generate the partially reduced coenzyme Q ubisemiquinone, the DT-diaphorase is unique since it can directly reduce CoQ *via* 2 electron transfer without intermediate formation of the semiquinone (Beyer et al, 1996). CoQ can also be reduced by the mitochondrial respiratory chain (Genova et al, 2003; Bentinger et al, 2007). Another mechanism that may contribute to the antioxidant activity of CoQ is the interaction of superoxide dismutase with CoQH<sub>2</sub> and DT diaphorase resulting in inhibition of coenzyme autoxidation (Beyer, 1992). Besides the energetic role of coenzyme Q as mobile electron carrier, the antioxidant activity of CoQH<sub>2</sub> is important to decrease the oxidative modification of mitochondrial CoQ pool associated to the impairment of the electron transport in the respiratory chain observed during the lipid oxidation of mitochondrial membranes (Forsmark-Andrée et al, 1997). It was showed that the antioxidant effects of CoQ in microsomes and mitochondria are also mediated by vitamin E recycling (Kagan et al, 1990). Recently, it was demonstrated that the enzymes: lipoamide dehydrogenase, thioredoxin reductase and glutathione reductase can also reduce CoQ (Olsson et al, 1999; Xia et al, 2001; Xia et al, 2003).



The high antioxidant efficiency of CoQH<sub>2</sub> depends on several factors, including its localization into the membranes, hydrophobicity, the efficiency as scavenger of free radicals and recycling antioxidant cellular systems. Mitochondria are directly implicated with oxidative stress conditions, due to the constant generation of superoxide anions (O<sub>2</sub>•<sup>-</sup>) by the respiratory chain, a process which is normally counterbalanced by the antioxidant defense system composed of superoxide dismutase, glutathione peroxidase and reductase, GSH and NAD(P)H. However, in mitochondrial dysfunctions, the excessive formation of O<sub>2</sub>•<sup>-</sup>, and consequently of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), leads to the generation of the extremely reactive hydroxyl radical (•OH) by means of the Fenton-Haber-Weiss reaction (Sies, 1997). Stress oxidative is thought to be involved in the etiology of many human diseases (Brookes et al, 2004) but also in cell signaling (Linnane et al, 2007) and endogenous and exogenous antioxidants are crucial to modulate these processes. CoQ and vitamin E addition in cultured cells attenuated ROS production, lipid peroxidation, mitochondrial dysfunction, and cell death induced by amitriptyline (Cordero et al, 2009). In Langendorff preparations of isolated heart, pretreatment with CoQ protected coronary vascular reactivity after ischemia/reperfusion radical scavenger activity (Whitman et al, 1997). CoQ was also able to ameliorate cisplatin-induced acute renal injury in mice (Fouad et al, 2010).

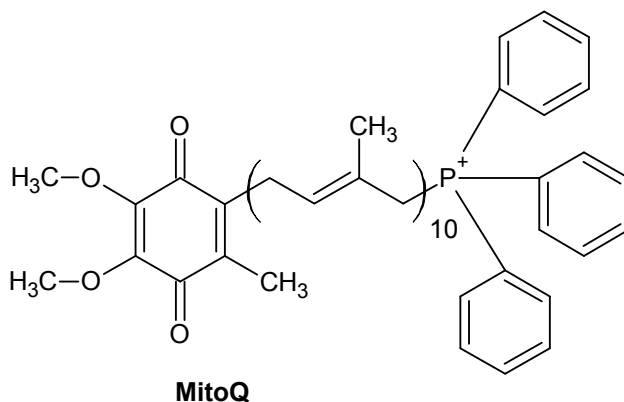


Fig. 5. Chemical structure of triphenylphosphonium-substituted coenzyme Q, MitoQ.

Many *in vitro* and *in vivo* studies showed that CoQ, mainly in its reduced state, may act as an antioxidant protecting membranes from oxidative damage (Beyer, 1990). Besides the antioxidant activity, CoQ participates as cofactor of uncoupling proteins and modulates gene expression associated to cell signaling, metabolism, transport, etc (Linnane et al, 2002). The hydrophobicity of CoQ allows its easy insertion into the mitochondrial inner membrane where it is converted to the reduced form by reductases (Beyer et al, 1996). Although the antioxidant activity of CoQ in biological membranes the relative high hydrophobicity disfavors its use as a therapeutic agent (Kelso et al, 2001). As an alternative, mitochondrial-targeted ubiquinone analogs, including Mito Q, and ubiquinone analogs with a decrease number of carbons in the side chain compared with CoQ10 were developed (Geromel et al, 2002). It was showed that the CoQ analogue decylubiquinone, but not CoQ, decreased ROS production associated to the inhibition of the MPT (mitochondrial permeability transition) and cell death in HL60 cells. Such effect is due to the antioxidant action of decylubiquinone either preventing ROS formation or scavenging ROS generated by cytochrome *bc*1

(Armstrong et al, 2003). MitoQ (Fig. 5) is an orally active antioxidant developed by the pharmaceutical industry to potentially treat several diseases. This compound retains the antioxidant activity of CoQ10 and the triphenylphosphonium cation (TPP<sup>+</sup>) substituent directs this agent to mitochondria (Tauskela, 2007).

In cultured cells MitoQ was able to accumulate into mitochondria and act against oxidative stress (Murphy & Smith, 2007; James et al, 2005). It was also demonstrated a protective effect of MitoQ in a sepsis model by decreasing the oxidative stress and protecting mitochondria against damage as well as by suppressing proinflammatory cytokine release (Lowes et al, 2008). It was proposed that the antioxidant action of MitoQ may be useful in the treatment of diseases associated to the impairment of mitochondrial Complex I (Plecitá-Hlavatá et al, 2009). On the other hand, it was recently showed that MitoQ may be prooxidant and present proapoptotic action due its quinone group that may participates in redox cycling and superoxide production (Doughan & Dikalov, 2007). Thus, the study of the mechanisms of antioxidant action and other effects of CoQ and derivatives must be considered for the development of quinone-based therapeutic strategies.

### 3.2 Cytochrome c

Similarly to that was described for CoQ, cytochrome c may also contribute to the generation and trapping of prooxidant species. It has been described that besides the participation in the respiratory chain and apoptosis, cytochrome c exhibits also a prooxidant peroxidase activity and an antioxidant superoxide oxidase activity. However, a whole view of the roles played by cytochrome c in cells leads to the conclusion that the respiratory and proapoptotic activities of this protein intrinsically contribute also to the cell redox balance.

It was demonstrate that loss of cytochrome c by mitochondria oxidizing NAD<sup>+</sup>-linked substrates results in respiratory inhibition associated to a significant increase of ROS production (Davey et al., 1998; Gnaiger et al., 1998; Rossingnol et al., 2000) The depletion of cytochrome c results in respiratory inhibition and maintains reduced the electron carriers upstream the heme protein with consequent increasing of the NAD(P)H levels. However, the terminal segment of the respiratory chain is more active than the proximal one in such way that only mild respiratory inhibition has been observed in cells undergoing apoptosis accompanied by cytochrome c release and increased production of ROS. Therefore, only almost total cytochrome c depletion could significantly promote respiratory inhibition and enhance of ROS production at complex I (Davey et al., 1998; Gnaiger et al., 1998; Rossingnol et al., 2000; Kushnareva et al., 2002) Considering the role played by cytochrome c in apoptosis, literature data have correlated this event to an increased peroxidase activity of the heme protein. In comparison with pentacoordinated heme proteins such as myoglobin and horseradish peroxidase, in the native form, cytochrome c reacts very slowly with peroxides (Radi et al., 1991). However, the peroxidase activity of cytochrome c can be favored in conditions leading to loss of the heme iron sixth coordination position with the sulfur atom of Met80 or the replacement of Met80 by other amino acid lateral chains (Nantes et al., 2000; Rodrigues et al., 2007; Nantes et al., 2001; Zucchi et al., 2003). A condition that can strongly favor the peroxidase activity of cytochrome c is the association with negatively charged membranes (Rytömaa, et al, 1992. Ott, et al., 2002. Mugnol, et al, 2008. Rytömaa & Kinnunen, 1994, Rytömaa, M & Kinnunen, 1995, Kawai, et al, 2005; Kagan, et al., 2005).

According to Kagan et al., (2004) the amount of cardiolipin in the outer side of the inner mitochondrial membrane can be increased in a proapoptotic condition and favor the

peroxidase activity of cytochrome *c*. In this scenario, the peroxidase activity of cytochrome *c* on cardiolipin should be involved in its detachment from the inner mitochondrial membrane to attain the cytosol and trigger apoptosis. In addition, the reaction of cytochrome *c* with lipid-derived carbonyl compounds results in the production of triplet excited species able to generate  $O_2(^1\Delta g)$  by energy transfer to molecular oxygen (Foote, 1968, Nantes et al., 1996; Estevam et al., 2004; Groves, 2006).

Considering the peroxidase activity of cytochrome *c* culminates with its detachment from the inner mitochondrial membrane leading to the death of cells with unbalanced redox processes, the pro-apoptotic activity of cytochrome *c* might be included, if not as antioxidant, but as a protective role of this protein for the whole organism.

However, the protective antioxidant activity of cytochrome *c* can also be exerted in a preventive rather than a destructive way. The elimination of superoxide ion by SOD generates hydrogen peroxide. As discussed before, hydrogen peroxide is a signaling molecule but its accumulation in cells should be prevented to avoid undesirable reaction with transition metal ions and the consequent generation of hydroxyl radical. Hydrogen peroxide can react with  $Fe^{III}$  respiratory cytochrome *c* and convert it to high valence species (oxoferryl forms) that are highly prooxidant species. The high valence species of cytochrome *c* can attack lipids and trigger a radical propagation leading to oxidative damages of mitochondrial membranes. Therefore, the cellular antioxidant apparatus includes catalase and GPx (glutathione peroxidase) that are responsible for hydrogen peroxide reduction.  $Fe^{III}$  cytochrome *c* competes with SOD for one electron reduction by superoxide ion. The reduction of cytochrome *c* by superoxide ion is more efficient than SOD to prevent oxidative stress because, by this way, the electron is devolved to the respiratory chain, does not generate hydrogen peroxide and further prevents the generation of high valence species of the heme protein. In an apparent paradox but consistent with the competition with cytochrome *c*, over expression of SOD1 has been related to an increase of the oxidative stress (Goldsteins et al., 2008). Cytochrome *c* can efficiently act as a true antioxidant by scavenging  $O_2^{\cdot-}$  without producing secondary and potentially harmful ROS (Pereversev et al., 2003).

Also, the reduction of cyt *c* heme iron by  $O_2^{\cdot-}$  impairs peroxidase activity on hydrogen peroxide and the consequent generation of radical and excited prooxidant species. As discussed before, even the conditions favoring the peroxidase activity of cytochrome *c* should not be considered exclusively harmful and damaging events since they culminate with detachment of cytochrome *c* from the inner mitochondria membrane to participate in the apoptosis in cytosol. It is important to note that the participation of cytochrome *c* in oxidative and nitrosative stress can also promote damages in the heme protein (Estevam et al., 2004; Rodrigues et al., 2007), including impairment of the proapoptotic activity (Suto et al., 2005). However, the association of cytochrome *c* with unsaturated lipid bilayers is shown to prevent these oxidative damages and preserve the apoptotic activity (Estevam et al., 2004; Rodrigues et al., 2007).

The contribution of cytochrome *c* for hydrogen peroxide elimination is probably not restricted to the peroxidase mechanism and superoxide ion trapping. It has been proposed the reduction of hydrogen peroxide by  $Fe^{II}$  cytochrome *c* in a mechanism named as electron-leak pathway.

At this point it is important to consider the role played by testicular cytochrome *c*. Reactive oxygen species generated in the respiratory chain are responsible for damages in biomolecules such as DNA, lipids and proteins of sperm that culminate with loss of cell

viability and infertility. Sperm are particularly susceptible to the undesirable effects of ROS because their high content of polyunsaturated fatty acids present in the plasma membrane and a low concentration of ROS scavenging enzymes in the cytoplasm (Jones et al, 1979, Huttemann et al., 2011; Sharma et al, 1999; Liu et al., 2006). Mammalian germ cells express two types of cytochrome c during their development: the somatic cytochrome c and a testis specific cytochrome c that shares 86,5% identity with the somatic counterpart. During meiosis, the expression of somatic cytochrome c declines and testis cytochrome c becomes the predominant form in sperm. Liu et al, reports that testis cytochrome c is three fold more efficient than the somatic one in the catalysis of H<sub>2</sub>O<sub>2</sub> reduction and is also more resistant to be degraded by the side products of this reaction. In line with the proposal that apoptosis is also an antioxidant protective mechanism, testis cytochrome c exhibited higher apoptotic activity in the well established apoptosis measurement system using *Xenopus* egg extract.

Therefore, testis cytochrome c can protect sperm from the damages caused by H<sub>2</sub>O<sub>2</sub> as well as promote the elimination of sperm whose DNA was damaged. Taken together the electron-leak pathway and apoptosis, probably related to a peroxidase activity are the contribution of testis cytochrome c for the biological integrity of sperm produced by mammalian cells.

Therefore, a delicate balance controls both antioxidant and prooxidant activities of cytochrome c with repercussions on both bioenergetics and cell death. In this regard, it is noteworthy that cytochrome c import to mitochondria, synthesis and activities underlying life and death fates for cells are regulated by signaling mechanisms and involves thiol redox balance, allosteric regulation and chemical modifications including nitration and phosphorylation. Cytochrome c is a nuclear-coded protein that is imported by mitochondria as apoprotein and, in the intermembrane space, is converted to the holoprotein by the covalent ligation of the heme group to cystein residues 14 and 17, a process catalyzed by the enzyme heme lyase (Dumont et al, 1991). The addition of the heme group confers redox properties for cytochrome c and enables it to participate, as terminal oxidant agent, in the thiol redox cascade involved in the import and assembly of TIMs (transporters of the inner mitochondrial membrane) (Chacinska et al, 2004, Riemer et al., 2011; Allen et al., 2005). The participation of cytochrome in the respiratory chain as electron carrier is also controlled by allosteric and covalent modification mechanisms. ATP has been characterized as a downregulator of the electron-transfer activity of cytochrome c. The mechanism may involve changes of both charge and structure of cytochrome c and is consistent with the adjustment of respiratory chain activity to the energy demand of cell signaled by the ATP/ADP ratio. Recent findings have strongly shown that the well-known mechanism of protein phosphorylation operates also in the control of proteins responsible for the oxidative phosphorylation. The technique of cytochrome c isolation in the presence of nonspecific phosphatase inhibitors enabled the identification of tissue-specific sites of cytochrome c and evidenced the activities of this protein is under the control of this specific cell signaling mechanism mainly operating in higher organisms (Huttemann et al., 2011). Previously, it was demonstrated that redox reaction of cytochrome c with a model aldehyde, diphenylacetaldehyde, is under the control of the protonation of two tyrosine residues (Rinaldi et al, 2004). More recent findings established the phosphorylation of cytochrome c tyrosine residues is involved in the control of the transmembrane potential that in health conditions should not attain the maximal to avoid increase of ROS generation (Yu et al., 2008; Zhao et al., 2010). The consequences of cytochrome c nitration in biological systems

have been investigated and demonstrated that a small structural change promoted by nitration of tyrosine 74 does not preclude ligation of cytochrome c to Apaf-1 but this cytochrome c form became unable to activate caspases (Garcia-Heredia et al., 2010). Similarly to CoQ, the more recent findings about cytochrome c biological functions operating under the control of cell signaling mechanisms led to investigations concerning the therapeutical use of cytochrome c properties by administration of exogenous proteins as well as by controlling its phosphorylation in pathological conditions (Huttemann et al, 2011; Piel et al., 2007, 2008).

Fig. 6 summarizes the antioxidant activity of cytochrome c.

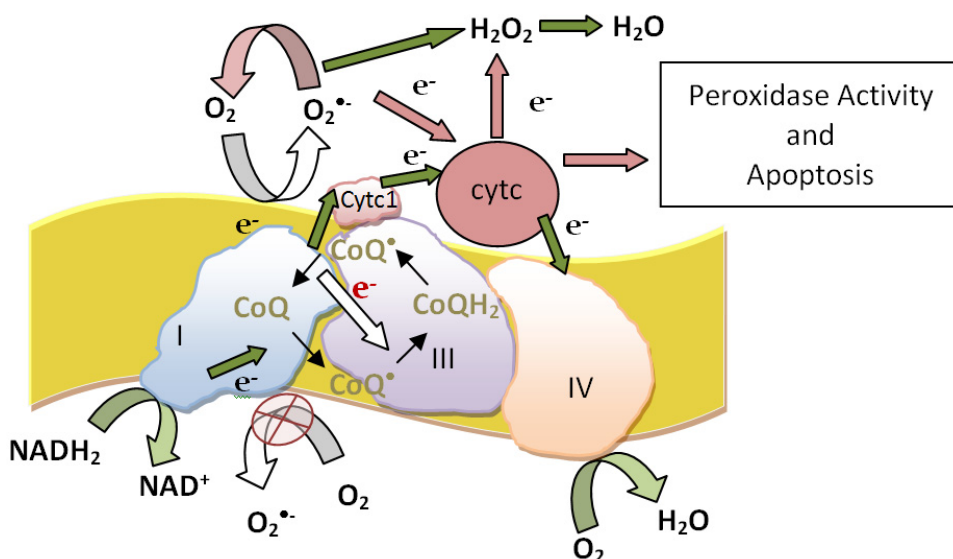


Fig. 6. Antioxidant activity of cytochrome c. In the respiratory chain, cytochrome c affects the generation of O<sub>2</sub><sup>•-</sup> and H<sub>2</sub>O<sub>2</sub> by making the electron transfer of the respiratory chain more fluent (green arrows). The heme protein also eliminates the generated O<sub>2</sub><sup>•-</sup> and H<sub>2</sub>O<sub>2</sub> through a cytochrome c mediated electron-leak pathway (red arrows). Further, the peroxidase activity of cytochrome c associated to apoptosis is also a protective mechanism for the whole organism as in the case of testis cytochrome c.

#### 4. Conclusion

The evolutionary acquisition of the O<sub>2</sub>-dependent aerobic metabolism resulted in a highly more efficient use of the energetic fuels and a cell signaling mechanism based on reactive species. Concerning the ROS, the primary species produced in mitochondria is O<sub>2</sub><sup>•-</sup> from which both the signaling molecule, H<sub>2</sub>O<sub>2</sub>, and the highly deleterious derivative, hydroxyl radical are generated. Therefore, a very efficient antioxidant apparatus was also evolved to assure cell redox balance and repair of oxidative damages. The antioxidant apparatus encompasses enzymes able to decompose reactive species (SOD, catalase) and repair oxidative damages (thioredoxin, glutaredoxine) and free radical trapping (ascorbic acid,

tocopherol, lipoic acid). More recently, cytochrome c was included in the category of antioxidant enzymatic apparatus due to its capacity to oxidize superoxide ion and devolve the electron to the respiratory chain as well as by the capacity to reduce hydrogen peroxide. The electron transport in the respiratory chain can also be considered an antioxidant activity of cytochrome c because it contributes for the fluency of electron transport. The antioxidant activity of CoQ is based on the direct and indirect trapping of free radicals and it is not restricted to mitochondria but exerted in the whole cellular and extra-cellular media. The beneficial antioxidant activity of CoQ has been studied with the aim to develop an antioxidant therapy by the use of CoQ analogous and derivatives. Figure 7 summarizes the antioxidant activity of mobile electron carriers of the respiratory chain.

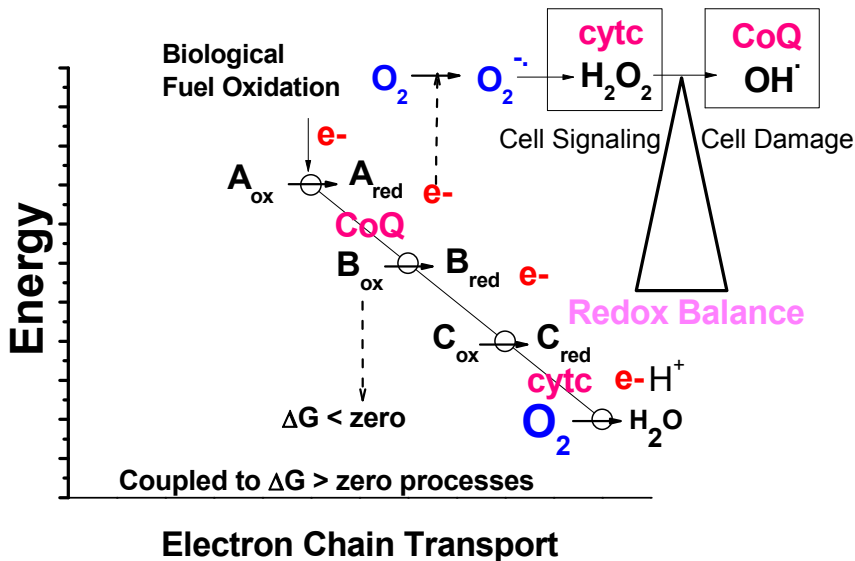


Fig. 7. Antioxidant activity of mobile electron carriers of the respiratory chain. The aerobic oxidation of biological fuels by using molecular oxygen as final acceptor of electrons in an electron transport chain allowed an efficient mechanism of withdrawing energy from biological fuels concomitant with the generation of reactive species for cell signaling but also able to promote cell damage. The redox cell balance is achieved by prevented the accumulation of reactive species without prejudicing the signaling function. Cytochrome c contributes to the maintenance of the adequate levels of hydrogen peroxide in cells by means of fluency of electron transport in the respiratory chain, oxidation of superoxide ion and reduction of hydrogen peroxide and CoQ by means of direct and indirect trapping of free radicals.

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# Mitochondrial Calcium Signalling: Role in Oxidative Phosphorylation Diseases

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## 1. Introduction

Mitochondria are double membrane-bound organelles that not only constitute the “cellular power plants” but also are crucially involved in cell survival, apoptosis, redox control, Ca<sup>2+</sup> homeostasis and many metabolic and biosynthetic pathways.

The mitochondria generate energy by oxidizing hydrogen derived from dietary carbohydrate (TCA: tricarboxylic acid cycle) and lipids (beta-oxidation) with oxygen to generate heat and energy in the form of ATP (Adenosine triphosphate). Energy generation in mitochondria occurs primarily through oxidative phosphorylation (OXPHOS), a process in which electrons are passed along a series of carrier molecules called the electron transport chain (ETC). This chain is composed of four multisubunit assemblies that are embedded in the mitochondrial inner membrane: complex I (NADH:ubiquinone oxidoreductase; EC 1.6.5.3), complex II (succinate:ubiquinone oxidoreductase; EC 1.3.5.1), complex III (ubiquinol:cytochrome-c oxidoreductase; EC 1.10.2.2) and complex IV (cytochrome-c oxidase; EC 1.9.3.1). Complexes I, III and IV actively translocate protons from the matrix into the intermembrane space using energy extracted from electrons passing through the chain. These electrons are liberated from NADH and FADH<sub>2</sub>, at complexes I and II, respectively, where they are donated to the lipophilic electron carrier coenzyme Q for further transport to complex III. From there, electrons are shuttled to complex IV by cytochrome-c. At this complex, electrons are finally used for the reduction of oxygen to water (Hatefi, 1985; Saraste, 1999) (Figure 1 A).

The energy released by the flow of electrons through the ETC and the flux of protons out of the mitochondrial inner membrane creates a capacitance across the mitochondrial inner membrane, the electrochemical gradient ( $\Delta P$ ) composed of an electrical potential ( $\Delta\psi$ ) and a concentration ratio ( $\Delta pH$ ). The potential energy stored in  $\Delta P$  is coupled to ATP synthesis by complex V (F<sub>0</sub>/F<sub>1</sub>-ATP-synthase; EC 3.6.1.34). As protons flow back into mitochondrial

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matrix through complex V, ADP and Pi are bound, condensed and released as ATP. With Complex V, the ETC complexes constitute the OXPHOS system. The OXPHOS system generates the vast majority of cellular ATP during oxidative metabolism. Some of the ATP is used for the mitochondrion's own needs, but most of it is transported outside the organelle by the adenine nucleotide translocator (ANT) and used for diverse cell functions (Hatefi, 1985; Saraste, 1999) (Figure 1 A).

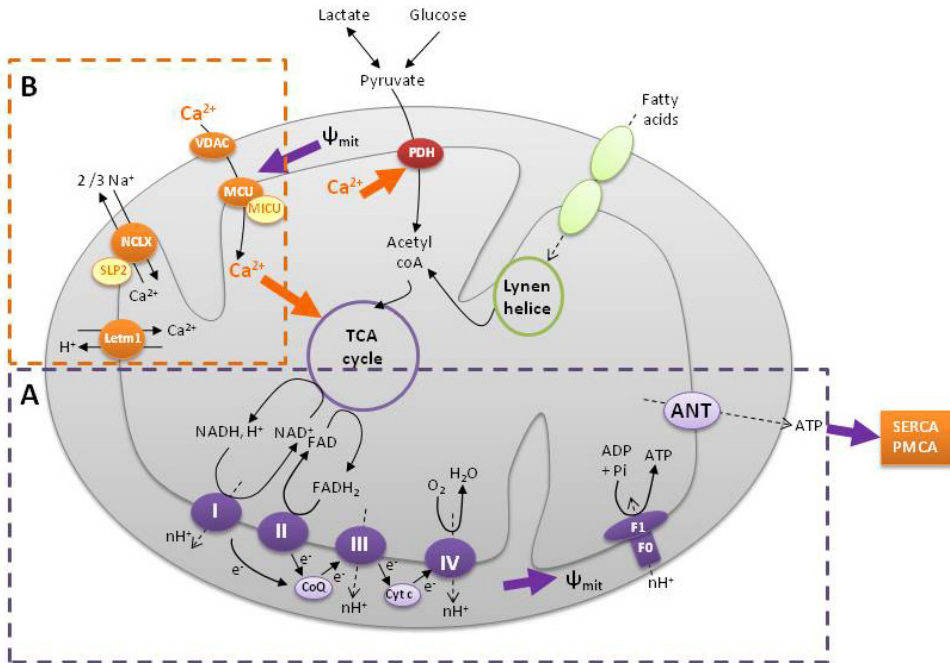


Fig. 1. Schematic view of of mitochondrial OXPHOS system (A), and. mitochondrial Ca<sup>2+</sup> influx and efflux mechanisms (B). Large size arrows indicate the interplay between mitochondrial Ca<sup>2+</sup> signaling and OXPHOS.

## 2. Genetics and pathology of OXPHOS

### 2.1 Genetics of OXPHOS system

The OXPHOS system is composed of more than 80 different proteins, 13 of which are encoded by the mitochondrial DNA (mtDNA) and the others by the nuclear genome (nDNA) (Chinnery & Turnbull, 2001; Wallace, 1992). There are seven mtDNA-encoded subunits in complex I, one in complex III, three in complex IV and two in complex V. Complex II consists solely of nDNA-encoded subunits.

The structure of human mitochondrial DNA (mtDNA) was reported ≈ 30 years ago (Clayton & Vinograd, 1967). The transcription products of mtDNA include 2 ribosomal RNA species (12S and 16S rRNA), 13 messenger RNAs and 22 transfer RNAs. Replication of mtDNA occurs independently from cell cycle phase and from replication of nuclear DNA. Mitochondrial DNA is present in 10<sup>3</sup>–10<sup>4</sup> identical copies in each cell, with the exception of

sperm and mature oocytes, in which mtDNA copy numbers are  $\approx 10^2$  and  $\approx 10^5$ , respectively. In general, there are believed to be two to ten copies of DNA per mitochondrion. The sequences of mtDNAs from unrelated individuals in human populations typically differ by about 0.3 %. Most individuals, however, have a single mtDNA sequence variant in all their cells (homoplasmy). mtDNA transmission occurred exclusively through the maternal lineage. Almost all of the nDNA-encoded OXPHOS subunits have been characterized at the cDNA level and several at the genomic level in humans. In general, the chromosomal distribution of the genes seems to be random, and expression of most gene products is ubiquitous but predominates in tissues or organs with a high energy demand.

Richard Scarpulla and co-workers have provided important insight into the regulatory mechanisms that are involved in the transcriptional control of OXPHOS genes (Gugneja et al., 1996; Huo & Scarpulla, 1999; Wu et al., 1999). They identified the nuclear respiratory factors NRF1 and NRF2, which act on overlapping subsets of nuclear genes that are involved in the biogenesis of the respiratory chain. Recent mammalian studies have identified PGC1 as a crucial regulator of cardiac mitochondrial number and function in response to energy demand (Lehman et al., 2000). Analysis of the expression pattern of OXPHOS genes revealed that their regulation might also be exerted post-transcriptionally (Di Liegro et al., 2000).

## 2.2 OXPHOS diseases

Among the inborn errors of metabolism, mitochondrial disorders are the most frequent with an estimated incidence of at least 1 in 10,000 births (reviewed in (Smeitink et al., 2001)). Although the term mitochondrial disorder is very broad, it usually refers to diseases that are caused by disturbances in the OXPHOS system. After the first description,  $\approx 40$  years ago, of a patient with “loose coupling” – a defect in the coupling between mitochondrial respiration and phosphorylation – by Luft and collaborators (Luft et al., 1962), thousands of patients have been diagnosed by measurement of OXPHOS-system enzyme activities. The great complexity of the OXPHOS system, which consists of proteins, some encoded by the mitochondrial genome and others by the nuclear genome, may explain the wide variety of clinical phenotypes that are associated with genetic defects in oxidative phosphorylation. Disease-causing defects can occur in a single OXPHOS complex (isolated deficiency) or multiple complexes at the same time (combined deficiency). OXPHOS diseases give rise to a variety of clinical manifestations, particularly in organs and tissues with high-energy demand such as brain (encephalopathies), heart (cardiomyopathies), skeletal muscle (myopathies) and liver (hepatopathies) (reviewed in (Finsterer, 2006a, 2006b; Schaefer et al., 2004)).

We have also to consider the presence of fundamental differences between mitochondrial genetics and Mendelian genetics when studying human OXPHOS diseases. These differences are linked to maternal inheritance of mtDNA, polyplasmly, heteroplasmy and the threshold effect, whereby a critical number of mutated mtDNAs must be present for the OXPHOS system to malfunction (Wallace, 2005).

One of the frequent OXPHOS disorders is Leigh Syndrome (OMIM 256000), an early-onset progressive neurodegenerative disorder, leading to death mostly within a few years after the onset of the symptoms. This disorder is characterized by lesions of necrosis and capillary proliferation in variable regions of the central nervous system. Clinical signs and symptoms comprise muscular hypotonia, developmental delay, abnormal eye movements, seizures, respiratory irregularities and failure to thrive. Other mitochondrial disorders caused by

OXPPOS defects include Mitochondrial Encephalopathy, Lactic Acidosis and Stroke-like episodes (MELAS; OMIM 540000), Myoclonic Epilepsy with Ragged Red Fibers (MERRF; OMIM 545000), Neurogenic weakness, Ataxia, Retinitis Pigmentosa/Maternally Inherited Leigh Syndrome (NARP/MILS; OMIM 516060), Leber's Hereditary Optic Neuropathy (LHON; OMIM 535000), and Mohr-Tranebjaerg syndrome (a.k.a. Deafness Dystonia Syndrome; OMIM 304700).

Because of the genetic complexity of the energy-generating system, many other diseases have been shown to be associated with defect in mitochondrial function (DiMauro & Moraes, 1993; DiMauro & Schon, 2003). For example, there is increasing evidence that inherited OXPPOS dysfunction is also implicated in diabetes, age-related neurodegenerative diseases, such as Parkinson's, Alzheimer and Huntington's diseases, and various forms of cancers (Shoubridge, 2001; Zeviani & Carelli, 2007).

### 2.2.1 Mitochondrial DNA mutations linked to OXPPOS diseases

The complexity of mitochondrial DNA mutations linked to OXPPOS diseases is that one mutation can cause a broad spectrum of clinical manifestations. Conversely, different mutations can be associated with the same clinical phenotype. Specific phenotypes include forms of blindness, deafness, movement disorders, dementia, cardiovascular diseases, muscle weakness, renal dysfunction, and endocrine disorders including diabetes. In the past 20 years, more than 100 point mutations and innumerable rearrangements have been associated with human mitochondrial diseases. In this context, it is worth mentioning, however, that we still lack comprehensive and unbiased epidemiological data about the frequency of known mtDNA mutations. Although tRNA genes as a whole represent  $\approx 10\%$  of the mtDNA, mutations in these genes account for  $\approx 75\%$  of mtDNA-related diseases.

We can identify three categories of pathogenic mtDNA mutations: rearrangement mutations, polypeptide gene missense mutations, and protein synthesis (rRNA and tRNA) gene mutations (reviewed in (Wallace, 2005)).

- Rearrangement mutations of mtDNA can be either inherited or spontaneous. Inherited mtDNA rearrangements are primarily insertions. The first inherited insertion mutation to be identified caused maternally inherited diabetes and deafness (Ballinger et al., 1992, 1994). Spontaneous mtDNA deletions result in a related spectrum of symptoms, irrespective of the position of the deletion end points. This is because virtually all deletions remove at least one tRNA and thus inhibit protein synthesis (Moraes et al., 1989). Thus the nature and severity of the mtDNA deletion rearrangement is not a consequence of the nature of the rearrangement, but rather of the tissue distribution of the rearranged mtDNAs.
- Missense mutations in mtDNA polypeptide genes can also result in an array of clinical manifestations. Three relatively frequently observed point mutations are A3243G in the tRNA(Leu)(UUR) gene, A8344G in the tRNA(Lys) gene and T8993G in the ATPase 6 gene and are associated with NARP when present at lower percentage of mutants or with lethal Leigh syndrome when present at higher percentage of mutants (Holt et al., 1990; Tatuch et al., 1992). Mutations have also been identified in mtDNA genes that encode proteins of the OXPPOS system, such as the cytochrome b gene and the mitochondrial complex I genes. A prominent example of the latter group of mtDNA protein-coding gene mutations is LHON, which is a common cause of subacute bilateral optic neuropathy that usually presents in early adult life and that predominantly affects

males. Most LHON patients harbor one of three point mutations that affect mtDNA complex I, or the NADH:ubiquinone oxidoreductase (ND) genes: G3460A in ND1, G11778A in ND4 and T14484C in ND6. Patrick Chinnery and colleagues showed that the mitochondrial ND6 gene is a hot spot for LHON mutations and suggested that the ND6 gene should be sequenced in all LHON patients who do not harbour one of the three common LHON mutations (Chinnery et al., 2001). Rare nonsense or frameshift mutants in Cytochrome oxidase subunit I (COI) have been associated with encephalomyopathies (Bruno et al., 1999; Comi et al., 1998).

- Pathogenic mtDNA proteins synthesis mutations can also result in multisystem disorders with wide range of symptoms. The most common mtDNA protein synthesis mutation is A3243G in the tRNA(Leu). This mutation is linked to a variety of clinical symptoms. When present at relatively low level (10%-30%) in the blood, the patient may manifest only type II diabetes. By contrast, when the mutation is present in > 70% of the mtDNA, it causes more severe symptoms including short stature, cardiomyopathy, Chronic Progressive External Ophthalmoplegia (CPEO; OMIM157640) and MELAS (Goto et al., 1990; van den Ouweland et al., 1994).

### 2.2.2 Nuclear DNA mutations linked to OXPHOS diseases

Nuclear DNA mutations linked to OXPHOS diseases includes defects in structural OXPHOS genes, faulty inter-genomic communication, and defects in OXPHOS assembly, homeostasis and import. Most nuclear gene mutations affect various protein subunits of complex I and complex II.

The first structural OXPHOS-gene mutation was reported in two sisters with Leigh syndrome and isolated complex II deficiency (Bourgeron et al., 1995). The pathogenic mutation was in the gene that encodes the flavoprotein: SDHA (succinate dehydrogenase subunit A). Subsequently, another family was found to have mutations in this subunit (Parfait et al., 2000). Very interestingly, two groups independently reported mutations of the complex II subunit D and C genes in hereditary paraganglioma – usually benign, vascularized tumours in the head and in the neck (Baysal et al., 2000; Niemann & Muller, 2000). This work has uncovered a new and surprising association between mitochondrial defects and carcinogenesis. Genetic characterization of Complex I deficiency in a patient with a Leigh-like presentation revealed a 5-base-pair (bp) duplication in NDUFS4 (NADH dehydrogenase (ubiquinone) Fe-S protein 4) that destroys the consensus phosphorylation site in the gene product and extends the length of the protein by 14 amino acids (van den Heuvel et al., 1998). Further studies have revealed that this duplication abolishes cyclic-AMP-dependent phosphorylation of NDUFS4, thereby impairing activation of the complex. Further complex I mutations have been identified and  $\approx$  40% of complex I deficiencies in children, in which the defect is detected in cultured skin fibroblasts, can now be explained by mutations in structural nuclear genes (Loeffen et al., 1998, 2000).

OXPHOS defects caused by defective interplay between the mitochondrial and nuclear genomes have also been described. The clinical features of the Mitochondrial Neuro-GastroIntestinal Encephalomyopathy syndrome (MNGIE) include ophthalmoparesis, peripheral neuropathy, leucoencephalopathy and gastrointestinal symptoms (chronic diarrhea and intestinal dysmotility). Muscle biopsy shows ragged red fibers (RRFs) and COX-negative fibers and either partial isolated complex IV deficiency or combined OXPHOS-complex deficiencies (Hirano et al., 1994). Mitochondrial DNA analysis in this

autosomal recessive syndrome showed mtDNA deletions, depletion, or both. The MNGIE locus was mapped to chromosome 22q13.32-qter, a region that contains the thymidine phosphorylase (TP) gene (gene symbol ECGF1). Studies on patients showed that TP activity was markedly decreased. Ichizo Nishino and collaborators found various homozygous as well as compound heterozygous ECGF1 mutations in the genomic DNA of MNGIE patients (Nishino et al., 1999). The precise mechanism by which TP deficiency leads to mtDNA rearrangements have still to be explained, but imbalance of the mitochondrial nucleotide pool is likely to have a role. Autosomal dominant Progressive External Ophthalmoplegia (adPEO) is an adult-onset mitochondrial disorder that is characterized by progressive external ophthalmoplegia and variable additional features, including exercise intolerance, ataxia, depression, hypogonadism, hearing deficit, peripheral neuropathy and cataract (Zeviani et al., 1990). Some patients carry mtDNA deletions, although the disease is inherited in an autosomal fashion. Of the two autosomal loci for this disorder, the 4q-adPEO locus includes the gene for the heart and skeletal muscle isoform of the ANT1. Kaukonen and collaborators (Kaukonen et al., 2000) identified two heterozygous missense mutations in this gene in several families and in one sporadic patient with adPEO.

Enzyme complex I and IV deficiencies are by far the most frequently observed abnormalities of the OXPHOS system. In sharp contrast to isolated complex I deficiencies, no mutations have been found as yet in the ten nuclear genes that encode the structural proteins of complex IV (Adams et al., 1997). The discovery of mutations in a nuclear assembly gene that is associated with COX deficiency resulted from chromosomal transfer experiments. This approach identified mutations in the SURF1 gene in patients with COX-deficient Leigh syndrome (Tiranti et al., 1998; Zhu et al., 1998). SURF1 is part of a cluster of unrelated housekeeping genes and is the only gene of this cluster that is known or believed to be involved in COX assembly (Tiranti et al., 1999). Nuclear gene defects that are associated with isolated complex III or complex V deficiencies have not yet been discovered. In recent years, four inherited neurodegenerative diseases, Friedreich ataxia, hereditary spastic paraplegia, human DDP syndrome (deafness/dystonia peptide) and dominant optic atrophy (OPA1) have also been shown to be mitochondrial disorders that are caused by nuclear DNA mutations in the genes for frataxin, paraplegin, DDP and OPA1, respectively. Mitochondria obtained from heart biopsies of Friedreich ataxia patients disclosed specific defects in the citric-acid cycle enzyme aconitase, and complex I-III activities (Rotig et al., 1997). The causative Friedreich ataxia protein, frataxin, has an essential role in mitochondrial iron homeostasis, and Friedreich ataxia can therefore be considered as an OXPHOS homeostasis defect. Muscle biopsies from the autosomal recessive form of patients with hereditary spastic paraplegia revealed histochemical signs of a mitochondrial disorder, namely RRFs, COX-negative fibers and succinate dehydrogenase-positive hyperintense fibers (Casari et al., 1998). Linkage and subsequent mutation analysis revealed large deletions in a gene dubbed paraplegin (Casari et al., 1998). Owing to the homology with a yeast mitochondrial ATPase with both proteolytic and chaperone-like activities, it has been suggested that this form of hereditary spastic paraplegia could be a neurodegenerative disorder due to OXPHOS deficiency, attributing a putative function in the assembly or import of respiratory chain subunits or cofactors to paraplegin (Di Donato, 2000). The DDP syndrome, an X-linked recessive disorder also known as the Mohr-Tranebjaerg syndrome, is associated with a novel defect in mitochondrial protein import (Koehler et al., 1999). The defective gene is homologous to the yeast protein Tim8, which belongs to a family of

proteins that are involved in intermembrane protein transport in mitochondria. Therefore, the DDP syndrome should be considered as the first example of a new group of mitochondrial import diseases (Koehler et al., 1999). Finally, OPA1 is caused by defects in a dynamin-related protein that is targeted to mitochondria and might exert its function in mitochondrial biogenesis and in stabilization of mitochondrial membrane complexes (Delettre et al., 2000).

### 3. Models to study OXPHOS diseases

#### 3.1 Cybrids and Rho<sup>0</sup> cells

Cybrids, or “cytoplasmic hybrids,” are cultured cells manipulated to contain introduced mitochondrial DNA (mtDNA). Cybrids have been a central tool to unravel effects of mtDNA mutations in OXPHOS diseases. In this way, the nuclear genetic complement is held constant so that observed effects on OXPHOS can be linked to the introduced mtDNA. The cybrids are produced by first treating mitochondrial donor cells with cytochalasin B to weaken the cytoskeleton, before subjecting the cells to a centrifugal force, either as attached cells or in suspension. The dense nuclei are extruded, leaving plasma membrane-bound “cytoplasts” containing cell cytoplasm and organelles, including mitochondria. These cytoplasts are then fused with a nuclear donor cell line. The first mammalian cultured cell phenotype identified to segregate with mtDNA was in human (HeLa) cells, where mtDNA imparted resistance to the antibiotic chloramphenicol (Spolsky & Eisenstadt, 1972). Several other mtDNA-linked drug-resistant phenotypes were identified in mammalian cells in the 1970s and 1980s, including resistance to the complex III inhibitors antimycin and myxothiazol (Howell & Gilbert, 1988) and to the complex I inhibitor rotenone (Bai & Attardi, 1998). The development of robust DNA-sequencing methods leads to the identification of single-base substitutions in the 16S rRNA gene of the mtDNA of independently derived yeast, mouse, and human chloramphenicol cell lines (Blanc & Dujon, 1980; Kearsey & Craig, 1981). These pioneering studies were in turn followed by identification of the first cytochrome b mutants (Howell & Gilbert, 1988) and more recently ND5, ND6, and COI mutants.

The second cellular OXPHOS model corresponds to the isolation of a human cell line without mtDNA (called Rho<sup>0</sup> cells). Employing an approach first used in yeast (Slonimski et al., 1968), cells were incubated with low levels of the drug ethidium bromide, which intercalates DNA. Low levels of the drug selectively inhibits the gamma-DNA polymerase responsible for mtDNA replication, and with ongoing cell division, the mtDNAs are “diluted” to the point where clones can be isolated without detectable organelle genomes. King and Attardi (King & Attardi, 1989) also discovered the absolute requirement for pyruvate gained by these cells and confirmed the previous observation from Paul Desjardins and collaborators (Desjardins et al., 1985) that mtDNA-less cells also required added uridine for growth. This allowed a selection regime to be used after cytoplast- Rho<sup>0</sup> cell fusion so that unfused Rho<sup>0</sup> cells could be eliminated and cybrids selected with the use of an appropriate nuclear drug-resistant marker (King & Attardi, 1989). Apart from their value in cybrid experiments, such Rho<sup>0</sup> cells represent a unique research tool by themselves. They are a surprising reminder that OXPHOS is dispensable, at least for some differentiated mammalian cell types. In this instance, ATP production is 100% from glycolysis, so the cells acidify culture media very rapidly by producing large quantities of lactate. They retain functional mitochondria (except lacking OXPHOS), which show a transmembrane potential

(probably from the electrogenic exchange of ATP for ADP) and can import the hundreds of other proteins needed for non-OXPHOS functions. The pioneering cybrid work using the selectable markers was limited in the sense that endogenous mtDNAs were also present; that is, the cybrids were heteroplasmic. The Rho<sup>0</sup> cell approach allowed creation of homoplasmic or heteroplasmic cells, depending on the mtDNA donor cell(s) used.

### 3.2 Human fibroblasts

The use of individual patient's cells in tissue cultures enables the study of specific defects. With respect to cell type, myoblasts are most likely to express the phenotype observed in muscle, but it is generally not feasible to derive myoblasts for each diagnostic muscle biopsy, because most of the muscle tissue is used up for enzymatic, pathological and molecular workup. Moreover, myoblasts are not representative of some liver-specific phenotypes. An alternative to myoblasts, are fibroblasts, which are much easily obtained during a muscle biopsy or after (Robinson, 1996). Fibroblasts cultures are in general, the most obtainable and renewable source of cells for both diagnosis and research. The major drawback with fibroblasts in culture is that they sometimes fail to maintain the diseased phenotype. This is especially true for fibroblast cultures derived from tissue specific forms of mitochondrial diseases. Nevertheless, many patients do express mitochondrial dysfunction in primary fibroblasts albeit the defect is sometimes unmasked only under stressful growth conditions in culture media, devoid of glucose or serum (Iuso et al., 2006; Robinson, 1996; Taanman et al., 2003). Therefore, patient's fibroblast harboring nuclear encoded mutations can be a suitable tool to study OXPHOS diseases and a platform for the search for treatments by small molecules, using individual approaches tailored to a specific defect.

### 3.3 Mouse models

Despite some obvious limitations, our ability to mimic human disease in animal models is undoubtedly one of the most important technological breakthroughs in modern genetics. Since the first knockout mice with impaired OXPHOS were generated in 1995 (reviewed in (Smeitink et al., 2001) and (Larsson & Rustin, 2001)), eight others have been described. Classical knockout (KO) technology has been achieved for the manganese superoxide dismutase gene (SOD2) and the ANT1. These mice can be considered as secondary OXPHOS-deficient mice because the genes are only indirectly related to the OXPHOS system. SOD2 is an oxygen radical scavenger in the mitochondrial matrix, which acts as a first line of defense against the superoxide that is produced as a by-product of OXPHOS (Li et al., 1995). To gain further insight into the effects of the ANT1 mutation in particular, study the regulation of nuclear and mitochondrial genes in the skeletal muscle of mice KO of ANT1 (Murdock et al., 1999) revealed upregulation of 17 genes that fall into four categories: nuclear and mitochondrial genes that encode OXPHOS components; mitochondrial tRNA and ribosomal RNA genes; genes involved in intermediary metabolism; and an eclectic group of other genes, among which are genes previously unknown to be related to mitochondrial function.

Knockout mice for the mitochondrial transcription factor A (TFAM) can be considered primary OXPHOS mice, because TFAM has a direct role in the regulation of OXPHOS gene expression. Using a conditional knockout approach, three distinct TFAM knockout mice have been created (Larsson et al., 1998; Wang et al., 1999): one for skeletal and cardiac muscle; one for cardiac muscle alone; and one for pancreatic  $\beta$ -cells. TFAM is essential for



mitochondrial biogenesis and embryonic development, and the conditional knockouts have indicated that the OXPHOS system is crucial for normal heart function and insulin secretion. Five mouse models that were specifically designed to mimic isolated complex I deficiency in humans involve the *NDUFS4* gene. This gene constitutes a mutational hotspot in humans. Four models are KO or conditioned KO for *NDUFS4*, the fifth one corresponds to a point mutation in *NDUFS4*. The whole-body and neuron-targeted *NDUFS4* KO mice displayed small size and displayed weight loss. This was accompanied by ataxia, blindness, hearing loss, loss of motor skills and death from a fatal encephalomyopathy. The Purkinje cell specific KO mice only manifested mild behavioral and neuropathological abnormalities. Homozygote point mutation *NDUFS4* mice were not viable, demonstrating that the presence of mutated *NDUFS4* protein leads to a much more severe phenotype than complete absence of *NDUFS4* (reviewed in (Roestenberg et al., 2011)).

Two mouse models for Friedreich ataxia have also been created (Puccio et al., 2001). Like the *ANT1*- and *SOD2*-deficient mice, these mice can also be considered as secondary OXPHOS-deficient mice. The frataxin-deficient mammals showed time-dependent iron accumulation and will allow the detailed study of the mechanism of frataxin involvement in iron metabolism and iron-sulphur biogenesis.

Finally, Jun-Ichi Hayashi's group, using a completely different approach, generated mice that carry large-scale mtDNA deletions (Inoue et al., 2000). Synaptosomes from mouse brains with naturally occurring somatic mtDNA mutations were fused with  $\text{Rho}^0$  cells. Each fusion event introduced a variable number of mutant and wild-type mtDNAs, which then repopulate the  $\text{Rho}^0$  cell, creating a cybrid cell line. Enucleated cybrid cells were fused to donor embryos and implanted in pseudo pregnant females. In this way, they generate heteroplasmic founder female animals in which mtDNA deletion transmission was obtained for three generations (Inoue et al., 2000).

#### 4. Calcium signalling and mitochondrial OXPHOS physiology

Calcium ( $\text{Ca}^{2+}$ ) is one of the most common second messengers in intracellular signalling networks. Periodic fluctuations in cytosolic calcium concentration ( $[\text{Ca}^{2+}]_{\text{cyt}}$ ) is driven by electrical activation of voltage-gated  $\text{Ca}^{2+}$  channels (VGCC) or by agonist stimulation of plasma membrane receptors and the subsequent formation of  $\text{Ca}^{2+}$ -mobilizing second messengers, such as inositol 1,4,5-trisphosphate ( $\text{IP}_3$ ).  $\text{IP}_3$  binds to its receptor the  $\text{IP}_3\text{R}$  (inositol 1,4,5-trisphosphate) on the endoplasmic reticulum (ER) membrane leading to  $\text{Ca}^{2+}$  release from the ER to the cytosol. In excitable cells,  $\text{Ca}^{2+}$  release from the ER occurs also through ryanodine receptors (RyR) that function as  $\text{Ca}^{2+}$ -activated  $\text{Ca}^{2+}$  channels which further amplify  $\text{Ca}^{2+}$  signals originating from other sources.

The frequency, amplitude and/or duration of cytosolic  $[\text{Ca}^{2+}]_{\text{cyt}}$  spikes can be detected and decoded by downstream  $\text{Ca}^{2+}$ -sensitive proteins providing a versatile pathway for extracellular stimuli to exert control over a wide range of metabolic pathways (Berridge et al., 2000).

Complex buffering systems that include multiple  $\text{Ca}^{2+}$ -buffering proteins, ATP-dependent  $\text{Ca}^{2+}$  pumps (SERCA (sarco-endoplasmic Reticulum  $\text{Ca}^{2+}$  ATPase) accumulating  $\text{Ca}^{2+}$  from the cytosol to the ER, and PMCA (Plasma membrane  $\text{Ca}^{2+}$  ATPase) extruding  $\text{Ca}^{2+}$  from cytosol to the extracellular space), and the sodium- $\text{Ca}^{2+}$  exchanger ( $\text{Na}^+/\text{Ca}^{2+}$ ), work together to restore  $[\text{Ca}^{2+}]$  back to resting levels. Mitochondria also play an important role in shaping  $\text{Ca}^{2+}$  signals by utilizing potent mitochondrial  $\text{Ca}^{2+}$  uptake mechanisms.  $\text{Ca}^{2+}$

uptake into mitochondria plays an important role in cellular physiology by stimulating mitochondrial metabolism and increasing mitochondrial energy production (Duchen, 1992). However, excessive  $\text{Ca}^{2+}$  uptake into mitochondria can lead to opening of a permeability transition pore (PTP) and apoptosis.

#### 4.1 Interplay between $\text{Ca}^{2+}$ and OXPHOS

Mitochondrial bioenergetics and  $\text{Ca}^{2+}$  shaping are mutually regulated. Indeed, on the one hand, mitochondria  $\text{Ca}^{2+}$  accumulation enables the activity of OXPHOS and ATP production; on the other hand, mitochondrial ATP favours the effective functioning of the two major  $\text{Ca}^{2+}$  pumps PCMA and SERCA and actively participates in shaping cytosolic  $\text{Ca}^{2+}$  signals (Figure 1 A and B).

One important target for  $\text{Ca}^{2+}$  signals is the activation of mitochondrial oxidative metabolism and the consequent increase in the formation of ATP. Studies performed in 1960-1970 led to the demonstration that four mitochondrial dehydrogenases are activated by  $\text{Ca}^{2+}$  ions. These are FAD-glycerol phosphate dehydrogenase, pyruvate dehydrogenase,  $\text{NAD}^+$ -isocitrate dehydrogenase and  $\alpha$ -ketoglutarate dehydrogenase. FAD-glycerol phosphate dehydrogenase is located on the outer surface of the inner mitochondrial membrane and is influenced by changes in cytoplasmic  $\text{Ca}^{2+}$  ions concentrations. The other three enzymes are located within mitochondria and are regulated by matrix  $\text{Ca}^{2+}$  ions concentration. The effects of  $\text{Ca}^{2+}$  ions on FAD-isocitrate dehydrogenase involve binding to an EF-hand binding motif within this enzyme, leading to lowering of the  $K_m$  for glycerol phosphate very substantially (reviewed in (Denton, 2009)). Mitochondrial  $\text{Ca}^{2+}$  ions bind also directly to  $\text{NAD}^+$ -isocitrate dehydrogenase and  $\alpha$ -ketoglutarate dehydrogenase to decrease the  $K_m$  for their respective substrates, whereas an increase in the dephosphorylated and active form of pyruvate dehydrogenase is regulated by a  $\text{Ca}^{2+}$ -sensitive phosphatase (Bulos et al., 1984; Denton & Hughes, 1978; Denton et al., 1972, 1978, 1996; McCormack et al., 1990; McCormack & Denton, 1979; Robb-Gaspers et al., 1998). Extramitochondrial  $\text{Ca}^{2+}$  regulates the glutamate-dependent state 3 respiration by the supply of glutamate to mitochondria via aralar, a mitochondrial glutamate/aspartate carrier (Gellerich et al., 2010). A very recent finding suggests a novel paradigm in which the transcription of genes for mitochondrial enzymes that produce ATP and the genes that consume ATP is coordinately regulated by the same transcription factors (Watanabe et al., 2011). Thus, TFAM and TFB2M, recognized as mtDNA-specific transcription factors, were shown to regulate transcription of the SERCA2 gene (Watanabe et al., 2011).

It was also demonstrated that metabolites generated during energy production may influence  $\text{IP}_3\text{R}$ -mediated  $\text{Ca}^{2+}$  dynamics. Indeed, it was shown that reduced Nicotinamide adenine dinucleotide selectively stimulates the release of  $\text{Ca}^{2+}$  mediated by  $\text{IP}_3\text{R}$  (Kaplin et al., 1996). Another evidence of communication between cellular metabolism and  $\text{Ca}^{2+}$  signalling was reported recently by Bakowski and Parekh who showed that pyruvate, the precursor substrate for the Krebs cycle, directly increases the native  $\text{I}_{\text{CRAC}}$  (store operated  $\text{Ca}^{2+}$  influx channels at the plasma membrane) by reducing inactivation of the channel, thereby coupling oxidation of glucose and its own metabolism in the mitochondria to  $\text{Ca}^{2+}$  influx by the CRAC channel (Bakowski & Parekh, 2007).

In addition to serving as a target of  $\text{Ca}^{2+}$  signalling, the uptake of  $\text{Ca}^{2+}$  by mitochondria has important feedback effects to shape cytosolic  $\text{Ca}^{2+}$  signals. Rosario Rizzuto and collaborators (Rizzuto et al., 1993) were the first to make direct *in situ* measurements of mitochondrial

Ca<sup>2+</sup>. They showed that receptor-activated Ca<sup>2+</sup> signals caused rapid and large Ca<sup>2+</sup> signals in the mitochondrial matrix (mechanisms of mitochondrial Ca<sup>2+</sup> influx and efflux are detailed below).

## 4.2 Mechanisms of mitochondrial calcium influx and efflux

### 4.2.1 Mechanisms of mitochondrial calcium influx

Mitochondrial Ca<sup>2+</sup> uptake is dependent on the strong driving force ensured by their membrane potential (-180 mV, negative inside) built by the respiratory chain (for review see (Bianchi et al., 2004)). It has been assumed that [Ca<sup>2+</sup>]<sub>cyt</sub> far exceeding the micromolar range is required for net Ca<sup>2+</sup> uptake, however, such [Ca<sup>2+</sup>]<sub>cyt</sub> values have not been observed experimentally in the bulk cytoplasm. Ca<sup>2+</sup> diffusion in the cytoplasm is also controlled by protein binding (Allbritton et al., 1992). Thus, local Ca<sup>2+</sup> transients with amplitudes far exceeding those measured over the global cytoplasm are confined in cytosolic microdomains at the mouth of Ca<sup>2+</sup> channels beneath the plasma membrane or ER internal store. This concept was consolidated by the demonstration that mitochondria, forming a complex cytoplasmic tubulovesicular system (Tinel et al., 1999), are frequently apposed to the smooth as well as the rough ER. These contact points, have been observed in several cell types by means of electron microscopy or tomography (Mannella et al., 1998). The experiments by Rosario Rizzuto and Tullio Pozzan definitively demonstrated that Ca<sup>2+</sup> released through IP<sub>3</sub>R in these microdomains, induce supramicromolar, or even submillimolar Ca<sup>2+</sup> signals (Rizzuto et al., 1993).

Accordingly, the group of György Hajnoczky demonstrates that maximal activation of mitochondrial Ca<sup>2+</sup> uptake is evoked by IP<sub>3</sub>-induced perimitochondrial [Ca<sup>2+</sup>] elevations, which appear to reach values >20-fold higher than the global increases of [Ca<sup>2+</sup>]<sub>cyt</sub>. Incremental doses of IP<sub>3</sub> elicited [Ca<sup>2+</sup>]<sub>mit</sub> elevations that followed the quantal pattern of Ca<sup>2+</sup> mobilization, even at the level of individual mitochondria. These results and others by the same group allow concluding that each mitochondrial Ca<sup>2+</sup> uptake site faces multiple IP<sub>3</sub>R, a concurrent activation of which is required for optimal activation of mitochondrial Ca<sup>2+</sup> uptake (Csordas et al., 1999; Hajnoczky et al., 1995) and reviewed in (Csordas et al., 2006). Targeting aequorin to the outer surface of the IMM in HeLa cells made the measurement of [Ca<sup>2+</sup>] in the mitochondrial intermembrane space possible. After stimulation with histamine [Ca<sup>2+</sup>] rose in the intermembrane space to significantly higher values than in the global cytosol (Rizzuto et al., 1998). This observation has given a strong support to the concept that net mitochondrial Ca<sup>2+</sup> uptake occurs from high-Ca<sup>2+</sup> peri-mitochondrial microdomains.

The existence of physical support for the ER-mitochondrial interface has been indicated by co-sedimentation of ER particles with mitochondria and electron microscopic observations of close associations between mitochondria and ER vesicles (Mannella et al., 1998; Meier et al., 1981; Shore & Tata, 1977). At these sites the shortest ER-OMM distance varies from 10 nm to 100 nm. In cells exposed to ER stress (serum starvation, tunicamycin) an increase in the ER-mitochondrial interface has been observed (Csordas et al., 2006). Also, coupling of the two organelles with a fusion protein increased the ER-mitochondria interface area, reduced the ER-mitochondrial distance to about 6 nm and greatly facilitated the transfer of cytosolic Ca<sup>2+</sup> signal into the mitochondria of RBL-2H3 cells (Csordas et al., 2006). Accordingly, our team showed that the truncated variant of the sarco-endoplasmic

reticulum  $\text{Ca}^{2+}$ -ATPase 1 (S1T) is induced under ER stress conditions. S1T is localized in the ER-mitochondria microdomains, increases number of ER-mitochondria contact sites, and inhibits mitochondria movements thus determining a privileged  $\text{Ca}^{2+}$  transfer from the ER to mitochondria leading to the activation of the mitochondrial apoptotic pathway (Chami et al., 2008).

Mitochondrial fission and fusion is another essential phenomenon for maintaining the metabolic function of these organelles as well as regulating their roles in cell signalling (Tatsuta & Langer, 2008; Yaffe, 1999; Chan, 2006). Changes in the relative rates of fusion and fission alter the overall morphology of the mitochondria affecting the function of the organelles both as regulators of survival/apoptosis and in  $\text{Ca}^{2+}$  handling. It has been shown that fusion is blocked (Karbowski & Youle, 2003) and mitochondria become fragmented during apoptosis (Frank et al., 2001). However, enhanced fission alone does not induce apoptosis and has even been shown to protect against  $\text{Ca}^{2+}$ -dependent apoptosis by preventing the propagation of harmful  $\text{Ca}^{2+}$  waves through the mitochondrial reticulum (Szabadkai et al., 2004).

The outer mitochondrial membrane is permeable to solutes and the inner mitochondrial membrane is impermeable to solutes that harbor the respiratory chain complexes. As described in chapter 1, the respiratory chain pumps protons against their concentration gradient from the matrix of the mitochondrion into the inter-membrane space, generating an electrochemical gradient in the form of a negative inner membrane potential and of a pH gradient, the matrix being more alkaline than the cytosol (Bernardi et al., 1999; Poburko et al., 2011).

$\text{Ca}^{2+}$  import across the outer mitochondrial membrane (OMM) occurs through the voltage-dependent anion channels (VDAC) (Simamura et al., 2008). VDAC is as a large voltage-gated channel, fully opened with high-conductance and weak anion-selectivity at low transmembrane potentials (< 20–30 mV), but switching to cation selectivity and lower conductance at higher potentials (Colombini, 2009; Shoshan-Barmatz et al., 2010). The precise mechanisms of VDAC conductance are however still under debate.

$\text{Ca}^{2+}$  import across the inner mitochondrial membrane (IMM) occurs through a  $\text{Ca}^{2+}$ -selective channel known as the mitochondrial  $\text{Ca}^{2+}$  uniporter (MCU) (Kirichok et al., 2004). Electrophysiological recordings of mitoplasts, small vesicles of inner mitochondrial membrane, revealed that the MCU is a highly  $\text{Ca}^{2+}$ -selective inward-rectifying ion channel (Kirichok et al., 2004). The MCU has a relatively low  $\text{Ca}^{2+}$  affinity ( $K_d \sim 10 \mu\text{M}$  in permeabilized cells (Bernardi, 1999)). The activity of the MCU had been known for decades to be inhibited by ruthenium red and its derivative Ru360 (Vasington et al., 1972), but its molecular identity has only been unraveled very recently. It has been reported recently that the process of  $\text{Ca}^{2+}$  accumulation undergoes complex regulation by  $\text{Ca}^{2+}$  itself. Thus mitochondrial uptake of  $\text{Ca}^{2+}$  was significantly reduced by inhibitors of calmodulin, suggesting that a  $\text{Ca}^{2+}$ -calmodulin-mediated process is necessary for activation of the uniporter but  $\text{Ca}^{2+}$  also appeared to inhibit its own uptake. However, in contrast to the sensitization of mitochondrial  $\text{Ca}^{2+}$  uptake, the  $\text{Ca}^{2+}$ -dependent inactivation was not sensitive to calmodulin blockers (Moreau & Parekh, 2008).

In recent years, several molecules have been proposed to be either an essential or an accessory component of the MCU. In 2007, the uncoupling proteins (UCP) 2 and 3 (Trenker et al., 2007) were proposed to be essential for the MCU. Indeed, UCP2/3 overexpression

increased mitochondrial  $\text{Ca}^{2+}$  elevations and the contrary is observed upon UCP2/3 depletion. In addition, mice lacking UCP2 exhibited a reduced sensitivity to the  $\text{Ca}^{2+}$  uptake inhibitor ruthenium red. However, these findings were disputed by another study that reported normal mitochondrial  $\text{Ca}^{2+}$  uptake in mice genetically ablated for UCP2 and UCP3 (Brookes et al., 2008). Furthermore, it was recently showed that UCP3 modulates the activity of sarco/endoplasmic reticulum  $\text{Ca}^{2+}$  ATPases by decreasing mitochondrial ATP production (De Marchi et al., 2011). The mitochondrial  $\text{Ca}^{2+}$  alterations associated with changes in UCP3 levels therefore reflect the exposure of mitochondria to abnormal cytosolic  $\text{Ca}^{2+}$  concentrations and do not reflect changes in MCU activity. These data indicate that UCP3 is not the mitochondrial  $\text{Ca}^{2+}$  uniporter. In 2009, Jiang and collaborators identified the leucine zipper EF hand containing transmembrane protein 1 (Letm1) as a molecule that regulate both mitochondrial  $\text{Ca}^{2+}$  and  $\text{H}^+$  concentrations (Jiang et al., 2009). Letm1 was reported to be a high-affinity mitochondrial  $\text{Ca}^{2+}/\text{H}^+$  exchanger able to import  $\text{Ca}^{2+}$  at low (i.e. sub-micromolar) cytosolic concentrations into energized mitochondria. Earlier studies had however linked Letm1 to mitochondrial  $\text{K}^+/\text{H}^+$  exchange and to the maintenance of ionic mitochondrial balance, the integrity of the mitochondrial network and cell viability (Dimmer et al., 2008; Nowikovsky et al., 2004). The high-affinity of Letm1 for  $\text{Ca}^{2+}$  and its postulated  $1\text{Ca}^{2+}/1\text{H}^+$  stoichiometry are at odds with the known properties of the MCU. Thus, Letm1 is not the dominant mechanism of mitochondrial  $\text{Ca}^{2+}$  uptake. Instead, Letm1 might contribute to an alternate mode of mitochondrial  $\text{Ca}^{2+}$  uptake, known as rapid mode of uptake (RaM), that was first reported in isolated rat liver mitochondria by Gunter's group. It was reported that mitochondrial  $\text{Ca}^{2+}$  sequestration via a the RaM occurred at the beginning of each pulse and was followed by a slower  $\text{Ca}^{2+}$  uptake characteristic of the MCU (Sparagna et al., 1995; Szabadkai et al., 2001). The implications of the coexistence of low and high-affinity modes of  $\text{Ca}^{2+}$  uptake have been recently reviewed (Santo-Domingo & Demaurex, 2010).

In 2010, Palmer and Mootha reported that a new mitochondrial EF hand protein MICU1 (for mitochondrial  $\text{Ca}^{2+}$  uptake 1) was required for high capacity mitochondrial  $\text{Ca}^{2+}$  uptake, and proposed that MICU1 acts as a  $\text{Ca}^{2+}$  sensor that controls the entry of  $\text{Ca}^{2+}$  across the uniporter (Perocchi et al., 2010). Building up on this discovery, the same group and another simultaneously identified the mitochondrial  $\text{Ca}^{2+}$  uniporter (Baughman et al., 2011; De Stefani et al., 2011). Using *in silico* analysis combined with phylogenetic profiling and analysis of RNA and protein co-expressed with MICU1, the group of Vamsi Mootha isolated a novel protein that co-immunoprecipitated with MICU1 (Baughman et al., 2011). Using the same database, the group of Rosario Rizzuto independently identified the same protein. From the 14 proteins characterized by two or more transmembrane domains and known to exhibit or lack uniport activity domains, these authors identified a protein with a highly conserved domain encompassing two transmembrane regions separated by a loop bearing acidic residues. Functional analysis confirmed that this protein behaves as expected for the mitochondrial uniporter, and it was therefore assigned the defining name of MCU. Mitochondrial  $\text{Ca}^{2+}$  uptake was strongly reduced by MCU silencing in cultured cells and in purified mouse liver mitochondria, whereas MCU overexpression enhanced ruthenium red-sensitive mitochondrial  $\text{Ca}^{2+}$  uptake in intact and permeabilized cells (De Stefani et al., 2011). The MCU is a 45 kDa protein that can forms oligomers (Baughman et al., 2011). Both studies mapped the MCU to the inner mitochondrial membrane, but disagreed on whether the N and C termini face the matrix of the inter-membrane space (Baughman et al., 2011; De

Stefani et al., 2011). Mutations of conserved acidic residues within the short sequence linking the two transmembrane domains abrogated the ability of MCU to reconstitute mitochondrial  $\text{Ca}^{2+}$  uptake, whereas mutation of a nearby serine residue ( $\text{S}_{259}$ ) conferred resistance to Ru360, indicating that the acidic residues are required for  $\text{Ca}^{2+}$  uptake and that  $\text{S}_{259}$  is critical for MCU sensitivity to ruthenium red (Baughman et al., 2011). Finally, and most convincingly, expression of the purified protein in planar lipid bilayers was sufficient to reconstitute ion channel activity in solutions containing only  $\text{Ca}^{2+}$  (De Stefani et al., 2011). The currents were carried by a channel of small conductance (6–7 pS), fast opening/closing kinetics, and low opening probability, and were inhibited by ruthenium red, as expected for the MCU. Proteins mutated at two of the conserved acidic residues failed to generate  $\text{Ca}^{2+}$  currents when inserted into bilayers and acted as dominant negative when expressed in HeLa cells. These data clearly identified MCU as mitochondrial  $\text{Ca}^{2+}$  uniporter. In accordance to the notion that mitochondrial  $\text{Ca}^{2+}$  overload enhances the sensitivity to apoptosis, it was also demonstrated that cells overexpressing MCU were more sensitive to apoptosis after treatment with ceramide and  $\text{H}_2\text{O}_2$  (De Stefani et al., 2011) (Figure 1B).

#### 4.2.2 Mechanisms of mitochondrial calcium efflux

Compared to the MCU, the proteins that catalyze the efflux of  $\text{Ca}^{2+}$  from mitochondria have received much less attention. The extrusion of  $\text{Ca}^{2+}$  from mitochondria is coupled to the entry of  $\text{Na}^+$  across an electrogenic  $1\text{Ca}^{2+}:3\text{Na}^+$  exchanger (Dash & Beard, 2008) that is inhibited by the benzothiazepine derivative CGP37157 ((Cox et al., 1993), and reviewed in (Bernardi, 1999)). The subsequent efflux of sodium ions by the mitochondrial  $1\text{Na}^+:1\text{H}^+$  exchanger (mNHE) eventually results in the entry of three protons into the matrix for each  $\text{Ca}^{2+}$  ion that leaves mitochondria.  $\text{Ca}^{2+}$  extrusion thus has a high energetic cost, as it dissipates the proton gradient generated by the respiratory chain (reviewed in (Bernardi, 1999)). The molecule catalyzing mitochondrial  $\text{Na}^+/\text{Ca}^{2+}$  exchange has been recently identified as NCLX/NCKX6, a protein localized in mitochondrial cristae (Palty et al., 2010), whereas stomatin-like protein 2 (SLP-2), an inner membrane protein, was shown to negatively modulate the activity of the mitochondrial  $\text{Na}^+/\text{Ca}^{2+}$  exchanger (Da Cruz et al., 2010). Functional evidence from knock-down and overexpression studies indicate that NCLX is an essential part of the mitochondrial sodium  $\text{Ca}^{2+}$  exchanger whereas SLP-2 is an accessory protein that negatively regulates mitochondrial  $\text{Ca}^{2+}$  extrusion (Figure 1B).

#### 4.2.3 Mitochondrial calcium overload: Activation of the permeability transition pore

When mitochondrial  $\text{Ca}^{2+}$  loads exceed the buffering capacity of inner membrane exchangers, an additional pathway for  $\text{Ca}^{2+}$  efflux from mitochondria may exist through opening of the permeability transition pore (PTP). The PTP is a voltage-dependent, cyclosporin A (CsA)-sensitive, high-conductance channel of the inner mitochondrial membrane (for reviews, see (Bernardi et al., 2006; Rasola & Bernardi, 2007)). Indeed, the interplay between the rate of mitochondrial  $\text{Ca}^{2+}$  influx and efflux modulates mitochondrial matrix  $\text{Ca}^{2+}$ , which in turn is widely considered to be a key factor for the regulation of the PTP open-closed transitions (Bernardi et al., 1999). Although opening of the PTP in response to  $\text{Ca}^{2+}$  has been documented in isolated mitochondria and permeabilized cells (Bernardi et al., 2006; Rasola & Bernardi, 2007), assessing opening of the PTP in intact neurons and other

primary cells in response to physiological activators that dictate cytosolic  $\text{Ca}^{2+}$  has remained a major challenge. Yet, opening of the PTP is often thought to be associated with pathophysiological processes (for reviews see (Hajnoczky et al., 2006; Rizzuto et al., 2003)). In these scenarios, activation of the PTP leads to respiratory inhibition, and thus ATP depletion, and the release of mitochondrial  $\text{Ca}^{2+}$  stores and apoptotic activators, ultimately resulting in cell death (Bernardi et al., 1999; Di Lisa & Bernardi, 2009). These have led to the idea that opening of the PTP by elevated mitochondrial  $\text{Ca}^{2+}$  is a terminal, pathologic event. However, it has been reported recently that CyPD-dependent PTP may participate in non-lethal  $\text{Ca}^{2+}$  homeostasis in cells and neurons (Barsukova et al., 2011).

## 5. Calcium deregulation in OXPHOS diseases

The direct consequences of OXPHOS defects include alteration of mitochondrial membrane potential, ATP/ADP ratio, ROS production and mitochondrial  $\text{Ca}^{2+}$  homeostasis. The varied biochemical changes that occur in cases of OXPHOS deficiencies have a direct effect on cellular functions. Yet, they are also key underlying mediators of the (retrograde) communication between the mitochondrion and the nucleus, which results in specific gene expression of both nuclear and mitochondrial genomes (see review (Reinecke et al., 2009)).

We will review in this chapter only  $\text{Ca}^{2+}$  deregulation in OXPHOS. We will discuss the consequences of such deregulation on mitochondrial function and the cross regulation between  $\text{Ca}^{2+}$  and bioenergetics in the development of cellular pathology. We summarized in Table 1 the alterations of subcellular  $\text{Ca}^{2+}$  signals in OXPHOS related diseases (Table 1).

Decreased proton pumping due to respiratory chain defects can result in reduced mitochondrial membrane potential and proton gradient, which are used to generate ATP. Deregulation of the membrane potential secondary to a deficiency in the respiratory chain may modify the kinetics and/or accumulation capacity of  $\text{Ca}^{2+}$  in the mitochondria, with possible consequences not only at the level of respiratory chain function (loop effect) and of the mitochondria in general, but also at the level of the ER function, which is largely dependent on  $\text{Ca}^{2+}$  concentrations, and at the level of cytosolic  $\text{Ca}^{2+}$  signalling, which plays a major role in regulating cell functions. Deficiencies of OXPHOS also result in other immediate and downstream metabolic, structural, and functional effects. These effects are closely associated with mitochondrial dysfunction. The nicotinamide dinucleotide (NAD) redox balance, which is converted to the reduced state in OXPHOS deficiencies, is a fundamental mediator of several biological processes, such as energy metabolism,  $\text{Ca}^{2+}$  homeostasis, cellular redox balance, immunological function, and gene expression (Munnich & Rustin, 2001; Ying, 2008).

It is important to mention that analyses of  $\text{Ca}^{2+}$  signalling targeting OXPHOS diseases are sporadic, partial and incomplete. This situation can be explained by : 1) the recent development of new techniques permitting detailed and specific subcellular  $\text{Ca}^{2+}$  analyses such as recombinant "aequorin" probes developed by the group headed by Professors Rizzuto and Pozzan, and the latest generation of GFP-based  $\text{Ca}^{2+}$  probes (camgaroos, cameleons and pericams) characterized by a great potential to analyse  $\text{Ca}^{2+}$  dynamics in mitochondria at the single cell level; 2) Absence of suitable "easy" study models (see chapter 3); and 3) the difficulty in the characterization of OXPHOS deficiencies (see chapter 2-2).

Disease	Gene	Mutation/Deficiency	Study model	Mitochondrial/Cellular pathology	Ca <sup>2+</sup> deregulation	Ca <sup>2+</sup> probe	References
MERRF	RNA <sub>19s</sub>	nt 8356 T/C	Cybrids	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; unchanged [Ca <sup>2+</sup> ] <sub>cyt</sub>	Aequorin	(Brini, 1999)
NARP	ATP <sub>6s6</sub>	nt 8993 T/G	Cybrids	↓ [ATP] <sub>mit</sub>	Unchanged [Ca <sup>2+</sup> ] <sub>mit</sub> & [Ca <sup>2+</sup> ] <sub>cyt</sub>	Aequorin	(Brini, 1999)
NARP	ATP <sub>6s6</sub>	nt 8993 T/G	Cybrids	Disturbed mitochondrial network and Actin cytoskeleton organization;	↑ Ca <sup>2+</sup> influx in NARP & Rho <sup>9</sup>	Fura 2, AM	(Szczepanowska, 2004)
MELAS	RNA <sub>12s</sub>	nt 3243 A/G	Fibroblasts	↓ Δ <sub>mit</sub>	↑ baseline level of [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ sequestration of [Ca <sup>2+</sup> ] <sub>mit</sub>	Fura 2, AM	(Moudy, 1995)
MELAS	RNA <sub>12s</sub>	nt 3271 T/C	Cybrids	Complex I, III, IV and V deficiencies; ↓ Δ <sub>mit</sub>	↑ time to clear up [Ca <sup>2+</sup> ] <sub>cyt</sub>	Indo 1, AM; Aequorin	(von Kleist-Retzow, 2007)
MELAS	RNA <sub>12s</sub>	nt 3344 A/G	Cybrids	Complex I, III, IV and V deficiencies; ↓ Δ <sub>mit</sub>	↑ time to clear up [Ca <sup>2+</sup> ] <sub>cyt</sub>	Indo 1, AM; Aequorin	(von Kleist-Retzow, 2007)
MELAS	RNA <sub>12s</sub>	nt 3202 A/G	Cybrids	Complex I, III, IV and V deficiencies; ↓ Δ <sub>mit</sub>	↑ time to clear up [Ca <sup>2+</sup> ] <sub>cyt</sub>	Indo 1, AM; Aequorin	(von Kleist-Retzow, 2007)
Leigh	NDUF57	nt C364A	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2004)
NC	NDUF51	nt G1854A	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2004)
NC	NDUF52	nt C1668T	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; unchanged [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2004)
NC	NDUF52	nt T1237C	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; unchanged [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2004)
NC	NDUF52	nt C686A	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; unchanged [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF52	nt C683A	Fibroblasts	Unchanged [ATP] <sub>mit</sub>	unchanged [Ca <sup>2+</sup> ] <sub>mit</sub> ; [Ca <sup>2+</sup> ] <sub>cyt</sub> & and [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF52	NC	Fibroblasts	Unchanged [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF52	NC	Fibroblasts	Unchanged [ATP] <sub>mit</sub>	unchanged [Ca <sup>2+</sup> ] <sub>mit</sub> ; [Ca <sup>2+</sup> ] <sub>cyt</sub> & [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF54	AAGTC471 <sup>(1)</sup>	Fibroblasts	Unchanged [ATP] <sub>mit</sub>	unchanged [Ca <sup>2+</sup> ] <sub>mit</sub> ; [Ca <sup>2+</sup> ] <sub>cyt</sub> & [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF54	nt C316T	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF54	nt C316T	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF54	C202G/G203 <sup>(2)</sup>	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF57	nt C364A	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF58	nt C280T	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF51	nt C1751/	Fibroblasts	↓ [ATP] <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
NC	NDUF51	nt C1268T	Fibroblasts	Unchanged [ATP] <sub>mit</sub>	unchanged [Ca <sup>2+</sup> ] <sub>mit</sub> ; [Ca <sup>2+</sup> ] <sub>cyt</sub> & [Ca <sup>2+</sup> ] <sub>ER</sub>	Fura 2, AM; Aequorin	(Visch, 2006)
Leigh	SDHA	nt C1684T	Fibroblasts	↓ [ATP] <sub>mit</sub> ; ↓ Δ <sub>mit</sub> ; ↑ ROS; ↓ mitochondrial movement;	↑ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↑ [Ca <sup>2+</sup> ] <sub>cyt</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>ER</sub>	Fluo 4, AM; X-Rhod-1, AM; Aequorin	(M'Baye, 2010)
Leigh	SURF1	KO	SURF1 <sup>-/-</sup> mouse	↑ ER-mitochondria contact sites COX deficiency; increased lifespan; protection from Ca <sup>2+</sup> -dependent neurotoxicity	↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ [Ca <sup>2+</sup> ] <sub>cyt</sub>	Fura, FF; Aequorin	(Dell'agnello, 2007)
Leigh	SURF1	Fibroblasts	Fibroblasts	COX deficiency	↓ SOC	Fura 2, AM	(Wasniewska, 2001)
Freidreich ataxia	Frataxin	GAA <sup>(9)</sup>	Fibroblasts	ND	↑ [Ca <sup>2+</sup> ]	BAPTA-AM	(Wong & Cortopassi, 1997)
Huntington	Htt	CAG <sup>(9)</sup>	Lymphoblasts	↓ Δ <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub>	Green-5N	(Panov, 2002)
Huntington	Htt	CAG <sup>(9)</sup>	Immortalized striatal cells	Normal mitochondrial function; increased ROS	↓ basal [Ca <sup>2+</sup> ]; ↓ [Ca <sup>2+</sup> ] <sub>mit</sub> ; ↓ IP <sub>3</sub> expression	Fura 2, AM; Aequorin	(Lim, 2008)
NC	NC	COX deficiency	Fibroblasts	COX deficiency	↑ P2Y <sub>1</sub> /2 expression; ↑ BK 1/2	Fura 2, AM	(Handran, 1997)
NC	NC	PDH deficiency	Fibroblasts	COX deficiency	Unchanged resting [Ca <sup>2+</sup> ]	Fura 2, AM	(Handran, 1997)
NC	NC	PDH deficiency	Fibroblasts	↓ Δ <sub>mit</sub>	↓ [Ca <sup>2+</sup> ] <sub>mit</sub>	Aequorin	(Padua, 1998)

BK: bradykinin; COX: cytochrome oxidase; Htt: Huntingtin; NC: non communicated; ND: not determined; ROS: reactive oxygen species; SOC: store operated Ca<sup>2+</sup> entry; PDH: Pyruvate dehydrogenase; KO: knock out; [Ca<sup>2+</sup>]<sub>cyt</sub>: cytosolic calcium-concentration; [Ca<sup>2+</sup>]<sub>ER</sub>: endoplasmic reticulum calcium-concentration; [Ca<sup>2+</sup>]<sub>mit</sub>: mitochondrial calcium-concentration; Ca<sup>2+</sup>, calcium. (1) Insertion; (2) Deletion; (3) repeat.

Table 1. Calcium deregulation in OXPHOS diseases



### 5.1 Calcium deregulation in MELAS, MERRF, NARP and LHON

Calcium deregulation was first reported in OXPHOS diseases linked to mitochondrial mutation. Brini and collaborators monitored subcellular  $\text{Ca}^{2+}$  signalling in cybrid cells with 0% and 100% of the MERRF (nt 8356 T/C) and NARP (nt 8993 T/G) mutations using cytosolic aequorin and aequorin probe targeted to the mitochondria. They showed a reduced mitochondrial  $[\text{Ca}^{2+}]$  ( $[\text{Ca}^{2+}]_{\text{mit}}$ ) transient in MERRF cells but not in NARP cells upon stimulation with IP<sub>3</sub>-generating agonist, whereas cytosolic  $\text{Ca}^{2+}$  responses ( $[\text{Ca}^{2+}]_{\text{cyt}}$ ) were normal in both cell types (Brini et al., 1999).

In another study, cybrid cells with 98 % of NARP mutation (nt 8993 T/G) and Rho<sup>0</sup> cells show a disturbed mitochondrial network and actin cytoskeleton. These cells show also a slower  $\text{Ca}^{2+}$  influx rates in comparison to parental cells. Authors postulate that proper actin cytoskeletal organization is important for CCE (capacitative  $\text{Ca}^{2+}$  entry) in these cells (Szczepanowska et al., 2004).

Abnormal  $\text{Ca}^{2+}$  homeostasis and mitochondrial polarization was also reported in fibroblasts from patients with MELAS syndrome. These cells showed an increased  $\text{Ca}^{2+}$  influx associated to a decreased mitochondrial potential (Moudy, 1995).

A comparative study was performed to establish sensitivity to oxidant in cybrid cells bearing the LHON, MELAS, or MERRF. The order of sensitivity to  $\text{H}_2\text{O}_2$  exposure was MELAS>LHON>MERRF>controls. Consistent with the hypothesis that death induced by oxidative stress is  $\text{Ca}^{2+}$  dependent, depletion of  $\text{Ca}^{2+}$  from the medium protected all cells from cell death. This study reveals indirectly that LHON as well as MELAS and MERRF show an increased basal  $\text{Ca}^{2+}$  load (Wong & Cortopassi, 1997).

In 2007, another study performed on cybrid cells incorporating two pathogenic mitochondrial mutations (nt 3243 A/G, nt 3202 A/G) reveal that the decreased ATP production by oxidative phosphorylation was compensated by a rise in anaerobic glycolysis. Regarding  $\text{Ca}^{2+}$  homeostasis, these cells did not show any alteration of  $\text{Ca}^{2+}$  signals in the cytosol but take longer to clear up the histamine induced  $\text{Ca}^{2+}$  signal in the mitochondria (von Kleist-Retzow et al., 2007).

All over, these studies revealed a deranged  $\text{Ca}^{2+}$  homeostasis in OXPHOS diseases linked to mitochondrial mutations. These alteration are not solely at the level of mitochondria but were also observed in the cytosol. Depending on the study model and/or mutation, increased cytosolic  $\text{Ca}^{2+}$  levels are linked to increased  $\text{Ca}^{2+}$  influx through the plasma membrane or reduced  $\text{Ca}^{2+}$  uptake capacity by the mitochondria.

### 5.2 Calcium deregulation in Complex I deficiency

The consequences of mitochondrial complex I deficiency on  $\text{Ca}^{2+}$  homeostasis was first studied in a genetically characterized human complex I deficient fibroblast cell lines harbouring nuclear NDUF57 (nt 364G/A) mutation linked to Leigh's syndrome. These cells show a reduced mitochondrial  $\text{Ca}^{2+}$  accumulation and consequent ATP synthesis (Visch et al., 2004). In 2006, the same group investigated the mechanism(s) underlying this impaired response. The study was conducted in fibroblasts from 6 healthy subjects and 14 genetically characterized patients expressing mitochondria targeted luciferase. The results revealed that the agonist-induced increase in mitochondrial ATP ( $[\text{ATP}]_{\text{mit}}$ ) was significantly, but to a variable degree, decreased in 10 patients. They also reported a reduced agonist-evoked mitochondrial  $[\text{Ca}^{2+}]$  signal, measured with mitochondria targeted aequorin, and cytosolic  $[\text{Ca}^{2+}]$  signal, measured with Fura-2, AM. Measurement of  $\text{Ca}^{2+}$  content of the ER, calculated from the increase in  $[\text{Ca}^{2+}]_{\text{cyt}}$  evoked by thapsigargin, an inhibitor of the ER  $\text{Ca}^{2+}$  ATPase

revealed also a decrease in mutated cells as compared to controls. Regression analysis revealed that the increase in  $[ATP]_{mit}$  was directly proportional to the increases in  $[Ca^{2+}]_{cyt}$  and  $[Ca^{2+}]_{mit}$  and to the ER  $Ca^{2+}$  content. This was the first report showing a pathological ER  $Ca^{2+}$  homeostasis in OXPHOS disease models. The authors postulated that the reduced ER  $Ca^{2+}$  content could be the direct cause of the impaired agonist-induced increase in  $[ATP]_{mit}$  in human complex I deficiency (Visch et al., 2006). However, the molecular mechanisms underlying ER  $Ca^{2+}$  deregulation were not revealed.

Another key cellular feature that was extensively investigated in patient fibroblasts harboring complex I deficiency is mitochondrial morphology. The quantification of mitochondrial morphology in a cohort of 14 patients fibroblast cell lines revealed two distinct classes of patient fibroblasts, one in which the cells mainly contained short circular fragmented mitochondria, and one in which the cells displayed a normal filamentous mitochondrial morphology (Koopman et al., 2007). Authors postulated that these differences are linked to ROS levels (Koopman et al., 2007). In a second report, the authors analyzed the relationship between mitochondrial dynamics and structure and  $Ca^{2+}$ /ATP handling in the same cohort. Regression analysis of the agonist-induced  $Ca^{2+}$ /ATP handling and mitochondrial morphology shows that increased mitochondrial number is associated to reduced  $Ca^{2+}$ -stimulated mitochondrial ATP and reduced stimulation of cytosolic  $Ca^{2+}$  removal rate (Willems et al., 2009).

### 5.3 Calcium deregulation in Complex II deficiency

The investigation of  $Ca^{2+}$  deregulation linked to complex II deficiency were largely performed upon complex II inhibition by 3-nitropropionic acid (3NP). The inhibition of complex II by 3NP is related to neuronal death, anatomic and neurochemical changes similar to those occurring in Huntington's disease (HD).

In primary cultures of rodent central nervous system, 3NP elicits an early increase in neuronal  $[Ca^{2+}]_{cyt}$  and both apoptotic and necrotic neuronal death (Greene et al., 1998). 3NP treatment produces a long term potentiation of the NMDA-mediated synaptic excitation in striatal spiny neurons. This also involves increased intracellular  $Ca^{2+}$  (Calabresi et al., 2001). To the mechanisms underlying increased  $[Ca^{2+}]_{cyt}$  upon 3NP treatment, it was shown that short treatment-induced  $[Ca^{2+}]_{cyt}$  increase occurs through NMDA-GLUR (Glutamate receptor) and VGCC and implicates also internal stores (Lee et al., 2002). In astrocyte cultures, Tatiani, R. Rosenstock and collaborators showed that 3NP is also able to release mitochondrial  $Ca^{2+}$  independently from internal stores and from  $Ca^{2+}$  entry through the plasma membrane (Rosenstock et al., 2004). Another group showed that 3NP-induced necrosis in primary hippocampal neurons is associated with an increase in both cytosolic and mitochondrial  $[Ca^{2+}]$ , decreased ATP and rapid mitochondrial potential depolarization. In this context, the increased  $[Ca^{2+}]$  was shown to result from  $Ca^{2+}$  influx through NMDA receptors (Nasr et al., 2003).

The occurrence of mitochondrial permeability transition (PT) was shown to be the cause of the loss of neuronal viability induced by complex II inhibition (Maciel et al., 2004). This is in line with studies showing increased susceptibility of striatal mitochondria to  $Ca^{2+}$ -induced PT (Brustovetsky et al., 2003) and that cyclosporine A (inhibitor of PT) protects against 3NP toxicity in striatal neurons (Leventhal et al., 2000) and astrocytes (Rosenstock et al., 2004). Accordingly, inhibition of mitochondrial  $Ca^{2+}$  influx by ruthenium red significantly reduces 3NP-induced cell death (Ruan et al., 2004).

The data obtained upon complex II inhibition by 3NP are in accordance with those obtained from Huntington's patients and transgenic mice. Mitochondria isolated from lymphoblasts of individuals with HD showed reduced mitochondrial potential and increased sensitivity to depolarization upon  $\text{Ca}^{2+}$  addition. Similar results were obtained in transgenic HD mice expressing mutated huntingtin (Panov et al., 2002). In addition, mitochondria from HD mice showed lower  $\text{Ca}^{2+}$  retention capacity. These mitochondrial abnormalities preceded the onset of pathological or behavioural tract by months, suggesting that mitochondrial  $\text{Ca}^{2+}$  deregulation occurs early in HD (Panov et al., 2002). In a recent study, Lim and collaborators explore  $\text{Ca}^{2+}$  homeostasis and mitochondrial dysfunction in clonal striatal cell lines established from a transgenic HD mouse model and showed transcriptional changes in the components of the phosphatidylinositol cycle and in receptors for myo-inositol triphosphate-linked agonist. The overall result of such changes is to decrease basal  $\text{Ca}^{2+}$  in mutant cells. Mitochondria from mutant cells failed to handle large  $\text{Ca}^{2+}$  loads and this seems to be due to increased  $\text{Ca}^{2+}$  sensitivity of the permeability transition. This study reveals a compensatory attempt to prevent the  $\text{Ca}^{2+}$  stress that would exacerbate mitochondrial damage in HD (Lim et al., 2008).

Our group was the first to investigate  $\text{Ca}^{2+}$  homeostasis in human fibroblasts isolated from a patient with Leigh's syndrome harbouring a homozygous R554W substitution in the flavoprotein subunit of the complex II (SDHA). Our study was conducted in parallel in control fibroblasts and in neuroblastoma SH-SY5Y cells upon inhibition of complex II with 3NP or Atpenin A5 at doses which did not induce cell death, thus affording to study complex II deficiency independently from cell death. We showed that mutation or chronic inhibition of complex II determined a large increase in basal and agonist-evoked  $\text{Ca}^{2+}$  signals in the cytosol and mitochondria, in parallel with mitochondrial dysfunction (membrane potential loss, ATP reduction and increased ROS). Cytosolic and mitochondrial  $\text{Ca}^{2+}$  overload are linked to increased ER  $\text{Ca}^{2+}$  leakage, and to PMCA and SERCA2b proteasome-dependent degradation. Increased mitochondrial  $\text{Ca}^{2+}$  load is also contributed by decreased mitochondrial motility and increased ER-mitochondrial contacts. These findings are interesting since they link for the first time OXPHOS-related mitochondrial pathology to the regulation of the stability of two major actors in  $\text{Ca}^{2+}$  signalling regulation, namely PMCA and SERCA. We postulate that SERCA2b and PMCA degradation is predictably related to a decrease of mitochondrial ATP production, since SERCA2b and PMCA degradation was also observed upon ATP synthase inhibition by rotenone. This phenomenon could be interpreted as an adaptation response to ATP demise in OXPHOS diseases. Our study revealed also the activation of a compensatory attempt to restore total ATP level through the activation of anaerobic glycolysis in a  $\text{Ca}^{2+}$ -dependent manner (M'Baya et al., 2010). This study revealed a double hint of  $\text{Ca}^{2+}$  signalling deregulation in complex II deficiency. On the one hand  $\text{Ca}^{2+}$  overload may favour the activation of glycolytic ATP production and on the other hand favoured  $\text{Ca}^{2+}$ -mediated mitochondrial pathology (M'Baya et al., 2010).

#### **5.4 Calcium deregulation in OXPHOS diseases linked to defects in OXPHOS assembly and iron homeostasis: COX and frataxin deficiencies**

Leigh's syndrome associated with COX deficiency is usually caused by mutations of SURF1, a gene coding a putative COX assembly factor. Fibroblasts isolated from patients harboring SURF1 mutation displayed a low  $\text{Ca}^{2+}$  influx through SOC (store operated  $\text{Ca}^{2+}$  channels) as

compared to control fibroblast (Wasniewska et al., 2001). The energy state of the mitochondrial membrane in mutated cells is naturally decreased. Accordingly, it was demonstrated that mitochondria can control SOC in a numerous cell types and that the collapse of mitochondrial membrane potential, either by an uncoupler or an inhibitor of the respiratory chain, greatly reduces the SOC (Makowska et al., 2000). In an earlier study, Handran and collaborators failed to document either mitochondrial morphology alteration or intracellular  $\text{Ca}^{2+}$  deregulation in COX-deficient human fibroblasts (Handran et al., 1997). This discrepancy between these results may be accounted on the partial recovery of COX enzyme activity in COX deficient fibroblasts. Fibroblasts are not a robust system for the study of mitochondrial dysfunction and cultured cells relies less on mitochondria for ATP production. It was thus concluded that this deficiency is not detrimental to fibroblast or that anaerobic respiration rescues the phenotype. In a strange manner, SURF1<sup>-/-</sup> KO mouse displayed mild reduction of COX activity in all tissues and did not show encephalopathy. These mice show a complete protection from *in vivo* neurodegeneration induced by exposure to high doses of kainic acid (a glutamatergic epileptogenic agonist). Thus the ablation of SURF1 drastically reduces the glutamate-induced increase of  $\text{Ca}^{2+}$  both in the cytosol and the mitochondria. Authors postulate that reduced buffering capacity by SURF1<sup>-/-</sup> mitochondria in the contact sites between mitochondria and plasma membrane or the ER may promote the feedback closure of the  $\text{Ca}^{2+}$  channels thus inhibiting the cytosolic  $\text{Ca}^{2+}$  transient rise (Dell'agnello et al., 2007).

As introduced in chapter 2-2-2, Friedreich's ataxia (FA) is an autosomal recessive disease caused by decreased expression of the mitochondrial protein frataxin. The biological function of frataxin is unclear. The homologue of frataxin in yeast, YFH1, is required for cellular respiration and was suggested to regulate mitochondrial iron homeostasis. Patients suffering from FA exhibit decreased ATP production in skeletal muscle. Accordingly, overexpression of frataxin in mammalian cells causes a  $\text{Ca}^{2+}$ -induced up-regulation of tricarboxylic acid cycle flux and respiration, which, in turn, leads to an increased mitochondrial membrane potential and results in an elevated cellular ATP content. Thus, frataxin appears to be a key activator of mitochondrial energy conversion and oxidative phosphorylation (Ristow et al., 2000).

It was reported that mean mitochondrial iron content was increased in FA fibroblasts harboring expansion of intronic GAA repeat in frataxin leading to its reduced expression, and that staurosporine-induced caspase 3 activity was higher in FA fibroblasts than controls. Treatment of cells with BAPTA, AM rescued FA from oxidant-induced death. These data indirectly demonstrate that FA fibroblasts displayed an increased cytosolic  $\text{Ca}^{2+}$  content leading to increased sensitivity to oxidative stress (Wong & Cortopassi, 1997).

### **5.5 Calcium deregulation linked to mitochondrial DNA polymorphism**

mtDNA is highly polymorphic and its variation in humans may contribute to individual differences in function as well as susceptibility to various diseases such as neurodegenerative diseases. Kazuno and collaborators searched for mtDNA polymorphisms that have mitochondrial functional significance using cybrid cells. Increased mitochondrial basal  $\text{Ca}^{2+}$  levels and increased agonist evoked cytosolic  $\text{Ca}^{2+}$  signals were observed in two closely linked nonsynonymous polymorphisms. Interestingly, these data highlight the role

of mitochondrial polymorphisms in the pathology of neurodegenerative diseases by affecting  $\text{Ca}^{2+}$  dynamics (Kazuno et al., 2006).

### 5.6 Calcium deregulation in Pyruvate Dehydrogenase deficiency

Aerobic metabolism may also affect mitochondrial  $\text{Ca}^{2+}$  homeostasis. Thus, deregulation of  $\text{Ca}^{2+}$  handling was also reported in human fibroblasts from a patient with an inherited defect in pyruvate dehydrogenase (PDH). Indeed, these cells show a decrease ability to sequester cytosolic  $\text{Ca}^{2+}$  into mitochondria without affecting basal cytosolic and mitochondrial  $\text{Ca}^{2+}$  levels. It was postulated that reduced mitochondrial uptake is linked to decreased mitochondrial potential (Padua et al., 1998).

## 6. OXPHOS therapies: The place for $\text{Ca}^{2+}$ modulating drugs

OXPHOS disorders are complex and heterogeneous group of multisystem diseases. The fact that they can result from mutations in hundreds of genes distributed across all of the chromosomes as well as the mtDNA, render the understanding of causative factors and the identification of common disease-related factors difficult. Accordingly effective therapeutic interventions are still not readily available. There are two main approaches to mitochondrial disease therapy: genetic and metabolic pharmacological (for recent review see (Roestenberg et al., 2011) and (Wallace et al., 2010)).

New approaches for genetic therapies for nDNA-encoded mitochondrial diseases as well as for mtDNA diseases are beginning to offer alternatives for individuals suffering from these devastating disorders. For mtDNA, these approaches include: (a) import of normal mtDNA polypeptides into the mitochondrion to complement the mtDNA defect, (b) reduction of the proportion of mutant mtDNAs (heteroplasmy shifting), and (c) direct medication of the mtDNA. Researchers are focusing also on the possible use of stem cell as a medication of OXPHOS disorders. However, these approaches are not as likely to relieve the devastating symptoms suffered by individuals with bioenergetic diseases.

The pharmacological approach includes the use of: (a) cofactors that increase the production of ATP (coQ, Idebenone, and succinate), (b) vitamins and metabolic supplements (thiamine, riboflavine, carnitine and L-arginine), (c) reactive oxygen species scavengers and mitochondrial antioxidants (CoQ/Idebenone, Vitamin E and Vitamin C), (d) modulators of PTP (cyclosporin A), and (e) regulators of mitochondrial biogenesis (bezafibrate and sirtuin analogs).

Current interventions based on metabolic correction include the use of mitochondrial-targeted drugs (compounds and peptides targeted to the mitochondrial matrix) such as mitoquinone "MitoQ", a derivative of coenzyme Q10, and SS-peptides, Szesto-Schiller peptides, a novel class of small cell permeable peptide antioxidants.

Another alternative to rescue mitochondrial bioenergetics defects is the use the mitochondrial  $\text{Na}^+/\text{Ca}^{2+}$  exchanger inhibitor benzothiazepine CGP37157 (Cox & Matlib, 1993). CGP37157 normalized aberrant mitochondrial  $\text{Ca}^{2+}$  handling during hormone stimulation of cybrid cells carrying the tRNALys mutation associated with MERRF syndrom (Brini et al., 1999). Short-term pre-treatment with CGP37157 (1  $\mu\text{M}$ , 2 min) fully normalized the amplitude of the hormone-induced mitochondrial  $\text{Ca}^{2+}$  signal in fibroblasts from patients with isolated complex I deficiency (Visch et al., 2004), without altering this

parameter in healthy fibroblasts. Similar result was obtained recently in a study including a large number of patient fibroblasts with complex I deficiency (Willems et al., 2009). Also the reduced maximal [ATP] in the mitochondrial matrix and cytosol were fully normalized by CGP37157 treatment. The effect of CGP37157 was independent of the presence of extracellular  $\text{Ca}^{2+}$ , excluding a stimulatory effect on  $\text{Ca}^{2+}$  entry across the plasma membrane (Willems et al., 2009).

It is worth to mention that CGP37157 may also stimulate the  $\text{IP}_3$ -induced release of  $\text{Ca}^{2+}$  from intracellular stores. In addition to these effects, CGP37157 was demonstrated to inhibit capacitative store refilling (Malli et al., 2005; Poburko et al., 2007). As far as its specificity is concerned, recent studies suggest that CGP37157 can also directly act on L-type  $\text{Ca}^{2+}$  channels (Thu le et al., 2006). Thus the use of this drug will hamper  $\text{Ca}^{2+}$ -stimulated processes that depend on  $\text{Ca}^{2+}$  entry across the plasma membrane (Luciani et al., 2007).

All over, these findings suggest that the mitochondrial  $\text{Na}^+/\text{Ca}^{2+}$  exchanger is a potential target for drugs aiming to restore or improve  $\text{Ca}^{2+}$ -stimulated mitochondrial ATP synthesis in OXPHOS deficiencies and highlight the role of  $\text{Ca}^{2+}$  deregulation in the development of mitochondrial and cellular pathology in OXPHOS diseases.

## 7. Conclusion

This literature analysis highlights the broad  $\text{Ca}^{2+}$  deregulation in different models of OXPHOS diseases and demonstrates the cross regulation between  $\text{Ca}^{2+}$  and bioenergetics in the development of mitochondrial and cellular pathologies. Some studies revealed also the potential use of  $\text{Ca}^{2+}$  modulating drugs to reverse mitochondrial pathology. These studies may encourage researcher to investigate systematically  $\text{Ca}^{2+}$  deregulation in OXPHOS and help to reveal new targets for the development of new or combined therapies to rescue mitochondrial pathology in these diseases.

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## 9. Abbreviations

ANT, adenine nucleotide translocator; ATP, adenosine triphosphate;  $[\text{Ca}^{2+}]_{\text{cyt}}$ , cytosolic calcium-concentration;  $[\text{Ca}^{2+}]_{\text{er}}$ , endoplasmic reticulum calcium-concentration;  $[\text{Ca}^{2+}]_{\text{mt}}$ , mitochondrial calcium-concentration;  $\text{Ca}^{2+}$ , calcium; DNA, Deoxyribonucleic acid, ETC, electron transport chain; ER, endoplasmic reticulum;  $\Delta\psi$ , electrical potential; IMM, inner mitochondrial membrane;  $\text{IP}_3$ , inositol 1,4,5-triphosphate;  $\text{IP}_3\text{R}$ , inositol triphosphate receptor; MCU, mitochondrial  $\text{Ca}^{2+}$  uniporter; NCX/HCX,  $\text{Na}^+/\text{Ca}^{2+}$  exchanger and  $\text{H}^+/\text{Ca}^{2+}$  exchanger; OMM, outer mitochondrial membrane; OXPHOS, oxidative phosphorylation; PMCA, plasma membrane  $\text{Ca}^{2+}$ -ATPase; SERCA, sarco-Endoplasmic reticulum  $\text{Ca}^{2+}$ -ATPase; RYR, ryanodine receptor; SERCA, sarco-Endoplasmic reticulum  $\text{Ca}^{2+}$ -ATPase; SOC, store operated channel.

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# Bioenergetics Theory of Aging

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## 1. Introduction

The average lifespan of people in developed countries has tripled since ancient times while its maximum longevity (about 120 years) has remained invariable. The strategic goal of gerontology is to exceed this limit, i.e. to develop remedies which would allow the living of an indefinitely long life. However there have not been any significant advances in solving this problem so far. There is still no answer to even the fundamental question: what is the primary cause of degradation for all of an organism's functions (otherwise known as aging)? Actually, there are too many answers to this question: over 300 aging theories have been developed, and each of them provides a different response (Medvedev, 1990), although the majority of these theories now have only historical importance. Theories of aging are traditionally divided into two alternative groups. First, stochastic theories claim that there are no specific aging genes and that an organism's deterioration is the result of damaging factors. Second, and by way of contrast, programmed-aging theories assert that longevity is predetermined by a genetic program. Stochastic theories have dominated the discussion since gerontology became a branch of science, and the idea that aging is programmed has not yet received wide recognition, even though there is a lot of empirical evidence supporting it. There are several factors which impede the wide recognition of this idea. First, there is no evidence that longevity is under the control of natural selection; and second, there is no convincing mechanism the programmed of aging. Adherents of this view currently search for longevity genes in a practically blind or ad hoc fashion (Holzenberger et al., 2003; Kenyon, 2010). Many such genes have been found for various organisms, ranging from unicellular creatures to mammals, but it is still unclear what processes they control (Anisimov, 2003).

There are several different theories which are currently under consideration and which are based on reliable, proven evidence: i) the free radical theory which claims that aging is caused by an increased damage rate in cell structures due to an increased generation-rate of reactive oxygen species (ROS) by their own mitochondria; ii) the protein error theory which states that the primary cause is the age-dependent retardation of the protein synthesis rate; iii) the replicative senescence theory which argues that an age-dependent organism's senility is caused by the limitation of cell proliferation. There is also reliable evidence in support of other theories which are not as popular, for instance the immunological theory and several versions of neuroendocrinal theories.

The goal of this report is: (1) to show that despite the beliefs of the supporters of the stochastic theories, longevity is controlled by natural selection, i.e. specific aging genes exist; (2) such genes program a lowering of the bioenergetics level (degradation of Gibbs energy,  $\Delta G$ ). In turn, such degradation results in an age-dependent increase in the ROS generation rate, a decrease in the protein synthesis rate, and a limitation of cell division. These three phenomena form the basis for a large number of secondary destructive processes which result in the degradation of all physiological organisms' functions, i.e. the causes of aging. The very idea that bioenergetics exerts an impact upon aging is not a novelty. Hasty and Vijg (2002) have recently stated in theory that proper energy-saving could support a living system indefinitely. B.N. Ames (2004) has remarked that mitochondrial bioenergetics supports the metabolism's cell processes and that its attenuation can result in the age-dependent degradation of all of an organism's physiological functions. And indeed, life as a phenomenon is characterised by a number of physical and chemical processes driven by the power of the bioenergetics machine. A gradual decrease in bioenergetics level can cause the degradation of all vital processes. However they also believe that the cause of age-dependent bioenergetics attenuation is to be identified with the mechanism postulated by the free-radical theory. The following fact seems to reject the assumption of the direct programming of bioenergetics attenuation: one of main bioenergetics parameters is the mitochondrial membrane potential  $\Delta\psi$ . In vitro tests have shown that the superoxide ( $O_2^{\cdot-}$ ) generation rate in the electron transport chain decreases as  $\Delta\psi$  decreases. Consequently, in the process of bioenergetics attenuation the ROS level should decrease, but the tests show its increase in all tissues. And only that version of the vicious cycle brought forward by the free-radical theory can explain this paradox. Another mechanism which we have already suggested explains the increase in the number of reactive oxygen species during programmed bioenergetics attenuation (Trubitsyn, 2006). The bioenergetics mechanism of aging under consideration represents the integration of several of the author's articles published earlier (Trubitsyn, 2006, 2006a, 2009, 2010, 2011).

## **2. The increase in the level of reactive oxygen species is predetermined by programmed bioenergetics decay**

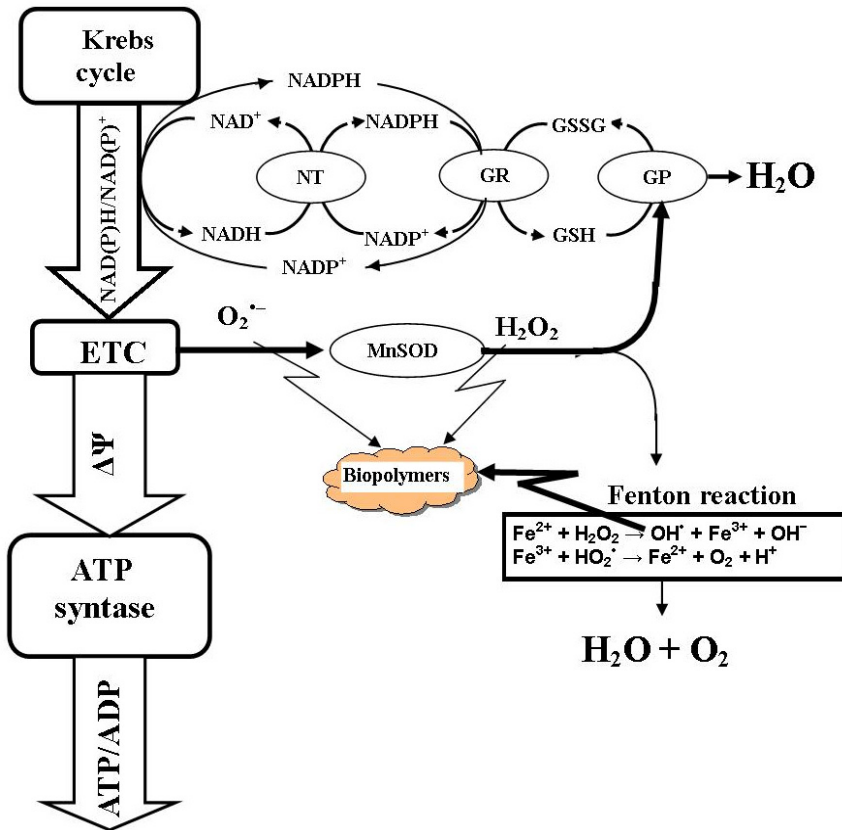
### **2.1 Introduction**

The free-radical theory of aging (the theory of oxidative stress, the oxidative damage theory and the mitochondrial theory of aging) was proposed by D. Harman (1956) in the middle of the 20th century and its improved version continues to dominate discussion. Its supporters claim that there are no specific aging genes because longevity cannot be controlled by natural selection (Kirkwood, 2002, 2008; Medawar, 1952). According to their view, age-dependent organism degradation results from the damage to cell structures by the ROS that are generated by mitochondria (Trifunovic & Larsson, 2008). This theory fascinates researchers by virtue of its simplicity and clarity. Indeed, it has been established that as an organism gets older, the ROS generation by the mitochondrial respiratory chain (electron transport chain) increases and the amount of damage to cell structures increases as well. The conclusion is obvious and the method for preventing aging is equally so: the neutralisation ROS by antioxidants. The age-dependent increase in the ROS generation rate is assumed to be just that: the ROS generated by mitochondria produce injury to its own mitochondrial DNA (mtDNA), which results in a defect in the respiratory chain. This, in turn, increases the rate of ROS production and as a result a vicious cycle arises.

When the free radical theory of aging appeared, it stirred up a brisk discussion which continues to this day. Empirical data has shown that there is no appreciable loss in the respiratory chain's functions during aging (Barrientos et al., 1996; Rasmussen et al., 2003). This is also supported by experiments indirectly related to the electron transport chain. For example, research into intra-cellular organelle transfers has shown that the mitochondria of old donors recover their functional activity completely when transferred to  $\rho 0$  HeLa cells (HeLa cells free of mtDNA) (Hayashi et al., 1994; Isobe et al., 1998). Mitochondrial dysfunctions are also eliminated when HeLa cell nuclei are transferred into the cells of old donors (Isobe et al., 1997). The authors concluded that nuclear factors are responsible for age-related mitochondrial deficiency. In addition, the conclusion that the age-dependent accumulation of mtDNA mutations is modulated by the nuclear genome was also made by Yao et al. (2007). The discussion has become especially vigorous over the last decade. On the one hand, based on this theory, it was claimed that "aging is no longer an unsolved problem in biology" (Hayflick, 2007; Holliday, 2006). On the other hand, R.M. Howes (2006) has declared that the "overly exuberant and exaggerated past expectations and claims of the free-radical theory have been quieted by extensive randomised, double-blind, controlled human studies. A half century of data demonstrates its lack of predictability and it has not been validated by the scientific method. Widespread use of antioxidants has failed to quell the current pandemic of cancer, diabetes, and cardiovascular disease or [even] to stop or reverse the aging process." His position is also supported by G. Bjelakovic et al. (2008) who have collected a great deal of data to show that antioxidants neither result in the beneficial effects expected nor do they increase life expectancy (in the best-case scenario). Gems & Doonan (2009) asked a question in a recent review: "Is the theory really dead, or does it just need to be modified?" Actually, there is more than ample evidence against the aging mechanism postulated by this theory than there is evidence in support of it.

## 2.2 Schema of the mitochondrial bioenergetics machine

Mitochondria generate about 90 percent of the energy in any eukaryotic cell. Therefore, only the mitochondrial bioenergetics machine will be considered here. Any energy system can be quantitatively described by its propellant power (F) and by its effect (A):  $F = kA$ : this is the force and the work in mechanical engineering (k is the friction) and the electromotive force and current in electrical engineering (k is the resistance). It is the free-energy change (Gibbs energy,  $\Delta G$ ) and current in chemical thermodynamics (in bioenergetics in particular). Such terms as the bioenergetics level and the level of energy production are used in bioenergetics to express the propellant power. To make it clear, let us recall that the  $\Delta G$  of macroergic (high-energy) coenzymes that function in the bioenergetics machine (ATP, NAD, NADP, GSH, etc.) is determined by the value of their concentrations ratio of the reduced form to the oxidised one and by the temperature. For ATP, for instance,  $\Delta G = \Delta G^0 - RT \ln[ATP]/[ADP][P_i]$ , where  $\Delta G^0$  is the standard Gibbs energy that is measured with everything at 1 molar concentration:  $[ATP] = [ADP] = [P_i] = 1M$ ; R is the gas constant; T is the absolute temperature. The more negative Gibbs energy there is, the higher the energy potential the bioenergetics machine generates. As follows from the above expression for  $\Delta G$ , the concentrations ratio of the reduced to oxidised forms of macroergic coenzymes ( $[ATP]/[ADP]$ ,  $[NADH]/[NAD^+]$ , etc.) is the only variable which determines the energy potential for warm-blooded animals.



*Bioenergetics machine.* The primary motive power,  $\text{NADH/NAD}^+$ , is created in the Krebs cycle. The mitochondrial membrane potential,  $\Delta\psi$ , is created by the electron flow from  $\text{NADH}$  to oxygen through the electron transport chain (ETC). ATP-synthase phosphorylates ADP into ATP at the expense of  $\Delta\psi$ . *Scavenging mechanism.* The superoxide radical ( $\text{O}_2^{\bullet-}$ ) produced by ETC is transformed into hydrogen peroxide,  $\text{H}_2\text{O}_2$ , by manganese superoxide dismutase (MnSOD).  $\text{H}_2\text{O}_2$  is then decomposed into  $\text{H}_2\text{O}$  and  $\text{O}_2$  mainly through the reaction that is catalyzed by glutathione peroxidase (GP) and partially through the Fenton reaction; the last produces an extremely aggressive hydroxyl radical. The glutathione peroxidase activity mainly predetermines the rate of the scavenging process. This activity is sustained by the energy provided by glutathione (GSH) oxidation. The thus GSSG formed is reduced again into GSH at the expense of the oxidation of  $\text{NADPH}$  in a reaction that is catalysed by glutathione reductase (GR). The  $\text{NADP}^+$  formed is reduced in turn at the expense of the oxidation of  $\text{NADH}$  in the reaction catalysed by nicotinamide nucleotide transhydrogenase (NT). The  $\text{NAD}^+$  formed is reduced by the reactions of the Krebs cycle. The  $\text{NADP}^+$  can also be directly reduced in the isocitrate dehydrogenase reaction of the Krebs cycle. The chain of these redox reactions is the electrons' pipeline from the Krebs cycle to glutathione peroxidase. *The mechanism of ROS increase.* The programmed bioenergetics decline leads to a proportional decrease in GP activity, which increases the  $\text{H}_2\text{O}_2$  level. As hydrogen peroxide is a substrate for the Fenton reaction, this augments the  $\text{H}_2\text{O}_2$  flow through the Fenton reaction, which elevates the content of free radicals. Thus, a decline in the bioenergetics level is followed by an increase in the total amount of reactive oxygen species and its aggressiveness.

Fig. 1. Scheme explaining the mechanism of the ROS increase under the bioenergetics decline.

Researchers divide energy-metabolism reactions into a different number of functional blocks depending upon their purpose. For example, Ainscow and Brand (1998) have divided it into nine blocks connected to each other by five intermediates. To solve the problem under consideration, the bioenergetics machine may be divided into three blocks (the Krebs cycle, the electron transport chain and ATP-synthase) connected by two intermediates ( $[\text{NADH}]/[\text{NAD}^+]$  and  $\Delta\psi$  (Fig.1)). According to this scheme, the output potential ( $[\text{ATP}]/[\text{ADP}]$ ) is generated in three stages. At the first stage, the primary electromotive force,  $[\text{NADH}]/[\text{NAD}^+]$ , is created by reducing  $\text{NAD}^+$  to  $\text{NADH}$ . This serves as the propellant power for stage two where electrons are transferred from  $\text{NADH}$  to oxygen via the electron transport chain, generating the mitochondrial membrane potential  $\Delta\psi$ . At the third stage,  $\Delta\psi$  is the electromotive force for ATP-synthase which generates the output potential. If there are no excessive loads (in stage four or close to it) then the  $[\text{NADH}]/[\text{NAD}^+]$  change results in a proportional change in  $\Delta\psi$  and in  $[\text{ATP}]/[\text{ADP}]$ .

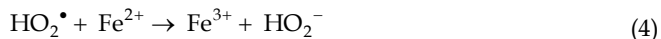
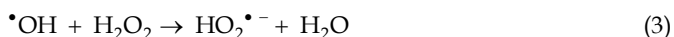
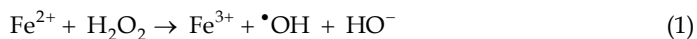
### 2.3 ROS-scavenging mechanisms

During the aerobic metabolism, a small number of the electrons that flow from  $\text{NADH}$  via the respiratory chain react with oxygen directly reducing oxygen to superoxide anion ( $\text{O}_2^{\bullet-}$  or  $\text{HO}_2^{\bullet}$ ) (Demin et al., 1998; Scandalios, 2002a) which can damage cell biopolymers. Cells have a protective system that can be conditionally divided into three functional lines of defence: preventative mechanisms, ROS-scavenging mechanisms, and emergency-response mechanisms. The preventative mechanisms either prevent  $\text{O}_2^{\bullet-}$  generation or oxidise superoxide back into  $\text{O}_2$  at its location of generation (Brand, 2000; Skulachev, 2001). The emergency-response mechanisms are actuated when the ROS amount exceeds a critical level and when the cumulative effect of other mechanisms cannot improve the situation. However ROS not only damage biopolymers but it also plays an important role in the regulation of transcription factors, growth factors and other intracellular signal systems (Brigelius-Flohe et al., 2003; Cerimele et al, 2005; Rhee, 1999; Scandalios, 2002). The cell needs ROS, but their concentration should be maintained at a safe level. Therefore, there is a dedicated ROS-scavenging mechanism to maintain the ROS homeostasis. This mechanism performs the  $\text{O}_2^{\bullet-}$  detoxification through a two-stage process (Fig. 1). At first, the manganese-containing mitochondrial superoxide dismutase (MnSOD) transforms superoxide into hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) (Jonas et al., 1989; Scandalios, 2002a) which is then decomposed by catalase and peroxidases. Most  $\text{H}_2\text{O}_2$  is decomposed in cytosol by catalase and in the mitochondrial matrix by the glutathione and thioredoxin systems (catalase is absent in the mitochondrial matrix) (Wei et al., 2001). The glutathione system consists of glutathione peroxidase (GP) and glutathione reductase (GR). The GP potency is maintained due to the oxidation of glutathione (GSH) which is converted into its disulphide form (GSSG). Next, the GR catalyses the reduction of the oxidised glutathione at the expense of NADPH oxidation (Arai et al., 1999; Jo et al., 2001; Iantomasi et al., 1993). The  $\text{NADP}^+$  thus formed is reduced again to NADPH in the isocitrate dehydrogenase reaction of the Krebs cycle (Jo et al., 2001). There is an analogous system - the thioredoxin system - which functions in parallel with the glutathione system and which also consists of thioredoxin peroxidase (TP) and thioredoxin reductase (TR) (Jo et al, 2001; Nordberg & Arner, 2001). Similarly, the TP potency is maintained by the oxidation of thioredoxin which is then reduced by TR, also at the expense of NADPH oxidation (Lewin et l., 2001). For the sake of simplicity, this parallel system is not shown in Fig. 1. The reaction that is catalysed by these peroxidases is

simple:  $\text{H}_2\text{O}_2$  takes two electrons from the glutathione (thioredoxin) and two protons from the environment and then decays into two water molecules:  $\text{H}_2\text{O}_2 + 2e^- + 2\text{H}^+ = 2\text{H}_2\text{O}$ . Only GP and TP catalyse this reaction directly; the other reactions are a pipeline by which energy is transferred from the Krebs cycle to glutathione peroxidase with thioredoxin peroxidase providing their activity (Iantomasi et al., 1993). The activity of any energy-dependent chemical reaction depends upon the energy supply (Westerhoff & van Dam, 1987). Therefore, the more the NADPH/NADP<sup>+</sup> ratio is generated in the Krebs cycle, the higher the GP and TP activity, and vice versa. It was shown experimentally that bioenergetics attenuation results in decrease of the scavenging mechanism's activity (Jo et al., 2001). It should be also noted that the ROS-scavenging mechanism can to some extent adapt to changes in the ROS level: the cell responds to a higher ROS concentration by a higher synthesis rate for MnSOD and glutathione-system enzymes (Meewes et al., 2001). An increase in the gene expression of those enzymes is mediated by the transcription nuclear factor- $\kappa\text{B}$  that is activated under excessive amounts of ROS (Scandalios, 2002a; Schreck et al., 1991).

## 2.4 Fenton reaction

There is additional the ferrous-ion catalysed means of hydrogen peroxide decomposition, which is called the Fenton reaction. In its simplest form, the Fenton chemistry is a chain mechanism of certain reactions in which  $\text{H}_2\text{O}_2$  breaks up into water and oxygen and where  $\text{Fe}^{2+}$  is regenerated (Dunford, 2002):



As distinct from the glutathione system, the iron decomposes  $\text{H}_2\text{O}_2$  due to its ability to undergo cyclic oxidation and reduction. However, such redox activity of iron can generate free radicals capable of causing a wide range of biological injuries (Liu et al. 2003). The hydroxyl radicals ( $\cdot\text{OH}$ ) formed during the Fenton reaction are true chemical predators: indeed, the reactivity of  $\cdot\text{OH}$  is so great that, if they are formed in living systems, they will react immediately with whatever biological molecule is in their vicinity, producing secondary radicals of variable reactivity (Halliwell & Gutteridge 1984; Yu & Anderson 1997). Among  $\text{O}_2\cdot^-$ ,  $\text{H}_2\text{O}_2$  and  $\cdot\text{OH}$ , only the hydroxyl radical can directly cause double-stranded DNA breaks (Aruoma 1994).

## 2.5 The mechanism of age-dependent increase in ROS level

The Fenton reaction actually shunts the ROS-scavenging mechanism. As a result,  $\text{H}_2\text{O}_2$  molecules are decomposed both by the glutathione system and the Fenton reaction. As the two ways of hydrogen peroxide decomposition compete for the substratum, the fraction of



$H_2O_2$  which can produce  $\cdot OH$  ( $Q_r$ ) is predetermined by both the activity of the Fenton reaction ( $A_f$ ) and that of glutathione peroxidase ( $A_g$ ):  $Q_r = A_f / (A_f + A_g)$ . Thus, the lower the level of the activity of glutathione peroxidase and thioredoxin peroxidase, the higher the level of ROS production.

As has been mentioned, a decrease in the energy metabolism rate should, in theory, result in a lowering of the  $O_2^{\cdot-}$  generation rate. Indeed, this is just what happens. However the concentration of the other ROS does not only depend upon the  $O_2^{\cdot-}$  generation rate: the programmed age-dependent delay in the bioenergetics level results in a decrease in GP and TP activity. This raises the concentration of their substrate,  $H_2O_2$ . Since hydrogen peroxide is a substrate for the Fenton reaction as well, it augments the current through this reaction. As a result, the total amount of ROS and their aggressiveness increases despite a decrease in the  $O_2^{\cdot-}$  generation rate.

## 2.6 Conclusion

Accordingly, the leading cause of the age-dependent increase in the amount of ROS and its aggressiveness is a programmed attenuation of cellular bioenergetics rather than a progressive accumulation of mutations in mtDNA due to the creation of a vicious cycle.

## 3. The age-dependent attenuation of bioenergetics underlies a decrease in the general level of protein synthesis

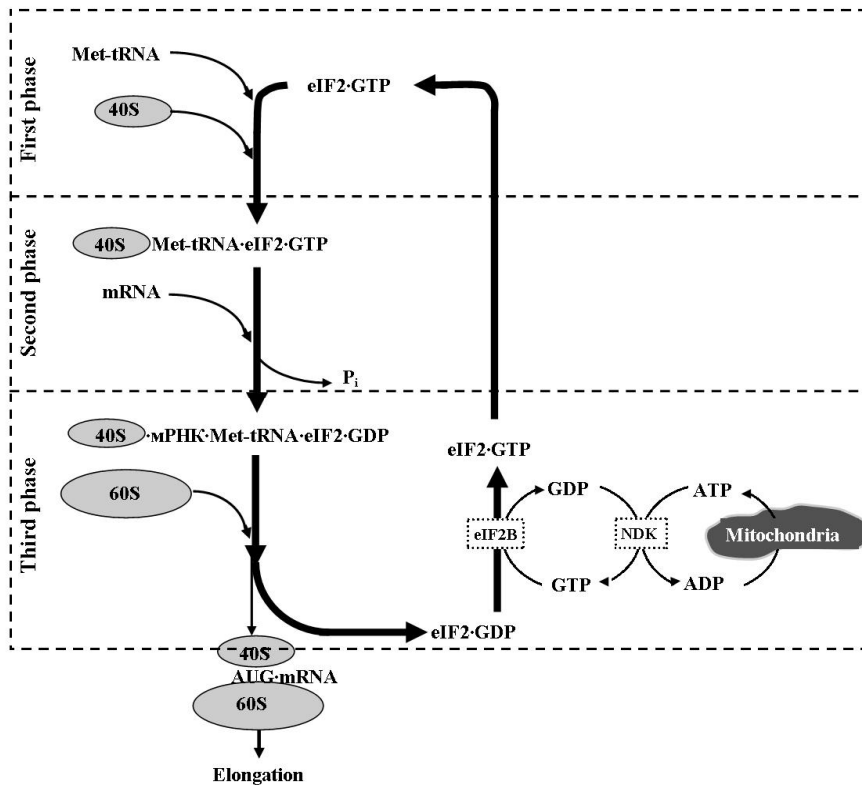
### 3.1 Introduction

A different popular aging theory, the protein-error theory, is based on the indisputable fact that the bulk protein synthesis slows down during aging (Rattan, 1996, 2009; Ryazanov & Nefsky, 2002). According to the theory, such retardation results in a decreasing protein turnover rate which causes the accumulation of defective macromolecules. S.I.S. Rattan (1996), who has investigated this process in detail, reports that "the implications and consequences of slower rates of protein synthesis are manifold, including a decrease in the availability of enzymes for the maintenance, repair and normal metabolic functioning of the cell, an inefficient removal of inactive, abnormal and damaged macromolecules in the cell, the inefficiency of the intracellular and intercellular signalling pathways, and a decrease in the production and secretion of hormones, antibodies, neurotransmitters and the components of the extra cellular matrix." The reason behind a slower protein synthesis rate is seen in the stochastic accumulation of molecular damage and the progressive failure of maintenance and repair (Rattan, 2009). It entails damage to fragments of the translation mechanism: "a decline in the efficiency and accuracy of ribosomes, an increase in the levels of rRNA and tRNA, and a decrease in the amounts and activities of elongation factors" (Rattan, 2006). At the same time, there is empirical evidence which allows for the explanation of the slowing down of overall protein synthesis by the attenuation of cellular bioenergetics.

### 3.2 The mechanism for the decrease in the level of cell protein synthesis

It was D.A. Young (1969) who discovered a relationship between the protein synthesis rate and the bioenergetics level for the first time. When conducting experiments on glucocorticoid hormones, he noticed that the rate of amino acids inclusion into a growing polypeptide chain depends upon the entry of carbohydrates (glucose, pyruvate, and lactate) into cells. An assumption was made that this effect is connected with the ATP generation rate. It was shown thereafter that the protein synthesis rate depends upon the ADP/ATP and GDP/GTP ratios

rather than on the absolute ATP value (Hucull et al., 1985; Mendelsohn et al., 1977; Young, 1970). In these tests, minor changes in the nucleotide diphosphate /nucleotide triphosphate ratio resulted in a significant effect on the range corresponding to a physiological energy level. The authors came to the conclusion that the ADP/ATP and/or GDP/GTP ratios are a physiological regulator of the protein synthesis rate.



The initiation of translation can be divided into three phases. Phase one: the initiator methionine transport RNA (Met-tRNA) binds with the pre-existing binary complex eIF2-GTP and the 40S ribosomal subunit to provide the pre-initiation complex 40S-Met-tRNA-eIF2-GTP. Phase two: the pre-initiation complex binds to messenger RNA (mRNA). When the pre-initiation complex stops at the initiation codon of the mRNA, the GTP molecule is hydrolysed to GDP, inorganic phosphorus (P<sub>i</sub>) is liberated and the energy of oxidation is spent on bond formation. This powers the ejection of the factors bound to the 40S ribosomal subunit in the third phase. The continuity of the initiation of these events requires the recycling of initiation factor molecules. eIF2 is released as an inactive binary complex with GDP and requires a guanine nucleotide exchange factor, eIF2-B, to catalyse regeneration of the eIF2-GTP. Energy support of regeneration is carried out at the expense of GTP oxidation. The GDP formed is then reduced at the expense of ATP oxidation in a reaction catalysed by nucleoside diphosphate kinase (NDK). The ADP formed is in turn reduced to ATP in the mitochondrial bioenergetics machine. The programmed bioenergetics decline decreases the eIF2 recirculation rate and thus reduces the general level of protein synthesis.

Fig. 2. The simplified scheme for the initiation of translation and its connection with bioenergetics.

The molecular mechanism of protein synthesis is currently well-understood and has been detailed in a number of reviews (Pain, 1996; Rattan, 2009). It was shown that the protein synthesis rate for eukaryotes is controlled at the translation level (Hucul, et al., 1985; Kimball et al., 1998). Among three translation stages (initiation, elongation and termination), the regulatory stage is the initiation (Hucul, et al., 1985; Kimball et al., 1998). The goal of this stage is the sequential binding of first the 40s and then the 60s ribosomal subunit to a messenger RNA molecule. At least 12 recirculation eukaryotic initiation factors (eIF) are involved in this stage. The initiation process can be divided into three phases (Fig. 2): (1) the association of the Met-tRNA initiator and several initiation factors with the 40s ribosomal subunit so as to form the pre-initiation complex; (2) the binding of this complex to a messenger RNA (mRNA) molecule, and (3) the addition of the 60s ribosomal subunit to assemble an 80s ribosome at the initiation codon.

The first initiation phase starts with the binding of the Met-tRNA initiator to a pre-existing double complex eIF2 GTP. When this preinitiation complex binds to mRNA at the second phase, GTP is oxidised to form GDP, and the oxidation energy is used to create bonds, with inorganic phosphorus being released. At the third stage, when the goal has been reached, the preinitiation complex disintegrates into separate initiation factors; these factors are then recycled to catalyse further initiation events. eIF2 is released as a binary complex with GDP, which is stable but not functionally active, i.e. it is unable to bind to a new Met-tRNA. A guanine nucleotide exchange factor, eIF2B, is required to catalyse the regeneration of the eIF2 GTP. Energy for such regeneration is provided by ATP oxidation to form ADP and the ADP is then reduced in the bioenergetics machine. Thus, the total protein synthesis level is originally regulated by the eIF2 recirculation rate which, in turn, depends upon the cellular bioenergetics value.

If the GDP-to-eIF2 GDP reduction is interrupted, the protein synthesis in the cell is blocked (Clemens, 1994). The natural mechanism protecting an organism in various stressful situations is based on this phenomenon: the phosphorylating of  $\alpha$ -subunit eIF2 by different specific protein kinases blocks the reaction of the GDP-to-GTP exchange, which results in a complete protein synthesis termination in the cell followed by apoptosis (Clemens, 1994; Clemens et al., 2000). Such specific protein kinases are expressed in the cell when emergencies occur, such as an occurrence of the double-stranded replicative form of viral RNA (Jeffrey et al. 2002; Pain, 1996; Robert et al., 2006), irreparable damage of the genetic apparatus (Zykova et al., 2007; Jeffrey et al, 2002), acute shortage in amino acids (Clemens et al., 2001; Harmon et al., 1984), and malignant cell transformation (Clemens, 1994, Mendelsohn et al., 1977). Under normal physiological conditions when there are no specific protein kinases, the GDP-to-GTP exchange rate in the eIF2 GDP complex (and, consequently, the total protein synthesis rate) is regulated by the cellular bioenergetics (Hucull et al., 1985).

### 3.3 Conclusion

Programmed bioenergetics decline is the original cause of overall protein synthesis decrease rather than the stochastic accumulation of molecular damage.

## 4. The Hayflick limit is caused by the age-related decrease in the bioenergetics level

### 4.1 Introduction

Tissue senility is the most visible phenomenon and one of the most harmful phenomena of organism aging. Its cause was determined half a century ago (Hayflick & Moorhead, 1961):

higher eukaryotic cells do not divide infinitely, and, after a certain number of doublings, they enter a nondividing but viable state. Human fibroblasts, for example, are able to divide  $53 \pm 6$  times over  $302 \pm 27$  days and be in a stationary state for  $305 \pm 41$  more days (Bayreuther et al., 1988). This limitation of division, the Hayflick limit, underlies the replicative aging theory, which is recognized to be one of the most striking modern aging theories (Anisimov, 2003). The main postulate of this theory is that, due to accumulation of old nondividing cells, tissue renewing homeostasis is violated, which causes their degradation (Hornsby, 2002; Itahana et al., 2004; Yegorov & Zelenin, 2003).

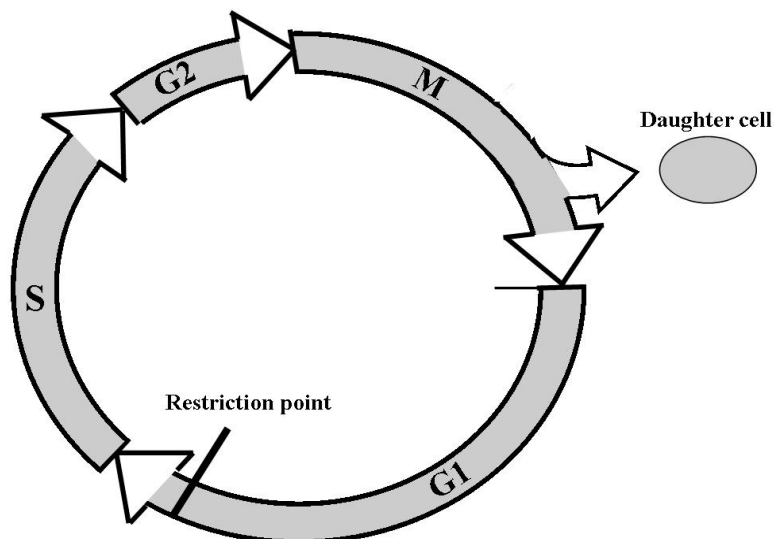
#### **4.2 Modern views on the cause of cell proliferation limitation**

A convincing mechanism of termination of old cells division was predicted theoretically by A.M. Olovnikov in 1971 and then confirmed experimentally (Greider & Blackburn, 1985). Vertebrates' chromosome ends from the DNA 3'-end have repeating nucleotide sequences – telomeres. They prevent fusion of chromosome ends, protect DNA from nuclease digestion, and participate in doubled chromosome disjunction in mitosis. In embryonic cells telomeres are synthesized by a special enzyme telomerase, which most somatic cells do not have. Because of the necessity of RNA-primer during DNA reduplication initiation, the telomere ends of somatic cells chromosomes are shortened with every cycle. As a result, after a certain number of doublings, the telomere end is depleted and divisions are terminated due to chromosome erosion (Itahana et al., 2004). This mechanism was confirmed by numerous empirical facts: 90–95% of potentially immortal cancer cells possess telomerase activity and the telomere end of their chromosomes is not shortened; suppression of telomerase activity in these cells causes shortening of the telomere end and division termination, i.e., aging; and restoration of telomerase activity makes them potentially immortal again. Therewith, facts contradictory to this conception were accumulated. The most convincing of them were obtained by a research group led by Blasco (Blasco et al., 1997). They obtained mice zygotes lacking a telomerase gene but with full-sized initial chromosome telomere ends. Mice developed from these zygotes were not only viable, but also fertile. This initial telomere length was sufficient to maintain normal viability of six mouse generations. In the first generation, for example, mice passed through youth and maturity successfully and died in old age having 80% of telomeres in reserve. Only in the fifth and sixth generations did anomalies caused by chromosome telomere end depletion appear. These data were confirmed by another group of authors led by Herrera (Herrera et al., 1999). They obtained an analogous mouse line, but with a shortened initial telomere end, and repeated the experiments of Blasco et al. These mice were viable for only four generations, and anomalies in late generations were related with depletion of telomeres in cells of tissues with the most intensive proliferation (Lee et al., 1998). By the present time, researchers of the telomere mechanism incline to the conclusion that loss of the telomere end indeed leads to chromosome erosion and cell death, but cell proliferation termination during normal physiological cell aging happens earlier than this critical moment and a cell that has expended all its proliferative potential still contains a significant telomere reserve. The telomere mechanism serves as an additional barrier on the road to reproduction of malignant cells (Itahana et al., 2004). The conclusion that there is nonparticipation of the telomere apparatus in the mechanism of termination of old cells' division could have been drawn from the very beginning. It followed from the results of the initial Hayflick experiments that, after a certain number of doublings, a cell enters a nondividing, but viable, state, and there is no sense in discussing viability if division termination due to chromosome

erosion is accepted. Therefore, the question of the Hayflick limit's nature is without answer. Apparently, an alternative reason for this phenomenon should be looked for in the mechanism of cell division.

### 4.3 The reason for termination of proliferation of old cells

The cell division cycle (proliferative cycle) is divided into four phases (Sherr, 1994): G1, S, G2, and M (Fig.1).



Cycle of cell reduplication is divided into 4 phases: G1 (gap 1), S (synthesis), G2 (gap 2), and M (mitosis).

Fig. 3. Phases of proliferative cell cycle.

In the G1-phase, precursor molecules necessary for DNA reduplication and doubling of all cell structures in the following division are synthesized. In the following S-phase, DNA is reduplicated, and after a short G2-phase, a cell enters M. Numerous studies have showed that all non dividing cells stay in the G1-phase. If a cell has passed through this phase, then it will pass through other phases automatically with almost equal speed. As far as entry of old cells into irreversible proliferative quiescence is concerned, we will be interested only in events occurring in the G1-phase. Control of the cell division rate is performed by endogenous and exogenous (for a cell) regulatory factors that are stimulators and inhibitors of proliferation. As an example of such regulation, the data of one of the first works in this field (Leof, et al., 1982) accurately reflecting the essence of the phenomenon are shown. The effect of different growth factors on mouse fibroblasts was studied. It was shown that, right after mitosis completion, a cell enters a proliferative quiescence state between the M and G1-phases (the G0-phase). To be removed from this state, a cell needed an external proliferative signal from platelet derived growth factor (PDGF). No structural or biochemical changes in a quiescent cell happened without the signal, and it remained insensitive to other proliferative stimuli. This primary stimulus is a competence factor. After a cell has received

this signal, the biochemical reactions for new division cycle preparation begin, stopping a period of time. For further development of biochemical events, epidermal growth factor (EGF), not PDGF, was necessary. The addition of EGF caused continuation of biochemical and structural changes, but after some time a new halt at the G1/S-transition occurred, which was called the restriction point R. The passage of the last several hours of the G1-phase happened only under somatomedin C stimulation (Sm-C). The last two factors were called the first and the second progression factors. All tissue cells are stimulated by its growth factors. In addition to growth factors, passing through a cell cycle is regulated by a large group of inhibitors (Sherr & Roberts, 1999; Sherr, 2000). Cells can leave a cycle and move to a quiescent state. There are three types of quiescence. (1) Irreversible quiescence, or the terminal differentiation state, in which cells lose growth factors' receptors and become incapable of returning to a proliferative cycle (for example, neural, secretory, and muscular). (2) Temporal quiescence necessary for a cell to function within one or another tissue. This occurs if a cell does not receive the necessary proliferative stimulus from growth factors or there are exogenous inhibitors in the environment that void their proliferative signal. Such cells retain the integrity of their receptor apparatus, and, in appropriate conditions, they are able to come back to a cycle (for example, hepatocytes, fibroblasts, and others). (3) Proliferative quiescence of old cells that spend all their proliferative potential is similar to temporal quiescence. Cells retain their receptor apparatus and the integrity of all structures necessary for proliferation, although division does not occur.

The first experiments to determine the reasons for termination of proliferation of old cells were performed by Rittling et al. (1986). They studied 11 biochemical reactions happening sequentially in the G1-phase in young and old cells. It was shown that, in old cells, all reactions occur in the same way as in young cells, but old cells stop at the restriction point and deepen in quiescence, not reflecting the proliferative stimulus by the second progression factor. If after some period of time these cells are stimulated by proliferative factors again, they will pass through all the stages of preparation to transfer to the S-phase and will come back to a proliferative quiescence. The authors concluded that, in old cells that have expended all their proliferative potential, the restriction point becomes impassable.

Events happening in the restriction point are studied intensely, mainly by researchers of carcinogenesis. Their interest is due to the fact that malignant cells pass this point without stopping, while a delay of the cycle of dividing normal postembryonic cells here is obligatory and, for old cells, as has already been mentioned, this point becomes an insuperable barrier. To date significant success in studying biochemical events in this point has been achieved.

The main regulators of reactions occurring in the division cycle are cyclin-dependent kinases (Cdks). They are the controllers of all events: they determine the order of reactions, their duration, and their intensity (Sherr, 1996). The function of cyclin-dependent kinases is simple: *de novo* synthesized gene-regulating proteins of a division cycle E2F leaves a translational conveyor, figuratively speaking, in a package. This package is retinoblastoma protein (Rb). Until these proteins are bound with Rb, they are inactive. Cyclin-dependent kinases phosphorylate Rb protein, and, after that, regulatory proteins are released and activate genes necessary for the division cycle (Sherr, 2000; Frolov & Dyson, 2004). Cdks themselves can be in an active or inactive state. Regulation of cyclin-dependent kinases'

activity is quite complex (Morgan,1995) but it is enough to know two principal moments to uncover the discussed topic: (1) Cdk is activated when it is conjugated with a specific cyclin (which is evident from its name) and (2) an active Cdk-cyclin complex can be deactivated again if it is conjugated with a specific inhibitor of cyclin-dependent kinases. To date eight types of cyclin-dependent kinases marked with the numbers Cdk1, Cdk2, etc.; ten types of cyclins marked with the Latin letters cyclin A, cyclin B, etc.; and a large group of Cdk inhibitors that have individual number labels and represent several families have been found in mammals. Three Cdks (2, 4, and 6); the cyclins D, E, and A; and the inhibitors of INK4 (p15<sup>ink4b</sup>, p16<sup>ink4a</sup>, p18<sup>ink4c</sup>, and p19<sup>ink4d</sup>) and CIP/KIP families (p21<sup>cip1</sup>, p27<sup>kip1</sup>, and p57<sup>kip2</sup>) regulate passage through G1 (Sherr & Roberts 1999; Sherr, 2000). INK4 inhibitors specifically interact with Cdk4 and 6 and function in the G1-phase until the restriction point, and CIP/KIP interact with all Cdks. Research on G1-phase events has increased greatly in the past decade. New biochemical participants and ways in which they interact have been found. Information about them can be found in several reviews and original papers (Bockstaele et al., 2009; Larrea et al., 2008; Rahimi & Leoff, 2007; Sherr, 2000). Here only the main events minimally sufficient for understanding of termination of old cells division will be discussed. Leaving out the details, the G1-phase passing scheme discussed in (Sherr, 1996; Sherr & Roberts, 1999) can be shown in the following way (Fig. 4). The level of inhibitor p27 in quiescent cells is high, which prevents the reaction for division preparation. In response to mitogen stimulation, cyclin D is expressed and the active complex cyclin D-Cdk4 is formed, as are phosphorylates Rb. As a result gene-regulating E2F proteins are released and phosphorylated Rb is degraded. Then E2F proteins activate enzyme genes necessary for DNA reduplication in the S-phase and cyclin E, Cdk2, and E2F genes. Released cyclin E and Cdk2 form an active E-Cdk2 complex, which began interacting with p27, phosphorylating Rb, and activating regulatory protein genes. It is important that the cyclin E-Cdk2 complex activates the genes of their components, i.e., it reproduces itself. As a result a positive feedback loop is formed and promotes rapid p27 removal and E2F proteins and S-phase proteins' avalanche-like increase, which allows a cell to pass through a restriction point. With this E2F increased expression induces synthesis of inhibitor p53, which terminates the E2F expression unnecessary in the S-phase. However, this and the following cycle reactions are outside the discussed topic. Two research groups simultaneously and independently drew a considerable specification of the character of interaction of p27 with active cyclin E-Cdk complex (Vlach et al, 1997; Sheaf et al., 1997). Until their works it was considered that p27 and active cyclin E-Cdk2 complex interaction had a single consequence—complex inactivation. They performed a study of the kinetics of the molecular interactions of these compounds and showed that not only does the inhibitor inactivate the complex, but the complex can also attack an inhibitor phosphorylating it on threonine 187. Figuratively speaking, there is a competition for survival between inhibitor p27 and the cyclin E-Cdk2 complex. Its outcome is determined by the reaction energy supply: with a high ATP level, the cyclin E-Cdk2 complex has an advantage. It phosphorylates p27; after that, this inhibitor becomes a target for ubiquitin-dependent proteolytic machinery and is destroyed. If the bioenergetics level becomes lower than a certain value, then even p27 inactivates cyclin E-Cdk2. As a result a positive feedback loop of E2F synthesis and S-phase transition are blocked. An ability to inactivate its inhibitor belongs only to cyclin E-Cdk2 complex and was not found in other analogous complexes.

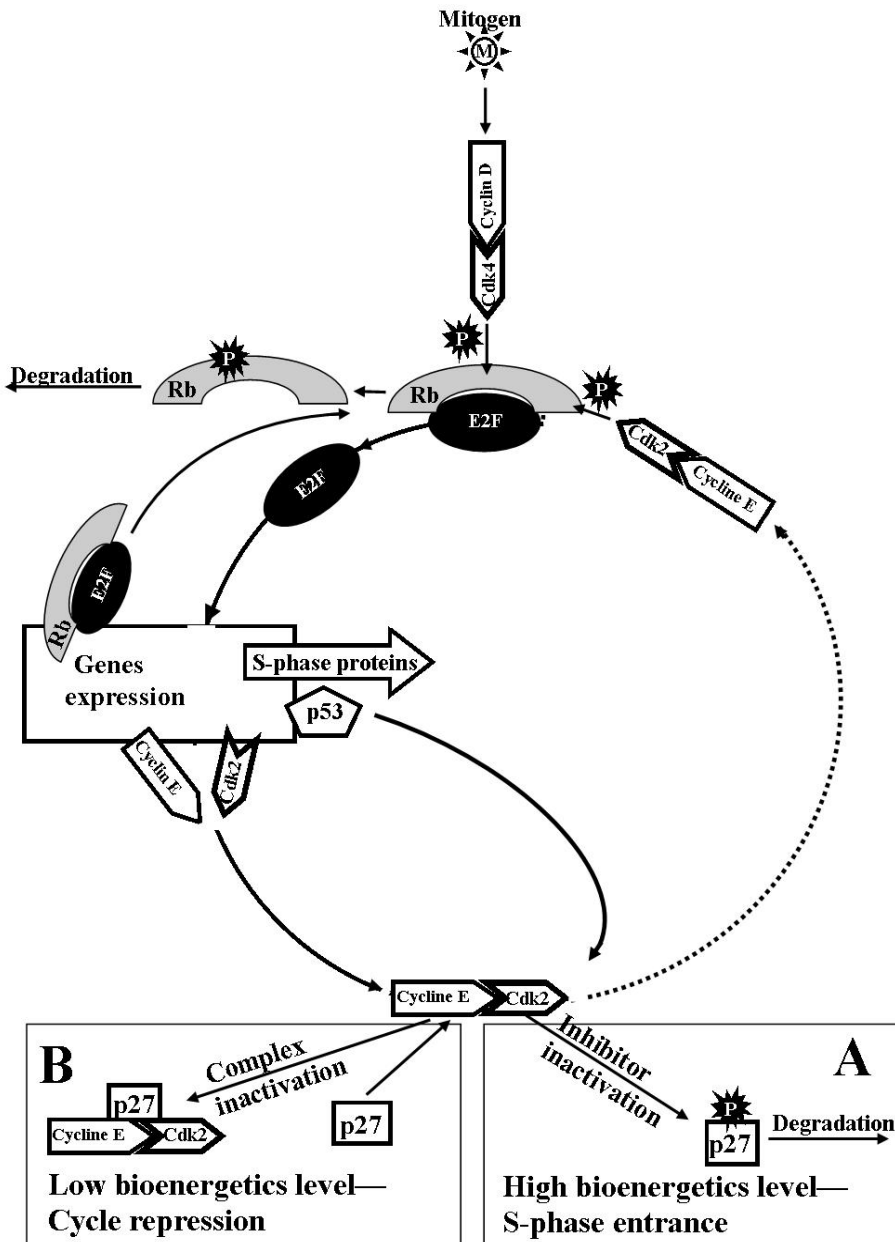


Fig. 4. Simplified scheme of control of passing through a restriction point.

In response to mitogen stimulation, an active cyclin D-Cdk4 complex is synthesized, which phosphorylates Rb protein. As a result gene-regulating E2F proteins are released and phosphorylated Rb degrades. E2F proteins activate genes of proteins essential for DNA



reduplication in the S-phase, cyclin E and cyclin-dependent kinase 2 (Cdk2) genes, as well as E2F itself. Combined cyclin E and Cdk2 form an active complex which interacts with inhibitor of cyclin-dependent kinases p27. Two consequences are possible. A. If the bioenergetics level is within the physiological norm, then Cdk2 activated by cyclin E phosphorylates p27. Then the inhibitor becomes a target for degradation. After that cyclin E-Cdk2 phosphorylates Rb and additional gene-regulating proteins are released. As E2F activates cyclin E, Cdk2, and E2F genes, then there is a positive feedback loop promoting rapid p27 removal and an avalanche-like increase of S-phase proteins, which allows a cell to pass through a restriction point. At the same time, increased expression of E2F induces inhibitor p53 synthesis, which inactivates cyclin the E-Cdk2 complex and terminates unnecessary S-phase E2F expression. B. If the bioenergetics level is below a certain critical level, then p27 forms a tight bond with the cyclin E-Cdk2 complex and inactivates it. As a result an increased expression of S-phase proteins does not occur, the p27 level remains high, and entry into the S-phase becomes impossible.

These data can explain the results of the abovementioned research by Rittling et al. The central event of the G1-phase restriction point of the cell cycle is triggering of a self-accelerating cascade of reactions controlled by the cyclin E-Cdk2 complex. This is an essential condition of inhibitor p27 removal and accumulation of all precursors for DNA reduplication and cell division. It is satisfied only with a normal physiological level of bioenergetics. When bioenergetics in old cells decreases until some threshold level, cyclin E-Cdk2 loses its ability to inactivate p27 and itself becomes a target. As a result inhibitor removal stops and S-phase transition becomes impossible. All this information can be summarized in the following way: cyclin-dependent kinase inhibitor p27 prevents passage through the restriction point. There is a special pump for its removal in a cell. Its work efficiency depends on the energy supply. During the programmed decrease of cell bioenergetics, below a certain threshold level, it stops inhibitor removal and cell division becomes impossible.

It should be mentioned that a critical level is achieved after a certain number of divisions. Thus, bioenergetics decrease and the lifespan depend not on the calendar time of an organism's existence, but from the number of past divisions in its critical tissues, i.e., the amount of the past divisions is a biological clock. An organism counts time on proliferative clock.

## **5. Longevity is under control of natural selection**

### **5.1 Introduction**

Several lines of evidence show that genes exert strong controls on longevity and patterns of aging (Carey, 2003; Holzenberger et al., 2003; Kenyon, 2010; Vaupel, 2003). Therefore, the specific genes that program longevity and the selective pressure that would lead the genes to the development during evolution are to exist (Bredesen, 2004; Mitteldorf, 2004; Skulachev, 2001). The most of evolutionists, nevertheless, deny the possibility that longevity is under the control of natural selection (Medawar, 1952; Kirkwood, 2002). In 1952 P.B. Medawar has shown that life expectancy is not under control of individual (Darwinian) natural selection. He has noticed that animals in habitat never live till an old age and perish from the various external reasons at youngish age; therefore the natural selection cannot differentiate them by the longevity sign. Hence the specific genes programming aging cannot exist. This conception dominates till now.

The aim of this section was to show the mechanism by which natural selection controls species-specific longevity. The ecological approach was used to solve the problem. As known from ecological laws, the intrinsic population growth rate ( $r_{in}$ ), the length of the generation ( $T$ ), and the net reproductive rate ( $R_0$ ) are interconnected by dependence, according to the following formula:  $r_{in} = \ln R_0 / T$  (MacArthur & Connell, 1966). It is shown here that during evolution the  $r_{in}$  value is stabilized by interpopulation (group) natural selection (not individual selection) at the level which corresponds to environmental pressure in the ecological niche of the species. This leads to the conclusion that species-specific longevity and fertility are under the control of natural selection and depend inversely on each other.

### 5.2 Population size oscillations and extinction risk

The state of a population's size over the long-term is a measure of population welfare. Stability or an increase in size testifies to the well-being of the community, but a decrease indicates that the population is under risk of extinction. A practical determination of this criterion represents a difficult problem because biological systems are dynamic. Successive changes in biological systems are termed "disturbance" (White & Pickett, 1985). Disturbances are inherent in all biological communities and occur on a wide range of quantitative, spatial, and temporal scales (Pickett & White, 1985). The size of any population determined by observation is in fact its value at an instantaneous time cut-off (Southwood, 1981). Population number can change in time by hundreds, thousands, and in some species, even by millions (Nicholson, 1954). Population size oscillations are forced by varying environmental factors, such as the infections, the availability of food, the number of predators and parasites, etc. The mean population size, population number averaged over some period of observation, is a much more informative characteristic. Based on theoretical averaging over a prolonged time interval, this parameter is considered to be the dynamically equilibrium size ( $N_{eq}$ ). However, the fate of a population depends on its minimal size ( $N_{min}$ ), i.e., the lowest value which a population reaches in the process of oscillations.  $N_{min}$  depends on both  $N_{eq}$  and swings in the population size. The minimal population size is a genetic bottleneck that is an evolutionary event in which the population is often reduced by several orders of magnitude (Leberg, 1992; Richards & Leberg, 1996). Populations are potentially immortal, but each of them is always subject to the risk of extinction due to minimum viable population size (Green, 2003; Tracy & George, 1992). The last is the smallest population size that will persist over some specified length of time with a specified probability (Hedrick & Gilpin, 1996). If a population size is reduced below this value, even if for a moment in time, then the population becomes doomed to extinction during future generations due to genetic drift (Cherry & Wakeley, 2003; Gilpin & Soule, 1986). Therefore, the extinction risk is maximal in the  $N_{min}$  state because a significant part of a population is prevented from reproducing. This increases genetic drift, as the rate of the drift is inversely proportional to the population size (Frankham, 1996; Lande, 1993; Shaffer, 1981).

### 5.3 The interpopulation natural selection

The mechanism of interpopulation natural selection is simple: "Small populations can fluctuate out of existence quite rapidly" (Leigh, 1975). In other words, preferred extinction

of populations having less  $N_{min}$  is the essence of interpopulation natural selection. Natural selection, as a whole, consists of two stages. During the first stage, the classical Darwin-Wallace individual selection rejects organisms which are less adapted to the given environment. As the members of the population serve as an environmental factor for each individual, attributes can arise that are useful only to their carriers but neutral or harmful for the other individuals. Such attributes become harmful for the community, but they are supported by individual natural selection. Longevity and a number of psychological attributes, for example, are a concern to them (Gadgil, 1975). The interpopulation selection takes such attributes under control as the populations are units of natural selection in the second stage (Levins, 1962; Wilson, 1973). If any attribute decreases  $N_{eq}$  or increases the amplitude of oscillations and spreads in the population, then the population perishes as a whole. In contrast, the attributes that increase  $N_{min}$  promote population survival, which is an evolutionary mechanism for developing characteristics that are useless or even harmful for individuals, but beneficial for the community (e.g., altruism, care of posterity, and bravery). To determine the direction of evolution for a specific attribute of a species' populations, it is necessary to assess the dependence of  $N_{min}$  from a quantitative expression of this attribute. The pressure of group selection is always directed to an increase in  $N_{min}$ .

#### 5.4 Evolution mechanism of longevity and fertility

To solve the problem under consideration, we need to consider the dynamics of populations of an abstract species of vertebrates with overlapping generations. In so doing, we shall determine the dependence on  $N_{min}$  from the intrinsic population growth rate ( $r_{in}$ ) at a various value of environment pressure in the species' ecological niche, remembering thus that

$$r_{in} = \ln R_0 / T \quad (1)$$

A change in size of population,  $dN/dt$ , depends on the difference between birth and death rates:

$$dN / dt = dN_b / dt - dN_m / dt. \quad (2)$$

Accordingly, population size influences birth and death rates:

$$dN_b / dt = bN \quad \text{and} \quad dN_m / dt = mN \quad (3)$$

where  $b$  and  $m$  are density-dependent are birth and death rates, respectively.

Population size does not influence the birth and death rates directly, but through changes in environmental parameters. When the population size increases, food resources are exhausted, the number of predators and parasites grow, infections are increased, and living space per capita declines. All this raises the level of environmental pressure upon a population. As a result, the birth rate decreases but the death rate increases (Fig. 5):

$$b = b_{in} - aN; \quad m = m_{in} + jN \quad (4)$$

where  $b_{in}$  and  $m_{in}$  are intrinsic are birth and death rates that are realized, provided that  $N$  is negligible;  $a$  and  $j$  are environmental pressures on the birth and death rates respectively. Substituting  $b$  and  $m$  from equation (4) in equation (2), and taking into account equation (3), it follows that:

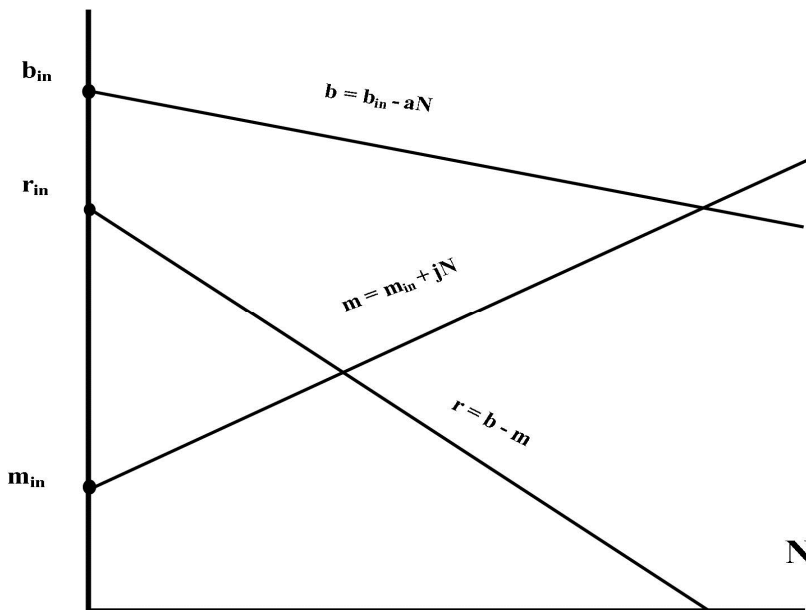
$$dN / dt = (b - m)N = (b_{in} - m_{in})N - (a + j)N^2 \quad (5)$$

Having designated  $b_{in} - m_{in} = r_{in}$  and  $a + j = p$ , equation (5) can be rewritten as

$$dN / dt = N(r_{in} - pN) \quad (6)$$

where  $r_{in}$  is the intrinsic population growth rate ( $time^{-1}$ ), and  $p$  is the environmental pressure ( $time^{-1}N^{-1}$ ).

The dynamics of any population is complicated by feedback among population size and the environmental pressure. The environmental conditions vary after changes in population size with some time delay. Let, for example, population size grow from  $N_{min}$  at time  $t_0$  to  $N_{eq}$  at time  $t$ . At once, as the population size reaches  $N_{eq}$ , the environmental pressure remains at the level that existed at the moment,  $t - \tau$ . The time delay,  $\tau$ , is the time necessary for the breeding of parasites and predators and a reduction of food resources and vital space per capita. As a result, the population size proceeds to increase to the equilibrium point  $N_{eq}$ , and reaches the point,  $N_{max} > N_{eq}$ . As this state is unstable, the population size is reduced and, for the same reason, passes the  $N_{eq}$  point and falls to  $N_{min} < N_{eq}$ ; this is the nature of auto-oscillations about  $N_{eq}$  (Macfadien, 1963; May, 1973). Being forced out of the equilibrium condition, a population enters an auto-oscillation regimen and the amplitude of the oscillations can serve as a criterion of population responsiveness to environmental variability.

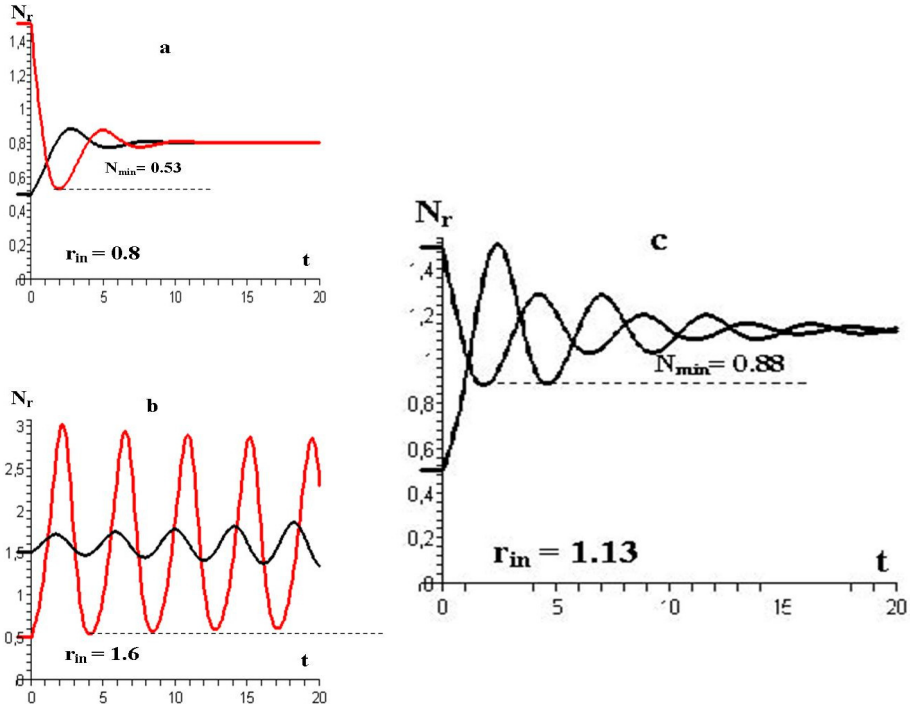


The increase in the population number leads to a decrease in  $b$  and an increase in both  $m$  and  $r$  relative to their intrinsic values,  $b_{in}$ ,  $m_{in}$ , and  $r_{in}$ . The slopes of the line depend on the environmental pressure on the birthrate ( $a$ ) and mortality ( $j$ ).

Fig. 5. Dependence of birth ( $b$ ) and death ( $m$ ) rates and the population growth rate ( $r$ ) from the population number ( $N$ ).

With the delay effect, equation (6) becomes:

$$dN_t / dt = N_t(r_{in} - pN_{(t-\tau)}) \tag{7}$$



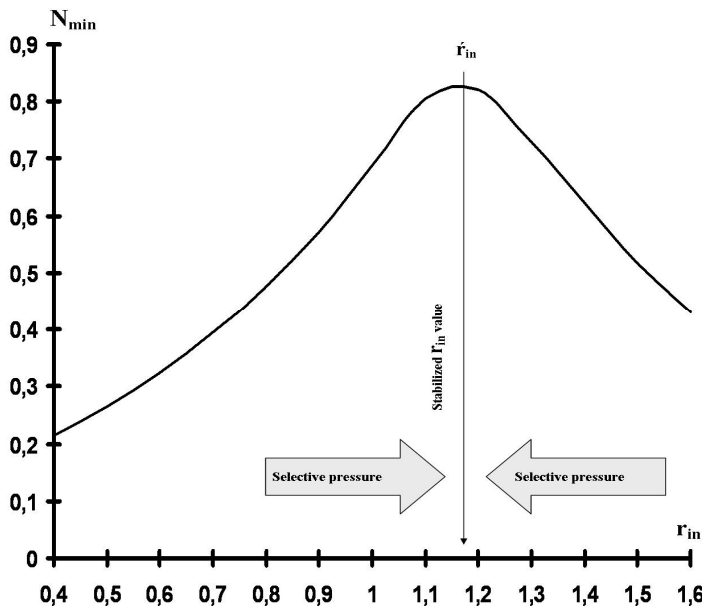
Exes: abscissa is time and the ordinate is the current population number divided by the equilibrium at time  $t_0$  ( $N_r = N_t/N_{eq}$ ). The consequences of two situations in the environment are modulated (two curves): (1) a favorable coincidence that raises the outbreak of the population number ( $N_0 > N_{eq} = 1.5$ ) and (2) coincidence of severe conditions that causes population depression ( $N_0 < N_{eq} = 0.5$ ). (a) Populations having small values of  $r_{in}$  are reduced to the minimal value after outbreaks of numbers (red curve): coincidences of favorable circumstances in the environment threaten the existence of such populations to a greater extent. (b) Populations having large values of  $r_{in}$  reach the lowest number after a state of decay (red curve): coincidences of unfavorable circumstances threaten the existence of such populations to a greater extent. (c) There is an optimal  $r_{in}$  value under the present environmental pressure when favorable and unfavorable environment cataclysms are followed by an equal aftereffect. The value of  $N_{min}$  is maximal under this  $r_{in}$ ; this  $r_{in}$  value is maintained by interpopulation selection.

Fig. 6. The influence of the intrinsic population growth rate on parameters of population size oscillations.

It can be seen that the dynamics of the population are determined by three parameters:  $\tau$  and  $p$ , are factors of the habitat, but  $r_{in}$  is an intrinsic characteristic of the population. Each of the factors influences oscillation characteristics. Parameter  $\tau$  is the regeneration time of density-dependent environmental factors. As the environmental pressure is a complex value, then  $\tau$  is also a multifactorial distributed characteristic of the environment (Schley &

Gourley, 2000). However, it can be accepted as a discrete characteristic at solving many tasks analogous to our problem (May, 1981; Schley & Gourley, 2000). The numerical solution of equation (7) shows that  $\tau$  influences the amplitude of the population size oscillations: the greater the  $\tau$ , the greater the amplitude of oscillations. Species that are under  $\tau < 0.3$  have the least variability; perturbed size of its populations monotonously return to the equilibrium state. In the range  $0.3 < \tau < 1.6$ , an oscillatory return to an equilibrium number occurs. The further  $\tau$  increases cause continuous oscillations. If  $\tau > 2.2$ , then populations become non-viable; the smallest external disturbance provokes increasing oscillations that decrease  $N_{min}$  to nil. It is apparent that within an ecological niche, in the overwhelming majority of vertebrate species the  $\tau$  value is limited by 0.4-1.5. Therefore, we shall accept in further calculations that this parameter of the ecological niche of the abstract species under consideration is equal to 1.

The numerical solution of equation (7) shows that the variation of  $r_{in}$  influences both the  $N_{eq}$  value and the amplitude of oscillations that predetermines changes in  $N_{min}$  (Fig. 6). The dependence of  $N_{min}$  from  $r_{in}$ , calculated with other parameters unchanged ( $p = 1$ ;  $\tau = 1$ ), is shown in Fig. 7. The curve of dependence  $N_{min}(r_{in})$  has a maximum under certain  $\hat{r}_{in}$ . As mentioned above, the selective pressure is always directed to an increase in  $N_{min}$ . In the case in point, the directions of selective pressure are opposite from larger and smaller  $r_{in}$  values. Hence, it appears that the intrinsic rate of population growth is stabilized by group selection on the level which corresponds to the maximal  $N_{min}$  value:

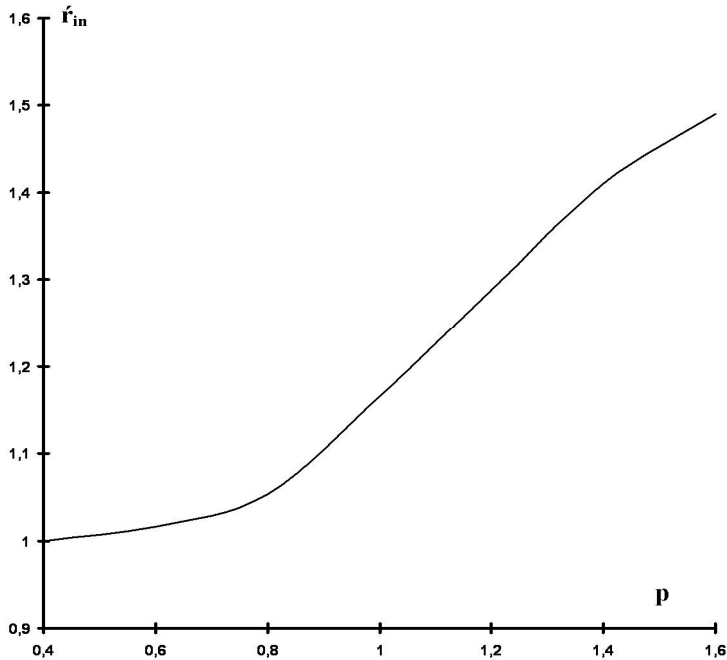


Under constant environmental parameters ( $p = 1$ ;  $\tau = 1$ ) the curve of dependence  $N_{min}(r_{in})$  has a maximum under a certain  $\hat{r}_{in}$ . As the extinction risk is inversely proportional to  $N_{min}$ , then selective pressure pushes  $r_{in}$  of populations of species to this value.

Fig. 7. Scheme of stabilization of the intrinsic population growth rate by interpopulation selection.

if the environmental pressure is constant, then any population of a species deviating from this value will have a greater extinction risk. As  $r_{in} = \ln R_0 / T$ , then the length of the generation and the net reproduction rate are stabilized by interpopulation natural selection. On a long-term temporal scale, the environmental pressure becomes constant.

However, in the course of evolution, it can gradually vary during a change of parameters of an ecological niche under influence, for example, changes of climate. The calculated dependence of the stabilized  $\hat{r}_{in}$  value from  $p$  shows that variation in environmental pressure causes a change of the stabilized intrinsic population growth rate: the greater the  $p$  value, the greater the  $\hat{r}_{in}$ .



An increase in environmental press in the ecological niche of a species in the course of evolution causes growth of the intrinsic population growth rate and vice versa.

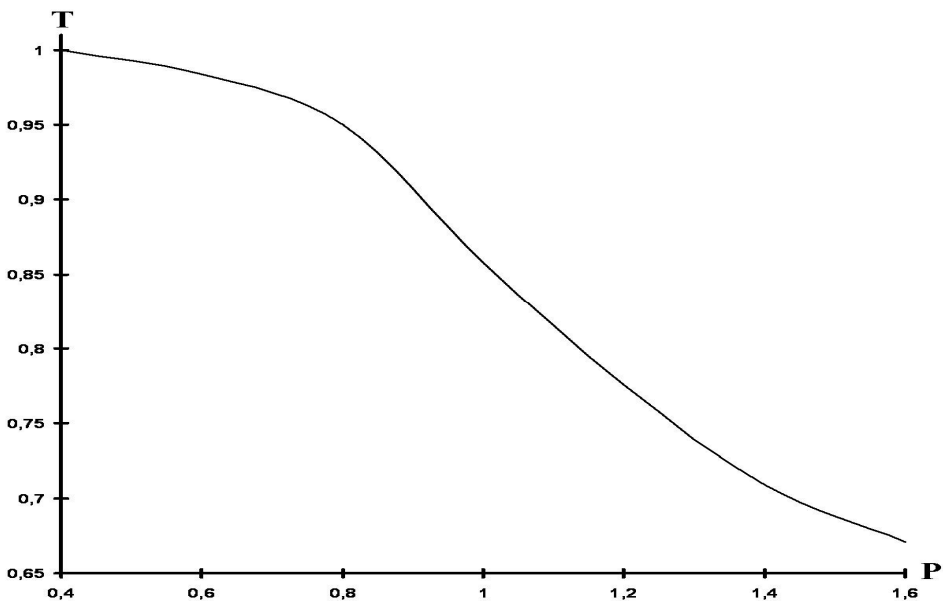
Fig. 8. The dependence of a stabilized intrinsic population growth rate ( $\hat{r}_{in}$ ) from environmental pressure ( $p$ ).

Thus, the value of the intrinsic rate of population growth is under natural selection control and it is predetermined by environmental pressure within the ecological niche of the species.

The conclusion that the intrinsic rate of population growth is stabilized by interpopulation natural selection can be made logically without resorting to mathematical calculations. Population size oscillations are inevitable because of stochastic variations in the environment and are harmful as they increase the extinction risk. The intrinsic rate of the population growth influences population responsiveness to environmental fluctuations. When a population is in a state of size reduction, the maximal  $r_{in}$  is preferably for oscillation damping. Under these conditions, a decrease in population size in any given half cycle of the oscillation will be minimal as the high rate of breeding serves as a brake for the decrease.

But, such  $r_{in}$  values will become threatening when the opposite phase begins as it intensifies the increase in population size. According to the theory of risk spread, the greater the extension of a population on top, the deeper it falls in foot. The same intensification of amplitudes is provoked by an inverse extreme value of the intrinsic population growth rate. A natural population cannot have such an extreme or any arbitrary of  $r_{in}$  value. There is an optimal value of the intrinsic rate of population growth which ensures minimal possible population oscillation (Fig. 6). That value is sustained by interpopulation natural selection because deflection of the  $r_{in}$  to any side from the value increases the population extinction risk; the above-stated mathematical calculations alone have demonstrated this.

Let's look now what in fact is hidden behind the intrinsic population growth rate. According to equation (1), these are two population characteristics: 1) the net reproduction rate and 2) the length of the generation, neither of which can be programmed by the genome directly. In a general sense, the length of the generation is the time from which the individuals are born to the time most offspring, on average, are produced for a population. The concept of "post-reproductive age" is applicable to the full only to post-industrial man and his/her pets. Animals of post-reproductive age are rare in natural habitats (Medawar, 1952). Analyses of cohort life tables of natural populations show that the length of the generation is actually equal to the mean survival of the population age-groups. Thus the average longevity in the habitat is under natural selection control.



The increase in environmental pressure in a species ecological niche results in a longevity decrease.

Fig. 9. Dependence of longevity (T) on environmental pressure in the ecological niche of a species.

The variation in the net reproduction rate corresponds to the variation in fertility of the population members. To understand it, we should recollect that  $R_0 = N_T/N_0$ , where  $N_0$  is the

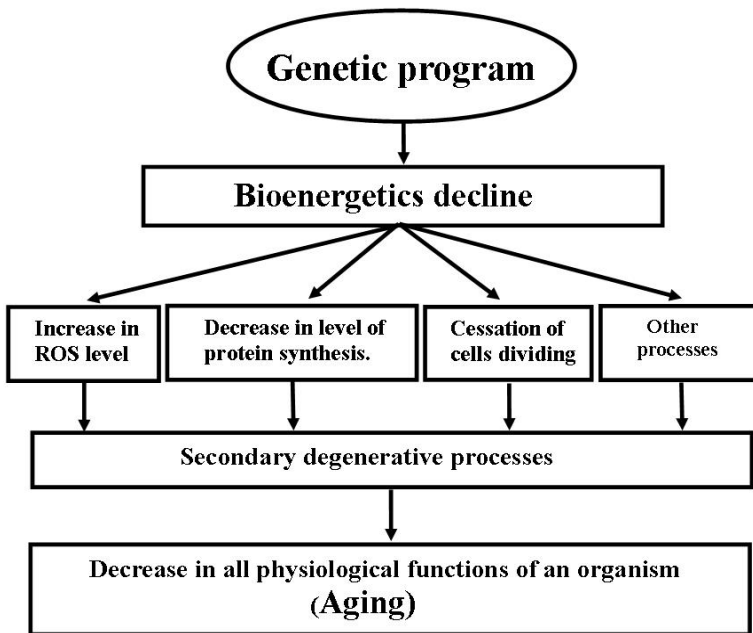


initial population size and  $N_T$  is the population size one generation later. It is apparent that if  $R_0$  is increasing in evolution, the fertility is growing, and vice versa.

Thus, longevity and fertility are actually under the control of interpopulation natural selection. The selective pressure acts on both components of  $r_{in}$  simultaneously, but the distribution of forces are unequal for different species because of environmental factor specificity. As a result, only a correlation between longevity and fertility exist in nature. This evolution mechanism of longevity is apparently applicable only for vertebrata. Invertebrates, by virtue of their huge variety, can have others, and various, evolution mechanisms determine species specific longevity.

## 6. The mechanism of aging

According to the above considerations, the mechanism of programmed aging is represented as follows (Fig. 10): the genetic program controls the only function - bioenergetics decline. The latter causes the increase in the ROS level, a lowering of the protein synthesis rate, the cessation of cells dividing and some other processes; every one of them in turn spawns a number of secondary harmful processes. As the number of cells dividing (proliferative time) increases, these destructive phenomena in an organism's tissues augment progressively, which gradually leads to the organism's destruction.



The genetic program decreases the bioenergetics level as the number of cell divisions augments. This results in the increase in the ROS level, the lowering of the protein synthesis rate, the cessation of cells dividing and some other injurious processes. In turn, each one of them spawns a number of secondary harmful processes which leads to a decrease in all of the physiological functions of an organism, i.e. aging.

Fig. 10. Scheme of the bioenergetics mechanism of aging.

## 7. Conclusion

Gerontology has entered the 21 Century with significant empirical baggage but without a theory capable of generalising the data and discovering the general regularities of the aging process. Instead, as mentioned, more than 300 different theories have been developed. There is still no consistent opinion as to what the primary driving force of aging actually is. The majority of researchers are convinced that there are no genes for aging and that stochastic factors underlie the aging. Those who trust in the programmed theory assume that almost every process influencing aging is governed by its own genes, i.e. aging is multifactorial. According to this, genes of aging exist and they control the sole driving force of aging - proliferative-dependent bioenergetics decline. It can be shown that this programmed process underlies, whether expressly or by implication, any theory of aging based on real phenomenon. This can provide the basis for the creation of a united theory of aging.

The present situation in modern gerontology does not suggest any hope of the achievement of the abovementioned strategic aim: numerous efforts to elaborate a remedy for senescence based on stochastic theories have yielded no result. The strict restriction of food (calorie restriction) is the only trick that has been developed which authentically increases species' maximal lifespan. The mechanism for this phenomenon is not yet understood, but it is easily explained by the bioenergetics theory: the lack of food detains cell division which in turn leads to a lag of the proliferative clock relative to calendar time. The programmed theories do not much promise success because of the large number of genes that operate in the ageing process. A decrease in the level of bioenergetics is apparently programmed by only a few genes. The analysis of the evolutionary plasticity of fruit fly populations has shown that longevity is programmed by no more than by three genes (Mylnikov, 1997).

One relevant inference to be made of the theory stated above is that the manipulation of any secondary phenomenon generated by the decline in bioenergetics cannot give effect to an increase in the maximal lifespan. A means to operate bioenergetics has to be found - it is the only way towards healthy and unlimited longevity. This is complicated problem but it can be solved in the near future: the bioenergetics machine is already studied well enough, the regulator of energetical homeostasis is visible, and the potent arsenal of experimental techniques is created. The period depends mainly on facilities for research.

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# Sirtuin-Dependent Metabolic Control and Its Role in the Aging Process

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## 1. Introduction

During last years, the protein family of sirtuins, composed by NAD<sup>+</sup>-dependent deacetylases, has emerged as a key factor in aging. From yeast to humans, sirtuins are involved in metabolic changes that induce a higher respiratory capacity accompanied by lower oxidative damage. They are involved in the control of glucose catabolism, fatty acid metabolism, respiratory chain activity in mitochondria and several other metabolic processes including control of antioxidant capacity in cells and tissues (Dali-Youcef et al., 2007; Elliott & Jirousek, 2008; Lomb et al., 2010; Pallas et al., 2008).

As these deacetylases are dependent on the NAD<sup>+</sup>/NADH ratio, they can be considered as important sensors of the metabolic status of the cells and probably because this they are one of the main family of proteins involved in the regulation of metabolism in the cell (Li & Kazgan, 2011). Further, their relationship with the AMPK-dependent pathway, that controls respiratory metabolism by inhibiting insulin-dependent signaling, highlights the importance of these proteins in metabolic regulation and especially in insulin-resistance, diabetes and obesity (Canto et al., 2009; Ruderman et al., 2010).

Sirtuins have been involved in aging process and considered important factors in delaying aging process and increase longevity (Guarente, 2000; Tissenbaum & Guarente, 2001). However, very recent studies have questioned the role of these deacetylases in longevity (Burnett et al., 2011; Viswanathan & Guarente, 2011). But their activity in yeast, worms and flies still permits to correlate its function in metabolism and dietary-dependent modulations with aging process (Guarente, 2008). However, to date, in mammals and, especially in humans, their role in longevity is not clear. Whereas in lower organisms only one member has been found, SIR2, in mammals, seven members have been described to date. This fact indicates a higher complexity in interactions, targets and functions in higher animals than in lowers. Further, in mammals, the specific distribution of these deacetylases among the different cell compartments also indicates several local-dependent influences of sirtuins.

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Aging can be considered a severe deleterious process that affects all the compartments in cells and also all the tissues and organs in the organism. Apart of the different theories of aging (Jin, 2010), the main common factor is the accumulation of non-metabolizable or degradable molecules into cells and tissues that impair their correct function. In few words, we age because our organism accumulates rubbish and we are unable to eliminate or recycle it. Most of the damaged molecules are the result of a unbalanced metabolism that produces high levels of reactive molecules accompanied by a low capacity of the endogenous antioxidant mechanisms of cells and the recycling mechanisms such as proteasome and autophagy or DNA-damage repairation (Asha Devi, 2009; Fleming & Bensch, 1991; Maynard et al., 2009; Perez et al., 2009; Sohal et al., 1994). As results, oxidized molecules accumulate into cells impairing their physiology at all levels. Then, a balanced and controlled metabolism will improve oxidant/antioxidant relationship and delay the accumulation of oxidized molecules in aging cells and tissues.

The present chapter is focused on the role of the metabolism in aging process and the importance of sirtuins in its control. We will describe the different pathways regulated by sirtuins and how modifications in NAD<sup>+</sup>/NADH ratio can affect the activity of these deacetylases. Moreover, we will discuss the possible role of NADH-dependent oxidoreductases in the control of metabolism through these proteins. Furthermore, the role of a known polyphenol, resveratrol, as agonist of sirtuins and caloric restriction in aging and metabolic control will be also revised.

## 2. Sirtuins, a heterogeneous family of protein deacetylases

Sirtuins are a family of proteins that share a conserved NAD<sup>+</sup>-dependent acetyl-lysine deacetylase and ADP-ribosyltransferase activity. They have been related to the regulation of the metabolism and also lifespan being involved in cell survival and apoptosis, cell proliferation and senescence. They are widely located in all the organs and near all the subcellular locations. The seven isoforms found to date in humans localize either in the nucleus, cytoplasm or mitochondria. The use of modified organisms showing increasing gene dosage of sirtuin orthologs in eukaryotes such as yeast, worms or flies have demonstrated that these enzymes are directly involved in lengthening of longevity (Guarente, 2007). Further, the relationship between calorie restriction and longevity indicate that metabolism is directly involved in aging, and then, as sirtuins are involved in the control of metabolism, a direct link between the activity and modulation of these proteins and a longer lifespan seems to be convincing (Balcerczyk & Pirola, 2010).

In contrast with class I, II and IV deacetylases, mainly involved in the control of epigenetic processes (Kuzmichev & Reinberg, 2001), sirtuins are members of the class III characterized to be dependent on NAD<sup>+</sup>. These enzymes catalyze the reaction shown in figure 1. They bind to a Nε-acetyl-lysines of the target protein and deacetylate them by using NAD<sup>+</sup> as substrate and producing nicotinamide (NAM) and 2'-O-acetyl-ribose (2'-O-AADPR) as products (Hirsch & Zheng, 2011). In this process, increasing levels of NAD<sup>+</sup> increase the activity of sirtuins whereas higher NAM or NADH levels exert an inhibitory effect (Wolberger, 2007). Further, the expression of sirtuins are also regulated by the ratio NAD<sup>+</sup>/NADH since higher mRNA levels have been found when NADH/NAD<sup>+</sup> levels rise (Gambini et al., 2011). Then, they can be considered as metabolic sensors since they can modulate their activity and levels depending on the ratio NAD<sup>+</sup>/NADH.

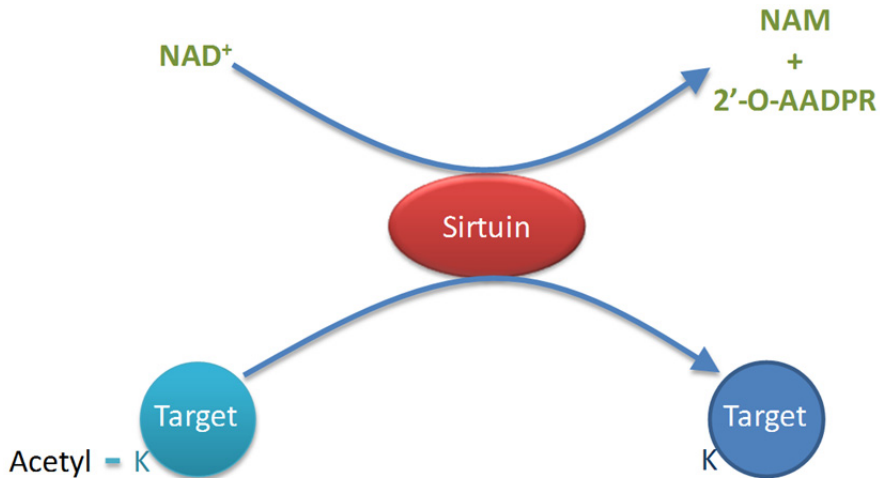


Fig. 1. Deacetylation of K-acetyl residues in targets of sirtuins.

The first member of this family studied in deep was the yeast Sir2. This deacetylase is responsible of silencing chromatin by deacetylation of histones (Blander & Guarente, 2004) and has been related to the increase in longevity in yeast, worms and flies. Apart of its activity reducing the accumulation of chromatin of ribosomal RNA (rRNA) genes in yeast, the prolongevity of Sir2 has been also related to the modulation of mitochondrial function providing benefit to slow aging and associated diseases (Guarente, 2008).

To date, seven sirtuins have been described in mammals. They are designed as SIRT1 through SIRT7. Based on the homology of the 250 aminoacids core domain, the mitochondrial SIRT3, the nuclear-cytosolic SIRT1 and the mainly nuclear SIRT2 show the closest homology to yeast SIR2 (Frye, 2000). However, if we attend to the alignment of the aminoacid sequence of the human members we can see that the identity at the aminoacid sequence is very low among the members of sirtuins family (Table 1) and only deacetylase sirtuin-type domain shows some homology being highly in the NAD<sup>+</sup>-binding and in the catalytic domains (Figure 2). A possible explanation for these high differences in sequence between the members of sirtuin family in mammals can be found in the plethora of targets that can be recognized by the different members of the family and in their different and selective locations into the cell.

	hSIRT1	hSIRT2	hSIRT3	hSIRT4	hSIRT5	hSIRT6	hSIRT7
hSIRT1	100						
hSIRT2	34.34	100					
hSIRT3	30.94	44.85	100				
hSIRT4	24.55	21.88	26.02	100			
hSIRT5	25.63	22.71	27.66	27.13	100		
hSIRT6	21.56	24.21	28.84	28.43	20.59	100	
hSIRT7	20.97	22.28	23.70	28.14	22.01	36.77	100

Table 1. Pairwise comparison of aminoacid sequences from the human sirtuin members. From BLAST (basic local alignment search tool) analysis of the indicated proteins in figure 2.

YSIR2/P06700 NPSNGI FVGRSFTKRESINARMEFLKYYG-----AHKFLDTYLPEDLNLSLYIYLKILGFEVKDQALIGTINSIVHINSQERVQDLGSAISVTVNVEDPLAKKQVTVRLIKDQRAINKVL 232  
 hSIR1/096EB6 NLYDDDDDDGEEEEEAAAAGYRONLLFGDEITINGFHSCESEEDRASHASSDWTFRPGYTFVQOHMIGDFDRTIKDLLETIPPEPPEDMTLWQIVINIISEPPKR---- 234  
 hSIR2/081XJ6 NLFSDTSLGQKER-----RCRKYICIVGAGISITAGIPDFSPSTGLD--NLEKXHLPEPEAIETISYFKKHPEFFALAKELYPGQFKPTICHYFMRLDKGILLRKTQNIIDL 172  
 hSIR3/09NTG7 ACQRVVMYVAGISITSPSIGIPDFSPGSLAS--NLQYDLPYPEAIFELFFHNPKPFFFLAKELYPGNKPNVHTFLRLLHDKGILLRLYTONIDVL 233  
 hSIR4/09YGE7 KLLAVMTGAGISITSPSIGIPDFSPGSLA--RTDRRPQIQHGDFRIPQRYWARNFVGFQFSIQPFAHWLSWFKLQKLVLYTONIDVAL 148  
 hSIR5/09NKA8 KHVILISAGVSAESGVTFFG--AGCYNR--KWAQDLATPLAFAHNRSWVEFYHRYREVMYKSEENAGHAIACEBTRLGHQGRVVVITONIDEL 145  
 hSIR6/08NET7 SSVVPHGAGISITSPSIGIPDFG-----PAGVWMEERGLAKPDTFFES-----RPTQIEMALYQLREYVGLLERFYSQNVJGL 118  
 hSIR7/09NRC8 KLVVVYTAGISITSPASIPDFG-----KLVVVYTAGISITSPASIPDFG-----VSAADLSEAEPTITMHSITRHLHEQKILVQHVVSQNDGEL 721  
 YSIR2/P06700 CTRLELNFTTIDHTOKLHWARKKILVLTGAGVSHSILGIPDFES--SEGFS--KIKHGLDDPODVENVNIEMHDPSPVYVNIAMNVLPEEKYSLPASHFKMLQMKGKLLRNYTONIDM 349  
 hSIR1/096EB6 ---KRRKDINTEIDAVKLLQECKKIIVLTGAGVSVSGIPIDFAS--DGLIARLANVDPDLPDQMEDIEYFKDPRFFFKAKELYPGQFQPSLCHKFLASDREKGLLRNTQNIIDL 350  
 hSIR2/081XJ6 ---RCRKYICIVGAGISITSPSIGIPDFSPSTGLD--NLEKXHLPEPEAIETISYFKKHPEFFALAKELYPGQFKPTICHYFMRLDKGILLRKTQNIIDL 172  
 hSIR3/09NTG7 ACQRVVMYVAGISITSPSIGIPDFSPGSLAS--NLQYDLPYPEAIFELFFHNPKPFFFLAKELYPGNKPNVHTFLRLLHDKGILLRLYTONIDVL 233  
 hSIR4/09YGE7 KLLAVMTGAGISITSPSIGIPDFSPGSLA--RTDRRPQIQHGDFRIPQRYWARNFVGFQFSIQPFAHWLSWFKLQKLVLYTONIDVAL 148  
 hSIR5/09NKA8 KHVILISAGVSAESGVTFFG--AGCYNR--KWAQDLATPLAFAHNRSWVEFYHRYREVMYKSEENAGHAIACEBTRLGHQGRVVVITONIDEL 145  
 hSIR6/08NET7 SSVVPHGAGISITSPSIGIPDFG-----PAGVWMEERGLAKPDTFFES-----RPTQIEMALYQLREYVGLLERFYSQNVJGL 118  
 hSIR7/09NRC8 KLVVVYTAGISITSPASIPDFG-----KLVVVYTAGISITSPASIPDFG-----VSAADLSEAEPTITMHSITRHLHEQKILVQHVVSQNDGEL 721  
 YSIR2/P06700 ESYAGI STDKLVOCGSEFATATV--TSHWNLPEKIRNLELPLPYVYKRRREYFPEGYNKRVGVAASQGSMSERPPYILNSYGVLPKPDITFFGEA--LPNKFHKSIREDDILEC 464  
 hSIR1/096EB6 EQVAGIOR--LIQCGSEFATASL--LEKXKVDCEAVRGDINOVVPRPRPAD-----EPLAKMKRPIVFFGEN--EPLAQFHRAMKYDKDEV 433  
 hSIR2/081XJ6 ERIAGLEQEDLVAAGTFYTSHSVSASGRHEYP LSNMKEKIFSEVTKDEDQS-----LVKPDIVFFGES--LPARFFSCMQSDFLKV 254  
 hSIR3/09NTG7 ERVSGI FASKLVEAAGTFASATIT--VQRPFFGEDIRADVMDRVPKRPVPTG-----VVKPDI VFFGEP--LPQRFLLHVV-DFPMA 312  
 hSIR4/09YGE7 HTKAGSR--LTELGCMDRVLIL--DQGEQTPRGVLQERFOVINPTWSAEHGLAPD--GDVFLSEEQVRSFOVPTVQVGGHKKPDVFFGDT--VNPDKVDVFKRVRKA 253  
 hSIR5/09NKA8 HRKAGTKN--LLELGSLFKTRTSSGVVAENKSPICPALSGKAPGFTQDASIP--VEKLPRSEACGGLLRPHVWFGEN--LDPALLEEVDRELAHC 242  
 hSIR6/08NET7 HVRSQFPRDKLAEIAGNMVVEEA--KKTQVVRDVTVMGLKATGRLETVAKARG-----LRARCELGRDITLDWEDS--LPDRDLALADEASRNA 207  
 hSIR7/09NRC8 HLRSGLPRTAISLGNMVIET--SVPNREEYVRVFDVYTERTALHRHGTGRTHK-----GTQLRDTIVHGERGTGLQGPLNWEAATEASRA 261  
 YSIR2/P06700 DILLICI GTSCLKVAP-VSEIVNMFVSHVQVLINRD-----FVKHAEFDLSLIGYCDDI----- 517  
 hSIR1/096EB6 DILLIVIGSSILKVRP-VALIPSSIPHEVPQILINREPLHLHFDEVLLEDGDVITINELHRLGGEYAKLCCNFPVKLSEITEKPRPTOKLAVLISELPEPLRVSEDSSESPERTSPDSSVI 552  
 hSIR2/081XJ6 DILLIVIGSSILQVOP-FASLISKAPLSTPRLLINKE-----KAGQSDPFLGMIMGLGGMDPDKKARVDYAMLGCDQG----- 328  
 hSIR3/09NTG7 DILLILGTSLEVP-FASLIEAVRSVPRLLINR-----LVGP-----LAWHPR--SRDYAQLGVDVHG-----V 370  
 hSIR4/09YGE7 DILLIVIGSSILQVYSGYRFLITAMEKLPITAINIG-----PTRSDDLACL----- 298  
 hSIR5/09NKA8 DILCLVIGTSSVYVPAAMFAPQVAAAGVVAENET-----TPATNFRHFQG----- 291  
 hSIR6/08NET7 DLSITVIGTSLQIRPSONLPLATRRGRILVINLQP-----TKHDRHADLIRHGVDVEMTRMLKHLGLEIPAWDGPVRLIE 283  
 hSIR7/09NRC8 DITILGSSILKLVKYPRLWCMTKPPSRPKLYIVN-----LQWTEKDDWAALKLHGKCCDDVMRLLMAELG----- 327  
 YSIR2/P06700 AMVAKGWTTPHKRWNLDKNNKFKCQ-----EKDKGVVYVTSDEHEKVL----- 562  
 hSIR1/096EB6 VTLLDQAAGNDDLDVSESKCMEKPEQVTSRNVESIAEMENPDLKNVYSGSTGERNERTSVAGTVRCKMFWNAEQIISRRLDNGYLFLLPNRYIFHGAEYVSDSEDDYVLSSSCG 672  
 hSIR2/081XJ6 LALAEILGWKLELDLVRREHASIDAQSGAVPNPSSAPSKPPPAKDEARTREKPEQ-----PDK----- 389  
 hSIR3/09NTG7 ESLVLLGWTEMRDLVORETGKLDG-----PDK----- 399  
 hSIR4/09YGE7 KLSNRCEGLLPIDPC----- 314  
 hSIR5/09NKA8 -----PCGTTPLPALAHENETS----- 310  
 hSIR6/08NET7 RALPPLPRPTPKLEKESSTRINGSIPAGKPECAQNHGSEFASPKRERPTSAPRPPKRVKAKAVPS----- 355  
 hSIR7/09NRC8 LEIPAYSNQDPIFLSLATPLRAGEGSHRSKSLCRNSREAPPCDRGAPLSSAPTLGGWFGRCGTRTKRKKVY----- 400

Fig. 2. Alignment of centre core of human sirtuins family in comparison with yeast sir2 (previous page). The figure represent Clustalw alignment from indicated yeast and human sirtuins indicated by their UniProtKB accession numbers. In yeast sir2, the deacetylase sirtuin-type dominium is from 245 to 529 (red arrow) that correspond with the highest homology sequence among the members of the family. The NAD<sup>+</sup> binding domains are indicated in green, there are the most conserved domains in the whole family. The active site is determined by a histidine at 364 position of sir2 that acts as a proton acceptor, the key histidines in other members have been determined in silico by homology. Although it has been indicated that these enzymes do not bind zinc, probable cystein residues able to bind zinc are also conserved in some of the members of the family (in blue). Regarding regulation, in sir2 two points of regulation by phosphorylation, phosphorylation at serine 23 and at tyrosine 400 have been determined (violet residues). None of them are conserved residues in human sirt forms. Further, in SIRT1, modifications at cysteines 395 and 398 by s-nitrosylation impede the binding of NAD<sup>+</sup> and then, the activity of the enzyme.

	S. cerev.	S. pombe	D. melanog.	C. elegans	D. rerio	M. musc.	H. sapiens
	SIR2	SIR2	SIR2.1	SIR2	SIR2	SIRT1	SIRT1
S. cerev.	100	41	43	39	45	40	40
SIR2							

Table 2. Pairwise comparison of the aminoacid sequences among yeast (*Saccharomyces cerevisiae*) SIR2 and higher homologues in model animals: fission yeast (*Saccharomyces pombe*); fly (*Drosophila melanogaster*); worm (*Caenorhabditis elegans*); zebrafish (*Dario rerio*); mice (*Mus musculus*) and human (*Homo sapiens*). The percentage of identity in comparison with *S. cerevisiae* sir2 protein is indicated. From BLAST analysis of the indicated proteins.

Among the other human sirtuins, SIRT4 and SIRT5 are mitochondrial sirtuins that show predominant ADP-ribosyl-transferase activity and a weak deacetylase activity and are involved in urea cycle regulation (Nakagawa & Guarente, 2009). On the other hand, SIRT6 and SIRT7 are considered as members of another subclass of sirtuins involved in reparation of DNA and the control of ribosomal RNA production through cell cycle (Lombard et al., 2008). Although it has been described that sirtuins does not bind zinc, Sir2, SIRT1, -2 and 3 share four proximal cysteines that can indicate the possibility of binding zinc (figure 2). These four Cys are highly conserved among these sirtuins and just following the catalytic histidine. Then, although this Zinc ion must be not involved in the catalytic activity, their presence can be important for the maintenance of the structure of the sirtuin. In fact, recently Sanders and coworkers (Sanders et al., 2010) have shown that the four-cysteine metal binding site resembles the Zn-ribbon structure of transcription factors such as TF-IIS, TF-IIN and RNA polymerase II subunit RPB9. Further, although the Zinc-binding site is too far from catalytic domain, its presence is important for the activity of the enzyme since the change of any cystein to alanine or addition of zinc chelators inhibits the *in vitro* deacetylase activity of sirtuins (Min et al., 2001).

Regarding post-translational regulatory mechanisms, sirtuins can be regulated by phosphorylation and sumoylation. In fact, in SIRT1 thirteen residues have been found to be phosphorylated *in vivo* (Sasaki et al., 2008) indicating a high ratio of regulation by kinases. Further, dephosphorylation by protein phosphatases *in vitro* results in the decrease of the NAD<sup>+</sup>-dependent deacetylase activity in SIRT1. On the other hand, sumoylation of SIRT1 at

Lys734 residue has been also reported (Yang et al., 2007). Sumoylation consist in the binding of small ubiquitin-like modifier (SUMO) proteins to lysine residues (Hay, 2001). Binding of SUMO protein to SIRT1 increases its deacetylase activity and mutation of SIRT1 at the Lys734 residue or desumoylation by the nuclear desumoylase SENP1 reduces the activity (Yang et al., 2007).

Finally, another regulatory mechanism also establishes a relationship of sirtuins with metabolism. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) is physiologically nitrosylated at its Cys150 residue and binds to Siah1. Further, the complex moves to the nucleus since Siah1 show a nuclear localization signal. In the nucleus, Siah1 interacts with SIRT1 and other proteins. By this mechanism, S-nitrosylation of SIRT1 by GAPDH inhibits its deacetylase activity but specifically in the nucleus (Kornberg et al., 2010).

### **2.1 Enzymatic activity of sirtuin**

As it has been above indicated (figure 1) sirtuins bind a Nε-acetyl-lysine of the target protein and deacetylate it by using NAD<sup>+</sup> as substrate and producing NAM and 2'-O-AADPR (Hirsch & Zheng, 2011). However, this mechanism is no completely clear. In the case of SIRT6, although the deacetylation of histone 3 by SIRT6 has been described (Kawahara et al., 2009), other authors indicate that the main activity of this sirtuin is the ADP-ribosylation (Liszt et al., 2005). However, more recent studies indicate that the ADP-ribosyl-transferase of sirtuins could be only some inefficient side reactions of the deacetylase activity without any relevant physiological role (Du et al., 2009).

### **2.2 Subcellular localization of sirtuins**

One of the key facts that determine the main targets of the different members of the sirtuin family is their respective subcellular localization. SIRT1 is found in the cell in both, the cytosol and the nucleus although it seems that nuclear localization is the most prevalent. However, recent research has demonstrated that SIRT1 is mainly sequestered in cytosol in highly glycolytic tumoral cells (Stunkel et al., 2007) indicating a metabolic-dependent localization of this deacetylase. On the other hand, SIRT3 is predominantly found in mitochondrial matrix (Schwer et al., 2002) although some studies have shown nuclear and also cytosolic locations (Sundaresan et al., 2008) whereas other authors have reported an exclusive mitochondrial localization (Cooper & Spelbrink, 2008). In the case of SIRT2, this sirtuin appears to be exclusively cytoplasmic (North & Verdin, 2007). SIRT4 and SIRT5 are located in the inner mitochondrial membrane or matrix (Michishita et al., 2005) and SIRT6 and SIRT7 are located in the nucleus (Schwer & Verdin, 2008).

### **2.3 Modulation of sirtuin levels**

Acting as metabolic sensors, these proteins respond to many processes that affect the energetic balance in the organism including aging, dietary interventions, fasting or exercise. Aging progress is associated with a gradual decline of several physiological processes in the organism. In heart, age-related in SIRT1, decline is accompanied by a higher level of oxidative stress and the decrease in the expression of endogenous antioxidant enzymes and their regulators (Ferrara et al., 2008). In central nervous system, aging results in decreased activity of SIRT1 in cerebellum that leads to the increase in acetylation of protein residues specially affecting motor function (Marton et al., 2010). In cell culture models, cellular senescence induced by ionizing radiation is accompanied by the decrease in the levels of SIRT1 (Hong et



al., 2010). On the other hand, the contrary effect of aging has been reported. In rats, an age-related increase in SIRT1 levels has been shown in skeletal muscle (Koltai et al., 2010).

Caloric restriction (CR) is the only dietary modification able to extend median and maximum lifespan in a number of organisms from yeast to mammals (Lomb et al., 2010). The effect of CR on lifespan extension is thought to be dependent on multiple different signaling pathways. CR decreases the activity of pro-aging pathways such as oxidative stress and insulin and growth hormone signaling whereas it stimulates the endogenous capacity of the cells against stress including antioxidant mechanisms (Qiu et al., 2010), DNA repair capacity and autophagy (Morselli et al., 2010). Further, the activity of mitochondria is modified in CR. Under CR, mitochondria show higher efficiency with lower reactive oxygen species production (Lopez-Lluch et al., 2006).

Many of the effects of CR on longevity have been associated to the induction of sirtuin activity in cells (Cohen et al., 2004). Studies performed in mice have demonstrated that SIRT1 protein levels increases during CR in many tissues including brain, white adipose tissue, muscle, liver and kidney (Kanfi et al., 2008). Moreover, loss-of-function and gain-of-function mouse studies have provided genetic evidences that indicate that SIRT1 is a key factor in the physiological response to CR (Imai, 2009). It is also important to highlight that SIRT1 has been related to the central response to low nutritional availability at the hypothalamus level probably playing an important role in the regulation of the whole metabolism in mammals (Satoh et al., 2010). Further, SIRT6 levels are also modulated by nutrient availability in a p53-independent mechanism. SIRT6 modulation is mainly through the stabilization of protein levels but not via increase of SIRT6-gene transcription (Kanfi et al., 2008).

The practice of exercise has been also considered to promote longevity and activate common pathways to CR probably by producing a metabolic stress in the organism (Lanza et al., 2008). Then, as in the case of CR, exercise also modulates the levels of sirtuins. In muscle, SIRT1 levels increases along aging and exercise training further increase the relative activity of this sirtuin (Koltai et al., 2010) indicated by an strong inverse correlation between nuclear activity of SIRT1 and the level of acetylated proteins. On the other hand, age-associated increase in SIRT6 levels is attenuated by exercise (Koltai et al., 2010). Exercise also increases SIRT3 expression in muscle and its activity is associated with a higher activity of AMP-dependent protein kinase (AMPK), cAMP-response element binding (CREB) and Peroxisome proliferator-activated receptor gamma coactivator 1- $\alpha$  (PGC1 $\alpha$ ) indicating its importance in mitochondrial biogenesis in muscle fibers especially in respiratory type I fibers (Palacios et al., 2009).

In heart, the aging-related decrease in MnSOD and catalase expression accompanied by the increase in oxidative damage levels indicated by TBARS and 4-HNE has been related to the decrease in the expression of SIRT1 (Ferrara et al., 2008). Exercise increases SIRT1 levels in heart reverting aging-related effect on MnSOD and catalase levels and its regulatory transcription factor, FOXO3a levels (Ferrara et al., 2008). Exercise not only modulates sirtuin levels in muscle or heart but also can modulate sirtuin levels and activity in central nervous system. Further, the modulation of SIRT1 by natural polyphenolic flavonoids such as resveratrol or quercetin may exert important beneficial effects in exercise performance (Lappalainen, 2011).

Sirtuin expression is also altered in cancer cells (Ashraf et al., 2006). This fact is important because these cells show a distinctive metabolism and higher growth in comparison with non-transformed cells. The different pattern of sirtuin expression in tumoral cells would confer to these cells higher resistance against exogenous agents and also control a different metabolism.

Other important issue in the regulation of sirtuin levels is the complex and new world of microRNAs (miR)-dependent regulation. Currently, the study of the regulation of sirtuin expression by microRNAs has demonstrated that these proteins are also regulated by this system. MiR-34a is markedly reduced in p53-null PC3 cells and its overexpression inhibits SIRT1 expression at the transcriptional level indicating a p53-dependent regulation of SIRT1 levels (Fujita et al., 2008). On the other hand, in mesenchymal transition processes in breast cancer, the downregulation of miR-200 has been related to the increase in the levels of SIRT1 in these cells contributing to the tumoral phenotype (Eades et al., 2011). On the other hand, the release of proinflammatory mediators in adipocytes in serum-free conditions is regulated by the inhibition of SIRT1 expression mediated by miR-132 (Strum et al., 2009). Further, miR-199a also represses SIRT1 in cardiomyocytes and its downregulation in low oxygen tension conditions derepresses SIRT1 expression at the same time than HIF-1 $\alpha$  (Rane et al., 2009). Other interesting miRs, miR-33a and b, are involved in the regulation of fatty acid oxidation including the levels of SIRT6. Increase in the levels of miR-33a and b decrease fatty acid oxidation and also insulin signaling in hepatic cell lines indicating a regulatory role of these miRs in important metabolic pathways in the cell (Davalos et al., 2011). Taken together, it is clear that the, to date, poorly clarified regulatory mechanisms depending on miRs complicate the regulatory mechanisms of sirtuin levels at posttranscriptional level.

During last years, small polyphenol molecules have also demonstrated capacity to increase sirtuin activity. Some years ago, we and others demonstrated that resveratrol, a polyphenol of the family of stilbenes found in grapes, dry fruits and berries, is able to extend lifespan in mice fed under high fat conditions (Baur et al., 2006). In this process, sirtuin activity was considered as an important factor. From them, several other works have demonstrated the importance of resveratrol and related compounds in sirtuin-dependent metabolic modifications. In fact, resveratrol is able to modulate insulin response (Zhang, 2006), and also regulate AMPK activity (Dasgupta & Milbrandt, 2007). In some cases, these effects have been related to sirtuin activity and in others, a sirtuin-independent effect has been suggested. In any case, in our hands resveratrol have shown capacity to increase SIRT1 and SIRT3 levels in cultured cells indicating the capacity to modulate sirtuin expression (Santa-Cruz Calvo et al., unpublished results), accordingly with already published results (Costa Cdos et al., 2011; Kao et al., 2010; Sulaiman et al., 2010).

### 3. Sirtuin-dependent metabolic regulation

As its can be concluded by the complexity of sirtuin interactions, the different partners and regulatory processes, this family of deacetylases is involved in many different physiological mechanisms in cells. In the following sections we are going to resume the most important findings about the role of these enzymes in metabolic control in relationship with the aging process. Taken into consideration that metabolic processes are involved in all the cellular processes, metabolic control by sirtuins is the most important function of these enzymes (Yu & Auwerx, 2009).

#### 3.1 SIRT1

Looking inside this deacetylase enzymes family, SIRT1 is one of the members that show more interactions and that respond to more factors. Mammalian SIRT1 has multiple targets including histones, transcription factors and other molecules that collectively modulate

several processes such as energy metabolism, stress response and cell survival (Tang, 2011). Its activity may decline with aging in many tissues and it has been proposed that its reactivation can produce beneficial effects (Tang, 2011).

One of the most important factors involved in the metabolic control regulated by SIRT1 is PGC1 $\alpha$ . SIRT1 functionally interacts with PGC1 $\alpha$  and deacetylates it (Nemoto et al., 2005). Deacetylation of PGC1 $\alpha$  activates this transcription factor that induce the expression of nuclear respiratory factor 1 (NRF1) and then, mitochondrial biogenesis. In fact, activation of SIRT1 induces deacetylation of PGC1 $\alpha$  and FOXO1 that finally control the transcriptional modulation for lipid catabolism (Canto et al., 2010). Further, deletion of SIRT1 alters fatty acid metabolism resulting in hepatic steatosis and inflammation (Purushotham et al., 2009). SIRT1-dependent regulatory mechanisms regulate the switch from carbohydrate to lipid as main energy sources in muscle. Limitation in glucose availability during fasting or exercise induces AMPK activity in muscle that acts as a prime initial sensor that activates SIRT1. PGC1 $\alpha$  is acetylated by the acetyltransferase GCN5 that together with SIRT1 control its regulation depending on nutritional status (Dominy et al., 2010). Activity of this GCN5 or inhibition by nicotinamide reduces SIRT1-dependent PGC1 $\alpha$  acetylation and decreases the expression of genes involved in mitochondrial biogenesis in muscle (Gerhart-Hines et al., 2007). Further, PGC1 $\beta$  is also acetylated on at least 10 lysine residues by GCN5 repressing its transcriptional activity, SIRT1 activity also deacetylates it and restores transcriptional activity (Kelly et al., 2009).

As a cycle of regulation, SIRT1 also controls the expression levels of PGC1 $\alpha$  in skeletal muscle through stimulation of its promoter activity probably with the activity of myogenic factors such as MEF2 and MyoD (Amat et al., 2009). On the other hand, PGC1 $\alpha$  is also involved in sirtuin expression since, as mitochondrial biogenesis is activated and some sirtuins are located in mitochondria, the expression of SIRT3 gene is also controlled by PGC1 $\alpha$ . This regulation is key in the differentiation of brown adipocytes (Giralt et al., 2011). Besides the high number of evidences demonstrating the relationship of SIRT1 activity and PGC1 $\alpha$ -dependent mitochondrial biogenesis, some other works indicate that SIRT1 overexpression reduces mitochondrial biogenesis (Gurd et al., 2009). This last paper is based on the correlation of SIRT1 levels with mitochondrial biogenesis. In this context, a recent paper indicate that there are a direct relationship between mitochondrial biogenesis and activity of PGC1 $\alpha$  with nuclear activity of SIRT1 although not with its protein content in skeletal muscle cells (Gurd et al., 2011) indicating that sirtuins levels are not necessarily related to the activity of these enzymes.

Another of the most studied targets of SIRT1 is the tumor suppressor p53. SIRT1 deacetylates K382 of p53/TP53 and inhibits its transcriptional activity impairing then, its ability to induce proapoptotic mechanisms and to modulate cell senescence. Further, it has been also reported that H<sub>2</sub>O<sub>2</sub>-induced cell senescence is accompanied by accumulation of acetylated p53 by decrease in the function of SIRT1 (Furukawa et al., 2007). Taken into consideration the role of p53 in nuclear and mitochondrial apoptosis (Moll & Zaika, 2001), SIRT1 seems to be a p53-dependent antiapoptotic factor.

On the other hand, modulation of p53 by SIRT1 also produces effects on cell metabolism since p53 seems to regulate mitochondrial respiration and glycolysis (Ma et al., 2007). In fact, p53 regulates the transcription of cytochrome c oxidase 2, an important factor in assembly of the cytochrome c oxidase complex (Fields et al., 2007), and then, an important factor in mitochondrial respiration. Then, high levels of SIRT1 in tumor cells will block p53-

dependent SCO2 transcription and contribute to the Warburg effect found in these cells. However, the relationship between SIRT1 and p53 is more complex at the transcriptional level. Transcription of SIRT1 is repressed by p53 via p53 response elements in its proximal promoter (Naqvi et al., 2010). However, another p53 binding site has been reported in the distal promoter of SIRT1. This binding site is necessary for SIRT1 induction under caloric restriction (Naqvi et al., 2010). In this site, p53 competes with the Hypermethylated-In-Cancer-1 (HIC1) transcriptional repressor and, then, activation of p53 derepresses SIRT1 transcription. Taken together all the information available about p53 and SIRT1 interaction, more research is necessary to clarify the complex system p53-SIRT1 and regulation of mitochondrial activity.

All these regulations implicate a contradictory role of SIRT1 in modulation of mitochondrial biogenesis and respiratory metabolism. If SIRT1 is activating PGC1 $\alpha$  by deacetylation and, then, inducing mitochondrial biogenesis, downregulation of the activity of p53 by the same SIRT1 will reduce the respiratory capacity by affecting SCO2 levels and Complex IV assembly. This contradictory effect would be explained by the different location of SIRT1 and then, modulation of different regulatory processes. Further, some other studies have indicated that despite the role of SIRT1 as deacetylase of p53, SIRT1 has little effect on p53-dependent transcription and does not affect many of the p53-mediated biological activities (Kamel et al., 2006). If these results are confirmed, they would explain how mitochondrial biogenesis and p53-repression can occur at the same time. Future research will clarify this complex regulation of mitochondrial respiratory metabolism.

### 3.2 SIRT2

The human SIRT2 is predominantly a cytosolic protein known to be a tubulin deacetylase (North et al., 2003). SIRT2 deacetylates lysine-40 of  $\alpha$ -tubulin and then, its knockdown results in tubulin hyperacetylation. Levels of SIRT2 increase dramatically during mitosis and is also phosphorylated during the G<sub>2</sub>/M transition. Then, SIRT2 is an important factor in the control of mitotic exit in the cell cycle (Dryden et al., 2003). Further, its interaction with the homeobox transcription factor, HOXA10, raises the possibility that SIRT2 also plays a role in mammalian development (Bae et al., 2004). The importance of tubulin activity in neuronal activity probably explains the important role ascribed to SIRT2 in neurodegenerative diseases (Harting & Knoll, 2010).

Regarding metabolism, information about SIRT2 is very limited and seems to indicate a lipid inhibitory role of this sirtuin in contrast with the role found with SIRT1 and 3. Its presence has been inversely correlated with the differentiation of preadipocytes to adipocytes by modulating the activity of FOXO1 (Jing et al., 2007). SIRT2 deacetylates FOXO1 and enhances its repressive interaction with PPAR- $\gamma$ , an essential factor in adipocyte differentiation (Wang & Tong, 2009). In contrast with the neuroprotection reported in some neurodegenerative processes, a neuroprotective effect of the decrease of sterol biosynthesis through SIRT2 inhibition has been also shown in the case of Huntington's disease (Luthi-Carter et al., 2010). On the other hand, silencing of SIRT2 induces intracellular ATP drop and cell death in neuronal PC12 cells (Nie et al., 2011) indicating metabolic regulatory mechanisms of this sirtuin. Further, the role of SIRT2 in expression of antioxidant systems has been also reported. Induction of MnSOD seems to depend on deacetylation of FOXOa by SIRT2 (F. Wang et al., 2007).

### 3.3 SIRT3

One of the most important sirtuin in metabolic regulation is SIRT3. Its localization into mitochondria and the diversity of targets including both metabolic and antioxidant components makes it in one of the immediate regulators of mitochondrial activity. In a recent paper, Kendrick and co-authors found that mice fed under high-fat diet develop fatty liver and show high levels of acetylated proteins in parallel with a decrease in SIRT3 activity (Kendrick et al., 2011). Moreover, deletion of SIRT3 further increases acetylation in high-fat fed animals and reduces the activity of respiratory complexes III and IV indicating a key role of this sirtuin in mitochondrial activity control. One of the direct targets of SIRT3 is succinate dehydrogenase (SDH, Complex II). Acetylated SDH show low activity and deacetylation by SIRT3 activates it (Finley et al., 2011). These papers indicate the important role of SIRT3 in the regulation of mitochondrial activities by deacetylation.

The role of SIRT3 in acetate metabolism has been also related to aging (Shimazu et al., 2010). Acetate plays an important role in cell metabolism being an important product of ethanol and fatty acid metabolism especially during fasting or starvation (Seufert et al., 1974). Acetate can be converted into acetyl-CoA by the activity of acetyl-CoA synthase enzymes in cytosol (AceCS1) or mitochondria (AceCS2). These enzymes are activated by deacetylation by both SIRT1 in cytosol and SIRT3 in mitochondria (Shimazu et al., 2010). An important role for SIRT3 in acetate metabolism has been suggested since both, SIRT3 KO and AceCS2 KO mice show overlapping phenotypes. However, to date no clear data about the role of acetate in aging process have been shown although AceCS-mediated synthesis in yeast has been associated with higher longevity (Falcon et al.).

The importance of SIRT3 in the protection against oxidative stress is also important since the protective effect of CR on oxidative stress is diminished in mice lacking SIRT3. This sirtuin is involved in the reduction of cellular ROS levels depending on the manganese-dependent mitochondrial superoxide dismutase 2 (MnSOD or SOD2) (Qiu et al., 2010). SIRT3 adjusts MnSOD activity to the mitochondrial nutrients availability and then, the production of mitochondrial ROS (Ozden et al., 2011). In this regulation, SIRT3 deacetylates two important lysine residues on SOD2 promoting its antioxidant activity.

Levels of SIRT3 are also regulated by the energetic status of the organism. SIRT3 levels increase by caloric restriction of exposure to low temperatures in brown adipocytes. Forced expression of SIRT3 and activity in a cell line for brown adipocytes enhances the expression of PGC1 $\alpha$ , UCP1 and another mitochondria-related genes whereas mutation of SIRT3 inhibits PGC1 $\alpha$ -dependent UCP1 expression (Shi et al., 2005). Diet and exercise signals also regulate SIRT3 and activate the AMPK and PGC1 $\alpha$  in skeletal muscle cells (Palacios et al., 2009) whereas this activation is much lower in SIRT3 KO animals. On the other hand, PGC1 $\alpha$  strongly stimulates mouse SIRT3 gene expression in muscle cells and hepatocytes (Kong et al., 2010) through binding to an oestrogen-related receptor binding element (ERRE) in its promoter region. Induction of SIRT3 is also essential for mitochondrial biogenesis and the expression of several of mitochondrial components including antioxidant systems (Kong et al., 2010).

Taken together, SIRT3 seems to be a key sirtuin that senses metabolic status through NAD<sup>+</sup>/NADH levels at the mitochondria and then, integrates respiratory metabolism and antioxidant systems.

### 3.4 SIRT4 and SIRT5

SIRT4 and SIRT5 are also mitochondrial sirtuins involved in the regulation of other metabolic processes essentially related with the urea cycle (Li & Kazgan, 2011). One of the main activities of SIRT4 in mitochondria is the downregulation of insulin secretion by beta cells by repressing the activity of glutamate dehydrogenase in response to aminoacids (Argmann & Auwerx, 2006; Haigis et al., 2006). Depletion of SIRT4 have also shown that this sirtuin seems to exert an opposite role than SIRT1 and SIRT3 since its depletion increases gene expression of fatty acid metabolism enzymes in hepatocytes (Nasrin et al., 2010). However, this effect is indirect due to compensatory mechanisms involving higher expression of SIRT1. However, putative contrary effects of this sirtuin in relationship with other members of the family cannot be discarded and further research involving specific inhibitors instead of gene depletion is needed.

In the case of SIRT5, this sirtuin, mainly located at the matrix of the mitochondria, is also involved in the regulation of the urea cycle (Nakagawa & Guarente, 2009). SIRT5 deacetylates the mitochondrial carbamoyl phosphate synthetase 1. This enzyme is the first and rate-limiting step of the urea cycle (Nakagawa & Guarente, 2009). Furthermore, deacetylation of cytochrome c has been also reported although the effect of this deacetylation in both, respiration or apoptosis, is not clear (Schlicker et al., 2008). To date, no other substrates of SIRT5 have been reported.

### 3.5 SIRT6 and SIRT7

SIRT6 is predominantly a nuclear protein broadly expressed in tissues showing the highest levels in muscle, brain and heart (Liszt et al., 2005). In any case, SIRT6 is mainly involved in DNA damage repair and is located in the nucleus. It is recruited to the sites of DNA double-strand breaks (DSBs) and stimulates DSB repair through both, nonhomologous end joining and homologous recombination by stimulating PARP-1 poly-ADP-rybosilase activity (Mao et al., 2011).

It seems that this sirtuins is closely involved in neural degeneration related to aging. In fact, a mice model lacking SIRT6 develops a degenerative disorder that mimics models of accelerated aging (Lombard et al., 2008, Mostoslavsky et al., 2006). This effect depends on a higher instability through the DNA base excision repair pathway, then, the accumulation of mutations in the genome leads to aging-associated degenerative phenotypes (Mostoslavsky et al., 2006). Furthermore, SIRT6-deficient mice show deficiency in growth and show severe metabolic defects indicating that the higher DNA-damage found in these animals is linked to a systemic metabolic deregulation that leads to age-related processes and death.

Neural SIRT6 has been also recently related to metabolic homeostasis in mammals. Neural-specific deletion of SIRT6 in mice produces postnatal growth retardation since these animals show low growth hormone (GH) and also insulin-like growth factor 1 (IGF1) levels (Schwer et al., 2010). However, unlike SIRT6-KO animals that die by hypoglycaemia and other severe metabolic defects (Mostoslavsky et al., 2006), neural-SIRT6 KO animals, reach normal size and even become obese. It seems that at the central nervous system, SIRT6 acts as a central regulator of somatic growth and metabolism by modulating neuroendocrine system. It seems that the main mechanism of action of SIRT6 in the regulation of gene expression and the control or systemic metabolism and aging is through the deacetylation of lysine 9 in histone H3. Recently it has been shown that hyperacetylation of H3K9 found in SIRT6-deficient cells leads to a higher NF- $\kappa$ B-dependent modulation of gene expression,

proinflammatory processes, apoptosis and cellular senescence (Kawahara et al., 2009). Then, the control of gene expression by histone modulation seems to be a key factor in SIRT6-dependent longevity effect.

Furthermore, the activity of SIRT6 in liver has been also reported. Rosiglitazone (RGZ) is used to protect liver against steatosis. This compound increases the levels of SIRT6 in liver at the same time that ameliorates hepatic liver accumulation affecting PGC1 $\alpha$  and FOXO1 (Yang et al., 2011). However, in SIRT6-deficient mice, RGZ was unable to decrease fat accumulation in hepatocytes and to affect PGC1 $\alpha$  and FOXO1 activity indicating an important role of this sirtuin in fat storage in liver. In this mechanism, SIRT1 could be also involved since it forms a complex with FOXO3 and NRF1 and activates the expression of SIRT6 (Kim et al., 2010). In this case SIRT6 would be the sirtuin that negatively regulates glycolysis, triglyceride synthesis and fat metabolism by deacetylating H3K9 and then, modifying the activity of the promoters of many genes involved in metabolic processes. In fact, the specific deletion of SIRT6 in liver causes profound alterations in gene expression that produce the contrary effects in glycolysis, triglyceride synthesis and fat metabolism.

The last member of sirtuins, SIRT7, is widely expressed in nucleolus and has been associated with active rRNA genes interacting with RNA polymerase I and with histones (Ford et al., 2006). This sirtuin is controlled by CDK1-cyclin B-dependent phosphorylation and dephosphorylation indicating that its activity is required to resume rDNA transcription in late telophase (Grob et al., 2009). In the case of SIRT7, studies performed by using murine cells lacking or overexpressing this sirtuin demonstrate that it is related with the tumorigenic potential and may enable cells to sustain critical metabolic functions because it inhibits cell growth under severe stress conditions (Vakhrusheva, Braeuer et al., 2008). These studies have also demonstrated the important role of this sirtuin in lifespan. In fact, mice lacking SIRT7 undergo reduction in mean and maximum lifespans and develop heart hypertrophy and inflammatory cardiopathy (Vakhrusheva, Smolka et al., 2008) probably by the impossibility to deacetylate p53 and regulate p53-dependent apoptosis.

#### **4. Sirtuins: Antioxidant mechanisms and autophagy**

Other of the important roles of sirtuins related to metabolism and aging is based on their activity to maintain cellular antioxidant mechanisms and autophagy systems. A great body of evidence has accumulated indicating that at the same time that sirtuins are modulating metabolism, they also regulate, in a coordinated mechanism, antioxidant systems and recycling systems in cells.

Altered ROS levels are observed in several age-related illnesses including carcinogenesis, neurodegenerative, fatty liver, insulin resistance, cardiac resistance, etc. In mitochondria MnSOD is the primary ROS scavenging enzyme to converts superoxide to hydrogen peroxide that is further converted to water by catalase and other peroxidases. In this mechanism SIRT3 exert a key role since changes in lysine acetylation modifies MnSOD activity in mitochondria (Ozden et al., 2011). Further, CR effect depends, at least in part, on sirtuin regulation but at the same time oxidative stress is reduced in CR by activation of antioxidant systems such as SOD2 in mitochondria by SIRT3 (Qiu et al., 2010).

In heart, the aging-related decrease in MnSOD and catalase expression accompanied by increase in the levels of oxidative damage indicated by TBARS and 4-HNE has been related to the decrease in the expression of SIRT1 (Ferrara et al., 2008).

Regarding recycling mechanism a correct balance between biogenesis and recycling of damaged structures is essential to maintain a correct homeostasis in the cell. Caloric restriction induces autophagy through induction of SIRT1. Transgenic expression of SIRT1 in human cells and in *C. elegans* induces autophagy whereas knockout of SIRT1 in the same cells and organisms prevents autophagy induced by resveratrol or nutrient deprivation (Morselli et al., 2010). Autophagy induction has been also related to the extension of lifespan by some agents such as spermidine and resveratrol in organism such as yeast, nematodes and flies (Morselli et al., 2009). In this process, deacetylation of FOXO3 by SIRT1 seems to be essential to the induction of the expression of genes involved in autophagy in caloric restriction (Kume et al., 2010). FOXO is an essential factor in the induction of autophagy and, as it has been above commented, in the antitumoral role of sirtuins (Zhao et al., 2010). All these works and some other more indicate that sirtuins not only control metabolism regulating essentially mitochondrial respiration and fatty acid oxidation but also regulate in a coordinated way the expression and activity of endogenous antioxidant systems and autophagy processes to eliminate damaged structures including mitochondria.

### 5. Sirtuins, prolongevity or healthspan effect?

The prolongevity effect of sirtuins was initially determined in yeast (Kaeberlein et al., 1999) and lower metazoan such as *C. elegans* (Tissenbaum & Guarente, 2001) and in *D. melanogaster* (Rogina & Helfand, 2004). However, very recently, these results have been revised and the prolongevity effect of sir2 in these animals has been related to transgene-linked genetic effects other than overexpression or sir2.1 in *C. elegans* or dSir2 in *D. melanogaster* (Burnett et al., 2011; Viswanathan & Guarente, 2011). Further, along last year, a considerable body of evidences indicates the controversial aspect of sirtuins in longevity studies. Calorie restriction clearly exerts a prolongevity effect on many organisms. In this effect, sirtuins were described as important factors in yeasts (Lin et al., 2000), *C. elegans* (Y. Wang & Tissenbaum, 2006) and *D. melanogaster* (Rogina & Helfand, 2004). However, other studies in yeast and *C. elegans* have argued about the role of sirtuins in caloric restriction-dependent longevity (Kaeberlein, 2010; Kenyon, 2010). Further, in mammals, overexpression of SIRT1 in mice does not increase lifespan (Herranz & Serrano, 2010).

These new concerns about the promising role of sirtuins in longevity do not affect other important functions of sirtuins in cell physiology. There is also an overwhelming body of evidences indicating that sirtuins play a crucial role in metabolic homeostasis. As, the activity of sirtuins depends strictly on the levels of NAD<sup>+</sup> which acts as co-substrate in the deacetylation activity catalyzed by sirtuins, changes in NAD<sup>+</sup> levels, reflecting modifications in the metabolic status of the cells, would modulate sirtuin activity. NAD<sup>+</sup>-dependence for sirtuin activity in cells confers to sirtuins the integrative role of metabolic sensors that modulates cell changes depending on the metabolic status of the cells. Furthermore, the broad group of targets of sirtuins activity in cells confers to these proteins the capacity to modulate executive proteins and also to influence transcription factors and histone proteins to change not only protein activity but also gene expression profile in cells accordingly to changes in metabolism (Canto & Auwerx, 2009).

In mammals, SIRT1 mediates the metabolic and transcriptional adaptations after nutrient deprivation or energy stress changes. These adaptations are centered in a higher respiratory activity of mitochondria. Calorie restriction induces the expression of sirtuins in many tissues and likely this regulation is related to the changes in metabolism found under



dietary restrictions (Bamps et al., 2009; Imai, 2009). Overexpression of SIRT1 in mice protects animals against metabolic damage caused by a fat-rich diet (Herranz et al., 2010). On the other hand, mice lacking SIRT1 show deficiencies in metabolism and are unable to increase lifespan in calorie restriction conditions (Herranz & Serrano, 2010). Further, resveratrol, a polyphenol considered as activator of sirtuins protects against metabolic and age-related diseases (Lagouge et al., 2006) and also increase lifespan in animals fed with fat-rich diets (Baur et al., 2006). However, accordingly with the above indicated recent studies that indicate that sirtuins do not affect longevity, in normal diet conditions, resveratrol is unable to increase lifespan in mice although delays age-related deterioration (Pearson et al., 2008). Many researchers have also demonstrated the role of sirtuins in protection of cell and tissues against different forms of injury through activation of FoxO and intracellular antioxidant systems (Hsu et al., 2010).

It has been recently proposed that energy metabolism can be importantly involved in the accumulation of high levels of advanced-glycosylation end (AGES)-products into cells and, then, in the impairment of cell and tissue activity (Hipkiss, 2008). In this process, NAD<sup>+</sup>/NADH ratio is importantly involved. Decrease of NAD<sup>+</sup> availability in ad libitum conditions decreases metabolism of triose phosphate glycolytic intermediates such as glyceraldehydes-3-phosphate and dihydroxyacetone-phosphate. These compounds can spontaneously decompose into methylglyoxal (MG), a highly toxic glycating agent that produces AGES. AGES and MG can be involved in mitochondrial dysfunction, the increase in ROS production and also affect gene expression and intracellular signaling. However, under CR or exercise NADH is oxidized to NAD<sup>+</sup> and also NAD<sup>+</sup> synthesis is activated. NAD<sup>+</sup> not only activate sirtuins but also reduces the levels of MG and then, reduces the deleterious effects of this compound (Hipkiss, 2008). This hypothesis directly links metabolism and its regulation to cell damage and then to aging indicating that sirtuins are directly involved in a more balanced metabolism and then, are important factors to be considered in aging, longevity and healthspan. Taken together, it seems clear that sirtuins are key factors in metabolic homeostasis and can increase healthspan and also show prolongevity effects in conditions of metabolic stress such as western food rich in unsaturated fat.

## 6. Conclusion

In the present chapter we have resumed the complex system regulated by sirtuins and involved in metabolic aspects that affect aging. Aging is a process that courses with the accumulation of damage into cells and organs. Most of the energy spent by cells is used to maintain the biological structures and the order into cells and tissues. When energy is deficient or the injury increases, damage in cells accumulates in structures that cannot be eliminated and that disturb their correct physiologic mechanisms. Accumulation of aberrant structures ends in the incapacity of cells to function properly and then, produce the decline in functionality found in aging. Sirtuins are key factors in this process. These deacetylases link energetic status of the cell with regulation of aerobic metabolism, reparation activities and antioxidant systems preventing the accumulation of damaged structures. Although the right role of these sirtuins in longevity is currently questioned, their activity as core of several regulatory processes make them important regulators in, at least, the correct physiology of the organism until death.

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# Energy Metabolism in Children and Adolescents

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## 1. Introduction

Energy metabolism is the most integral body function, and, as any functional activity, it has an effect on energy expenditure. Body energy expenditures are composed of three unequal parts: basal metabolism, energy supply of functional activity and energy expenditure on growth, development and the adaptive processes. The proportion of these expenditures is determined by the stage of individual development and specific life conditions.

Basal metabolism (the minimum level of energy production in conditions of complete rest), in its turn, is composed of three primary energy expenditure types: minimum level of vital physiological functions; intracellular futile cycles of biochemical processes; and reparative processes, including growth and development expenditure.

With age, basal metabolism expenditure and growth and development expenditure is considerably reduced, while functional expenditure can increase (for instance, muscle energy expenditure of an adult can be sometimes more than that of a child), but in any case they undergo important qualitative changes.

## 2. Age changes of basal metabolism

Methodological requirements for basal metabolism measuring are hard to be implemented outside a clinic, therefore metabolism in a state of rest is most commonly measured (lying down, comfortable temperature, 2-4 hours after food intake, without any stress factors), which is approximately 10-20% more than the level of basal metabolism. Present-day children have resting metabolism values even lower than standard norms of basal metabolism (Kornienko, 1979), proposed by Harris and Benedict (1919), which might be the result of acceleration of growth and development, observed up to the 1980s (Godina, 2009). With age the rate of resting metabolism (per body mass unit) is reduced – from infancy to the adulthood– by 1.5 – 2 times. The reasons for this reduction have been discussed for the last 150 years.

Since Max Rubner's time (1883) it has been known that as mammals gain body mass, heat production per mass unit is reduced, while the metabolism rate, relative to the surface space, is practically constant ("the rule of surface"). These metabolism changes were primarily explained by thermoregulation expenditure, but it turned out that in a thermoneutral conditions, without any extra heat production, this alignment persists. Moreover, this relation between metabolism rate and body size is observed in invertebrates (Schmidt – Nielsen, 1987; Ivanov, 1990).

For a long time the increased metabolic rate in infants has been attributed to metabolic expenditure on growth (Karlberg, 1952). But this hypothesis was not corroborated by facts. An infant's growth is most intense in the first 6 months after birth. The growth coefficient during this period is 4.0 (Schmal'hausen, 1935). At one year after birth, the coefficient is sharply reduced, by more than 10 times - to 0.3. Basal metabolism rate is at its peak at the age of one. Special calculations (Kornienko & Gohblit, 1983) proved that true expenditure on synthesis, associated with growth processes, even in the first 3 postnatal months, when the infant's growth velocity is at its peak, is no more than 20 kcal /day, which is 7–8% of the total expenditure. According to King et al. (1994), total energy expenditure of a woman body during pregnancy is on the average 325 MJ (77621 kcal). It is approximately a 20% increase in metabolism rate, compared to basal energy expenditure of a female. Evidently most of this energy expenditure is the expenditure on extra functions of maternal body systems, including the ones associated with the required adaptation to the increased physical load: during the second half of the pregnancy period the condition of the mother is bearing an extra load weighing from 2-3 kg to 10-12 kg (that includes the weight of the foetus, placenta, amniotic fluid, grown uterus, etc.). In fact, the growth processes takes a small part of the volume of energy expenditure. The energy expenditure on proliferative processes of kids older than one year is even less (under 1%), when the growth velocity becomes 12-15 times slower compared to intrauterine period.

Empiric formulae are used to express the relation between body size and metabolic rate. Kleiber (Kleiber, 1961) proposed the following formula for mammals, including humans:

$$M = 67.7 \cdot P^{0.75} \text{kcal / day} \quad (1)$$

Where M is the heat production of the whole body, and P is body mass.

But age changes in basal metabolism cannot be calculated using this equation. During the first year after birth, heat production is not reduced as required by the Kleiber equation, but stays on the same level or even increases, while the body mass during this period is tripled. Only one year after birth is the metabolism rate of 55 kcal/kg per day reached, "proposed" by the Kleiber equation for the body with the mass of 10 kg.

Only after 3 years does the basal metabolic rate starts to gradually reduce, and reaches the level of an adult person (25 kcal/kg per day) only during puberty.

Increase in the basal metabolic rate within the first year of an infant's life is correlated by some authors with a decrease in volume of intracellular space in most tissues. According to Brück (1970), if the oxygen consumption rate per mass unit of newborn infants in rest is 5.0 ml O<sub>2</sub>/kg/min, and in one-year infants – 8.2 ml O<sub>2</sub>/kg/min, then recalculated per an active cellular mass unit, it turns out that a newborn consumes 9.0 ml O<sub>2</sub>/kg/min, and a one year-old child – 10.9 ml O<sub>2</sub>/kg/min.

Rate of basal metabolism starts reducing from the age of three (Fig. 1). The first place among the probable reasons for this phenomenon is change in body composition correlated with age - increase in relative mass of tissue with a small rest metabolism rate (bone tissue, fat tissue, skeletal muscles, etc.). M. Holliday (1971) has already proven that a gradual decrease in the metabolism rate of children can be easily explained by the uneven growth of organs, presuming that the metabolic rate of tissue growth in the process of postnatal development is constant. For instance, it is known that mass of the brain (which greatly contributes to the level of basal metabolism) for newborns is 12% of their body mass, while in adults it's only 2%. Internal organs (liver, kidneys, etc.) also grow unevenly, and have a high level of energy

metabolism even during rest – 300 kcal/kg/day. At the same time, the muscle tissue whose relative quantity is almost doubled in the period of postnatal development, is characterized by a very slow resting metabolism rate – 18 kcal/kg/day.

It should be noted, that the dynamics of age changes in resting metabolism is not just a simple decrease in metabolism rate. As it is given in Fig. 1, periods characterized by a rapid decrease in metabolism rate, are replaced by age intervals where resting metabolism values are stabilized (Kornienko, 1979; Kornienko & Gohblit 1983; Kornienko et al, 2000). Taking this into consideration, a close correlation of changes in metabolic rate and growth velocity is found. Columns in Fig. 1 show relative annual increase in body mass. Turns out that, excluding the first year after birth, the higher the relative growth velocity, the higher the rate of resting metabolism lowering during this period. Inhibition of growth processes at the age of 1.5-2 coincides with the highest values of resting metabolism, and the increase in growth velocity by ages 6 through 7 is accompanied by a considerable decrease in metabolism. After this there is the next inhibition of growth, during which the level of metabolism is stabilized, and the next value decrease coincides with a new acceleration of growth processes. The last peak of resting metabolism is observed at about the age of 14 years, before the puberty growth spurt, and soon after that the energy metabolism rate is stabilized on the level typical for adults. According to longitudinal observations, all these changes are typical both for boys and girls, but in girls they are usually observed 0.5-1 years earlier (Kornienko & Gohblit, 1983).

Rate value of basal metabolism is especially important for diagnosing and treating several endocrinological diseases, as well as obesity. Because of that there are ongoing discussions in scientific literature about methods of calculating basal metabolism values using various formulae – Harris & Benedict (1919), the WHO committee and others (White & Seymour, 2005; Frankenfield et al., 2005; Garrel et al., 1996; Hayter & Henry, 1994; Tverskaya et al., 1998, etc.). Most contemporary authors consider the volume of cellular mass or the value of lean body mass the most important factor, as well as age, sex, constitution, race and ethnicity (Bosy-Westphal et al., 2009; McDuffie et al., 2004; St-Onge & Gallagher, 2010; Vermorel et al., 2005).

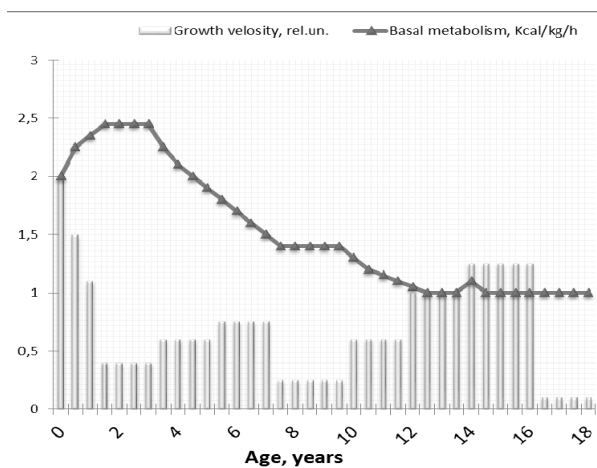


Fig. 1. Dynamics of growth velocity and basal metabolic rate in children from birth to maturity (after: Kornienko, 1979; modified)

Another factor might play an important role – the change in metabolic activity of tissues in a growing organism, that occurs with age (Conrad & Miller, 1956; Nagorny et al., 1963). To test this assumption, our laboratory researched age changes in the mitochondrial apparatus of various tissues (Demin, 1983; Kornienko, 1979). Using Chance's differential spectrophotometer we measured cytochrome a concentration, which is a terminal ferment of the oxidative chain of mitochondria, in tissue homogenates of Wistar rats during ontogeny (Fig.2). The higher cytochrome a concentration, the higher oxidation activity is developed by a given tissue under the influence of an appropriate stimulus, provided it is adequately supplied with substrates and oxygen. This data allows to compare not just the potential metabolic activity of various tissues, but also to observe its changes, including changes occurring with age.

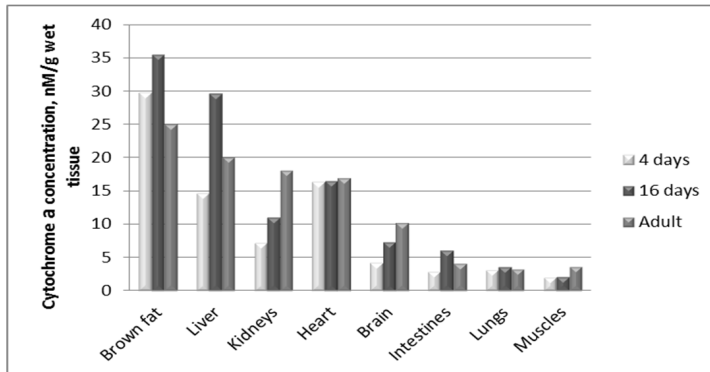


Fig. 2. Cytochrome a concentration in tissue homogenates of Wistar rat during ontogeny (after: Kornienko, 1979; modified).

Brown adipose tissue has the highest potential metabolic activity, both in young and adult rats; the liver is second in potential. Both tissues are characterized by the fast rise of cytochrome a concentration at the age of 16-20 days, which can be explained by the fact that at that time young rats leave their nest and start their separate life, which requires the activation of thermoregulatory processes. The food type changes at the same age, which has an effect on cytochrome a concentration in the intestine tissue. When adulthood is reached, cytochrome content in all these tissues is considerably reduced.

Content of oxidation ferments in cardiac and lung tissues is the most stable – it stays almost unchanged with age. But oxidation ferments in tissues of rat kidneys and brain increase approximately by a factor of 2.5 by adulthood. If the increase in tissue mass is considered, it turns out that the metabolic potential of brown adipose tissue during postnatal ontogenesis grows 10 times, the brain's - 11.4 times, the liver's -38.5 times, the kidney's -57 times, the skeletal muscles' -87 times. That directly affects the level and structure of energy metabolism.

It has been proven using this method (based on post-mortem materials from a trauma clinic) that cytochrome concentration is increased considerably in some grey matter areas in the brain cortex (4, 6, 10th and 17th fields according to Broadman), in the subcortical structures, and in the homogenates of children's whole brain at the age of 1–1.5, compared to the first months of life (Kornienko, 1979). Since at this age the human brain accounts for at least 50% of basal metabolism, it can be assumed that a more active oxidation processes of this tissue



will have an effect basal metabolism of the whole body. Important qualitative changes in nervous and mental activity occur in children age 1-2, due to differentiation processes in neural tissue (Farber & Machinskaya, 2009; Tsekhmistrenko et al., 2009). Meanwhile it has been proven 40 years ago that tissue differentiation in ontogenesis always starts with mitochondria development and a more active oxidation metabolism (Macler et al., 1971; Makhin'ko & Nikitin 1975).

Calculations by Kornienko (1979) have demonstrated that for humans the contribution of various organs to the basal metabolism is changes with age. The adult human brain accounts for 24% of basal metabolism, the liver for 20%, the heart for 10.2% and the skeletal muscles for 28%. A one-year old child's brain accounts for 53% of basal metabolism, while the skeletal muscles account only for 8%. The liver's contribution is about 18% (Fig.3).

### 3. Energy supply for functions during ontogenesis

#### 3.1 Daily energy expenditure structure

Unlike basal metabolism, which is the minimum level of body energy expenditure, average daily metabolism includes the sum of all expenditures associated with the realization of various body functions. Food processing and digestion, thermoregulation and muscle activity are the most power-consuming functions. Unfortunately, there is almost no data in literature on the energy value of mental activity (not taking into consideration the indirect calculations by Holliday, 1971).

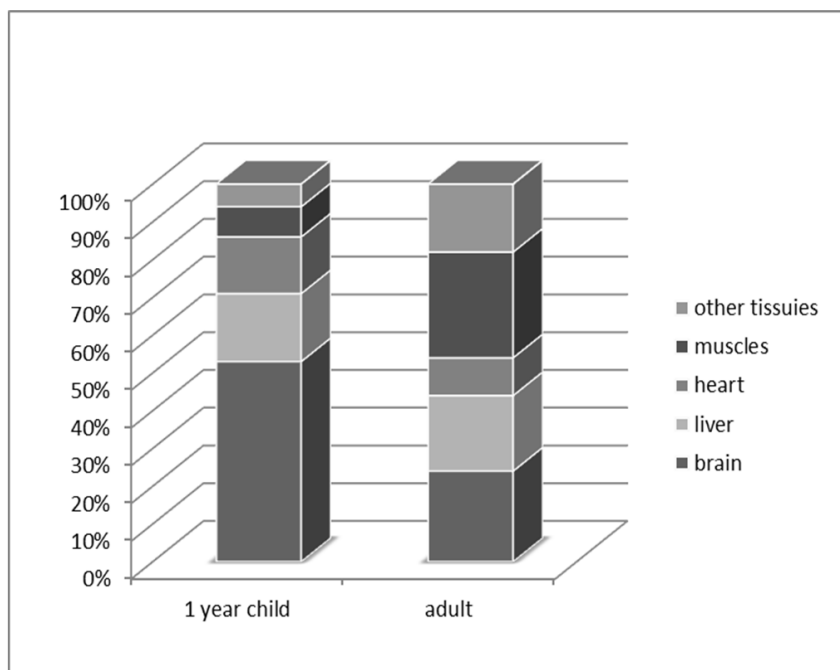


Fig. 3. Age changes in contribution of various organs and tissues into the structure of human basal metabolism (After: Holliday, 1971; Kornienko, 1979; modified)

### 3.2 Functional range

Various body tissues can change their metabolic activity to a different degree, ranging from rest to maximum functional activity. It depends on the organization of metabolic paths in cells that form the corresponding tissue. Based on content and activity data of vital energy ferments in body tissues, Demin (1983) calculated the hypothetical values of minimum and maximum metabolic activity for the liver, brain and muscles of a young man (Fig. 4). Characteristics of the functional range in skeletal muscles obtained using this method are close to the actual measured maximum energy expenditure (Son'kin, 1990; Kornienko, et al, 2000). As seen in fig. 3, muscles have both the highest potential for metabolic activity and the widest functional range. It should be noted that the maximum level of functional activity is carried out through the anaerobic metabolic processes, not limited by the possibilities of mitochondrial oxidation. The functional range value of various tissues can be affected differently depending on age. According to Demin (1983), this value for the brain is at its peak in childhood; for the liver it stays more or less the same at all periods of postnatal ontogenesis; for skeletal muscles it considerably increases from birth to the end of puberty.

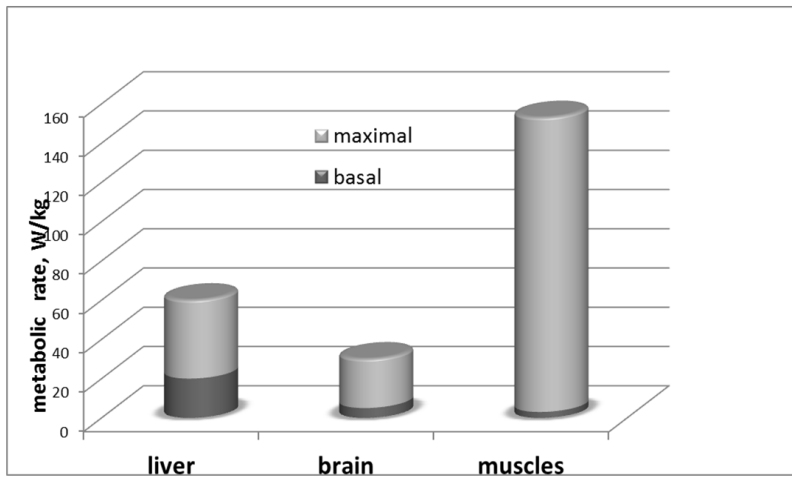


Fig. 4. Comparative characteristic of functional range in various tissues of human body (calculation for a young man) (After: Demin, 1985; modified)

The intensity of body functions in a child is much higher than of an adult. The rate of children's basal metabolism is 1.5-2 times higher, but the maximum activity level is considerably lower than that of an adult. This results in a smaller functional range, and that makes the child body's existence more stressful.

The high intensity of energy metabolism in children becomes particularly obvious when you look at the fact that the child's body reacts with higher intensity to an impact equal in power, demonstrating a higher lability of autonomic systems and metabolic processes. These differences are well known, when talking about muscle activity (Åstrand, 1952; Kornienko et al, 2000). The fact that similar differences are evident in metabolic reactions to other functional loads, in particular food load, is less known.

### 3.3 Specific – Dynamic (thermogenic) effect of food

The rate of heat production is considerably increased after food consumption, despite of lack of muscle activity, and it remains elevated for 2-3 hours (depending on the structure of food and other factors). Though the thermogenic effect of food is a known phenomenon and has been studied since the end of the 19th century, there is still no single opinion about its reasons and occurrence mechanisms. The simplest explanation, which states that extra energy production is required to activate a motor function of the gastrointestinal tract, has not been borne out by experiments: the thermogenic effect of glucose cannot be recovered in patients with diabetes and lab animals, even though carbohydrate is absorbed to the bloodstream and is extracted with urine (Lusk, 1919).

Today the most probable reason considered for the thermogenic effect of food is the effect of enterohormones produced by the duodenum epithelium. For example, it has been proven that the lack of these hormones in blood results in a lower body temperature, meaning heat production (Ugolev et al, 1976). But even in this case it is unclear which particular tissue accounts for extra heat production. Recently brown adipose tissue has been considered as the reason (Himms-Hagen, 1989; Nedergaard & Cannon, 2010), which, according to recent data, is preserved in adults (Nedergaard et al., 2007) and maintains substrate homeostasis (Son'kin et al., 2010).

A unique systematic research of age changes in the thermogenic effect of food substance (glucose) in school children was made in the laboratory of I.A.Kornienko (Kornienko et al, 1984). A standard test was used to evaluate glucose tolerance during this study: glucose was taken orally on an empty stomach in quantity proportional to mass (1g/kg). Content of glucose in blood in such a probe is usually increased during 30 minutes after intake and gradually normalizes within 2-3 hours. As glucose increases, with some delay (about 0.5 hours) oxidation processes start in the body, and in 3 hours the oxygen consumption levels return to the primary level. Total intensification of energy production with age for children of 7-8 up to 15-17 years is considerably reduced, especially for boys (Table 1).

The given data proves that reactivity of oxygen metabolism decreases with age, meaning efficiency of mechanisms providing homeostasis increases. The difference in age dynamics of thermogenic glucose effect for boys and girls is the most interesting phenomenon. It is known that adult women, on average, have a better tolerance to glucose than men (Korkushko & Orlov, 1974). Possibly, the given data reflects the formation of such sex differences.

Age, years	Boys	Girls
7 - 8	2.125 ± 0.16 (n=18)	1.825 ± 0.14 (n=23)
11 - 12	1.255 ± 0.10 (n=22)	1.365 ± 0.11 (n=21)
15 - 17	0.585 ± 0.06 (n=16)	1.060 ± 0.08 (n=14)

Table 1. Total thermogenic effect of glucose (per oral 1 g/kg) for school children for 3 hours of observation (kcal/kg, M±m) (After: Kornienko et al., 1984)

In the same research (Son'kin et al., 1975) it was proved that glucose put into the body depends considerably on their body constitution: children of 11-12 years with a low fat content in the body of no less 1/3 introduced glucose is oxidized in process of a thermogenic response to its putting into the body, while children with a high fat content a thermogenic response to input of glucose is considerably less. Similar results for adult persons are described in press of the last years (Nedergaard & Cannon, 2010).

Results obtained in such studies as well as other data about thermogenic effect of food cast doubt on the validity of widely used calculations of caloric food value. All such calculations do not take into account energy expenditure on digestion of food substances which are known to take from 1/5 up to 1/3 caloric value of the taken food substance. The problem is complicated by the fact that fats and proteins have a greater thermogenic effect than carbohydrates (Kassirsky, 1934), while mixed products have a smaller thermogenic effect than the total thermogenic effects of food substances they contain (Forbes & Swift, 1944). It is proven that liquid food, with similar calorie value has a less specifically dynamic effect than solids (Habas & Macdonald, 1998). We think that mechanical calculations of food calorificity based on the caloric equivalent of proteins, fats and carbohydrates in it which is widely used in clinic and health-improving systems, including paediatric practice (Morgan, 1980; Young et al. 1991; Schmelzle et al., 2004) need to be corrected.

### 3.4 Thermoregulation development in ontogenesis

Thermoregulation, support of constant temperature in the body core is determined by two basic processes: heat production and heat dissipation. Heat production (thermogenesis) depends primarily on the rate of metabolic processes, while heat dissipation is defined by heat insulation provided by cutaneous coverings, vascular reactions, active outer respiration and perspiration. Because of this, thermogenesis is considered a mechanism of chemical thermoregulation, and heat dissipation regulation - a mechanism of physical thermoregulation. Both these processes change with age, as well as their role in providing a constant body temperature.

As a result of laws of physics, increase in mass and body absolute dimensions reduces the contribution of chemical thermoregulation. Thus, the value of thermoregulation heat production for newborn children makes about  $0.5 \text{ kcal/kg} \cdot \text{hour} \cdot ^\circ\text{C}$ , and for adults -  $0.15 \text{ kcal/kg} \cdot \text{hour} \cdot ^\circ\text{C}$ .

A newborn child, if temperature of the environment lowers, can enlarge heat production to adult levels - to  $4 \text{ kcal/kg} \cdot \text{hour}$ . But because of lower heat insulation ( $0.15 \text{ } ^\circ\text{C} \cdot \text{m}^2 \cdot \text{hour/kcal}$ ) the chemical thermoregulation range of a newborn is small—no more than  $5^\circ$ .

At that it should be accounted that the critical temperature level ( $T_h$ ), switching thermogenesis for a healthy newborn is  $33^\circ\text{C}$ , by the adult period it falls down to  $27 - 23^\circ\text{C}$ . But in clothes with heat insulation usually making 2.5 CLO, or  $0.45 \text{ } ^\circ\text{C} \cdot \text{m}^2 \cdot \text{hour/kcal}$ ,  $T_h$  value falls down to  $20^\circ\text{C}$ , therefore a child in his usual clothes at room temperature is in a thermoneutral environment, meaning that in these conditions a child requires no extra expenditure to support body temperature.

If the temperature falls down below threshold values (for instance, during the change of a child's clothes), mechanisms of extra heat production switch on. For a child they are mainly, "nonshivering thermogenesis", localized in metabolically active tissues - liver and brown adipose tissue (Brück, 1970; Kornienko, 1979). Researches of the latest years have revealed that an acute short-term cooling of adults also results in activation of nonshivering thermogenesis in brown adipose tissue (Nedergaard et al., 2007; Son'kin et al., 2010), which is proved to be preserved for most adults residing in a moderate climatic zone (Nedergaard & Cannon, 2010). Another mechanism of thermogenesis is a cold-induced muscle tremor which is usually observed in adults when the cooling effect is strengthened or prolonged. For children this physiological mechanism turns out inefficient due to particular features of

the child's body constitution, therefore it is activated in the last turn, if temperature of the body core falls down despite the processes (Kornienko, 1979).

High activity of special mechanisms of thermogenesis in infants is connected not only with small size and large relative surface increasing heat insulation, not only with low heat insulation of cutaneous coverings, but with a relatively low level of basal metabolism, which has been noted before in this paper. Within the first year of life all these parameters are changing and the chemical thermoregulation activity is reduced. For a child of 5–6 months the importance of physical thermoregulation is considerably increased; it makes the temperature threshold and latent period of an interscapular brown adipose tissue activation almost double compared with the same parameters for infants 1-2 months old (Gohblit et al, 1975; Kornienko, 1979).

Under usual conditions the child older than 3 years old has a high value of heat flow in relation to the body surface unit, and heat insulation of cutaneous coverings is low, therefore children's skin is practically always warm. Even at the age of 4.5–5 years for girls and 5.5–6 years for boys the body heat insulation is very low:  $0.226 \pm 0.003 \text{ } ^\circ\text{C} \cdot \text{m}^2 \cdot \text{hour/kcal}$ , not changed a lot compared to infants. Their mechanisms of physical thermoregulation are poorly developed. Therefore, if such a child is in conditions of room temperature (+ 20°C) in underwear and T-shirt, in 80 cases of 100 his thermoregulatory heat production is activated (Kornienko, 1979).

Intensification of growth processes at the age of 5-7 years results in accelerating the length and surface area of extremities, providing a regulated heat exchange of the body with the environment. It is, in turn, results in the fact that from the age of 5.5–6 years (it is especially visible for girls) the thermoregulation function is considerably changed. The body heat insulation is increased, and the chemical thermoregulation activity is substantially reduced. This method of body temperature regulation is more efficient and it becomes predominant in further development with age. In girls this transformation of thermoregulation happens, on average, one year earlier than boys.

At the age of 10 years for girls and 11 years for boys quicker growth processes and considerably lower rate of basal metabolism which are typical for them are observed again. According to thermoregulation conditions, this age can be marked out as a crucial period: physical thermoregulation is activated again, with chemical thermoregulation becoming less important. For boys these changes are distinctly expressed at the age of 12 years.

The next stage of thermoregulation development is during pubescence, becoming apparent in the frustration of the forming functional system. For 11–12-year old girls and 13-year old boys, despite the continuous decrease in the resting metabolism rate, there is no corresponding adjustment of vascular regulation. Worse heat insulation facilities of covering tissues result in the fact that, notwithstanding the age tendency, the critical temperature shifts to higher values with the temporarily growing role of chemical thermoregulation – most teenagers (up to 80%) enlarge their heat production even under slight cooling conditions effects.

Distinct sex differences in dynamics of thermoregulation development are seen during pubescence (Kornienko & Gohblit, 1988). Parallel to decrease in basal metabolism, for girls after the second stage of pubescence (according to Tanner), heat insulation properties are rapidly increased, and the function of physical regulation is restored in full. By the age of 16 this process is usually over, and all thermoregulation parameters reach the values typical for adults. The same tendencies exist in boys, but by the age of 16 years, processes forming

mechanisms of physical thermoregulation are incomplete. Only in youths after pubescence do thermoregulation facilities reach their final level. Increase in tissue heat insulation to the level of 1.1 CLO allows to function without activating the chemical thermoregulation (meaning extra heat production) even when the environment temperature falls down by 10-15 degrees below thermoneutral. Such body reaction is naturally more economical and efficient.

The given data prove that in the process of postnatal ontogenesis the primary line of the system development providing temperature homeostasis is indirect (Falk, 1998). At each stage of individual organism development there is a complex dependence of thermoregulation active mechanisms on growth and development, the rate of metabolic processes and conditions of some autonomic functions. It is this dependence that determines a primary activity of physical or chemical thermoregulation mechanisms, providing temperature homeostasis at the corresponding stage of development.

#### **4. Muscle function energy supply development**

Muscle activity is the most energy-intensive function: even for a person engaged in mental work about half of daily energy expenditure is used to provide a contracting activity of somatic muscles. One of the first works researching ontogenesis of the muscle function energy supply was made by Robinson (1938), who discovered age changes in maximum oxygen consumption in children, teenagers and adults. The research of P.-O. Astrand (1952), still a classic, presents data of maximal aerobic capacity of people from 6 up to 60 years old.

As compared with other tissues, skeletal muscles have the greatest functional range (Fig.4) – metabolic process can change its velocity in muscles by a factor of dozens. Such amplitude of metabolic activity change is impossible to be explained through the work of mitochondrial apparatus; therefore muscles can get the energy required for contraction even from the glycolysis process in cytoplasm and macroergs reserves accumulated in cells in the form of ATP and creatine phosphate. It forms a specific character of muscle tissue energetics. These specifics were expressed by Margaria (1963) in his conception of three energy sources for the muscle activity: aerobic (oxidative, mitochondrial); anaerobic glycolytic (lactacide); anaerobic phosphagenic (alactacide). In combination with the anaerobic threshold conception (Mader & Heck, 1986; Skinner, 1993), these presentations are now the theoretic base of muscle bioenergetics (Volkov, 2010).

Ample data prove an uneven development of aerobic and both anaerobic sources with age, like, for example, heterochrony determines a qualitative peculiarity of skeletal muscles energetics at separate stages of ontogenesis (Guminskiy et al., 1985; Demin, 1983; Kornienko, 1979; Kornienko et al., 2000, 2005; Son'kin, 1988; 2007; Tambovtseva, 2003; Van Praagh, Dore, 2002).

##### **4.1 Aerobic (oxidative) source**

Facilities of aerobic energy supply in skeletal muscles are considerably changed in the course of individual development. It is provided by both the change in content of most important oxidizing ferments in the somatic muscle tissue (Kornienko, 1979), and structural change in the oxidative chain of mitochondria (Demin, 1983, 1985; Demin et al., 1987; Son'kin & Tambovtseva, 2011). Naturally, the most important factor is absolute and relative age increase in mass of somatic muscles. Generally, the maximum oxygen consumption

(MOC) rises proportionally to the muscle mass growth (Kornienko et al., 2000), but it lacks information about qualitative changes in muscle energy supply of children and teenagers (Son'kin & Tambovtseva, 2011).

Age, years	Cytochrome <u>a</u> concentration, nM/g raw mass of muscle tissue	Muscle mass, kg (after: Holliday, 1971)	MOC, l/min (after: Åstrand, 1952)	MOC, ml/kg muscle mass
Newborn	0,9	0,6	-	-
5 - 7	4,6	6,7	1,01	151
9	5,2	10,5	1,8	171
11	6,6	11,6	2,1	181
14	4,8	21,2	3,5	165
20	4,5	25,0	4,1	164
36-40	3,7	28,3	3,9	138

Table 2. Age changes in cytochrome a content in thigh muscle and human aerobic capacity (After: Kornienko, 1979)

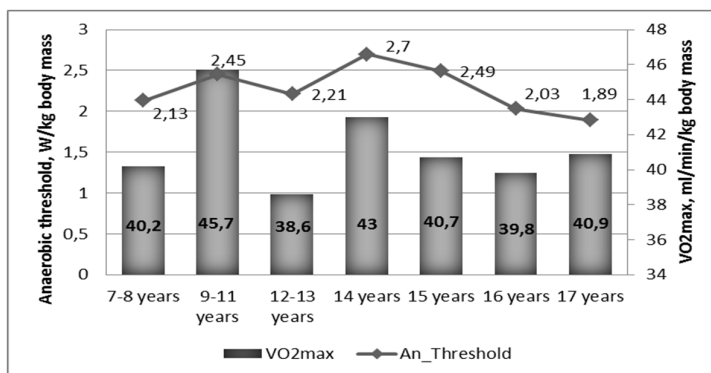


Fig. 5. Dynamics of aerobic capacity indices in schoolboys

Age dynamics of cytochrome a content - a terminal site of the oxidative chain - in human skeletal muscles (Kornienko, 1979; Demin et al., 1987) is given in Table 2. Calculations of the estimated value for specific MOC (per 1 kg of somatic muscle mass) are shown. As obvious from the given data, the highest cytochrome a concentration is registered in skeletal muscles for boys 9-11 years old. It is also proved by data of electron microscopic researches (Kornienko, 1979; Kornienko et al., 1987): the number of mitochondria in relation to the area of myofibrils for 11-year old boy is considerably more than in an adult man (Table 3). It is remarkable, that, according to data of morphologists, a capillary network in the muscles of extremities turns out to be more developed in children of 9-11 years (Topol'sky, 1951), which is the age when there is the highest content of oxidizing ferments in the muscle tissue. Thus, an age development of the energy production aerobic source in skeletal muscles does not happen monotonously, but gets the expressed maximum during prepubescence (Fig.5). These conditions have a considerable effect on the functioning of the muscle energy supply system.

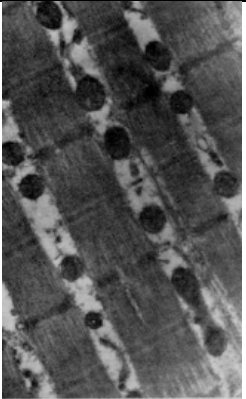
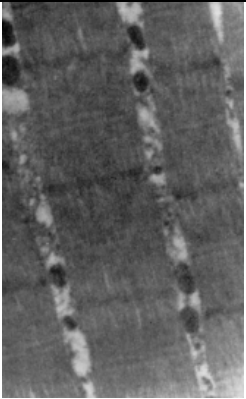
Index	11-year old boy	35-year old man	Difference, %
Electron micro photos of somatic muscle lengthwise cuts (m. Quadriceps Femori)			
Mean diameter of mitochondria, micron	236	175	-35
Mean thickness of myofibrils, micron	505	590	+14
Ratio of mitochondria area to myofibril area	0,034	0,016	-113
Ratio of mitochondria total area to myofibril total area	0,153	0,097	-58

Table 3. Morphometric indices of skeletal muscles mitochondria in 11-year boy and adult man according to electron microscopy (After Kornienko, 1979; modified)

Such special energetic structure of skeletal muscles for children in prepubescence, as we see it, is caused by the fact that this ontogenesis period is the preparation for the radical reconstructing structural and functional characteristics of somatic muscles, occurring during pubescence under the influence of sex hormones. We used special histochemical tests to prove this (Tambovtseva, 2003).

#### 4.2 Morpho-functional changes of skeletal muscles during postnatal ontogenesis

Fiber structure of mixed skeletal muscles is usually considered to be determined genetically and not dependent on age and training (Van Praagh & Dore, 2002; Yazvnikov et al., 1978). But according to results of histochemical investigations, the ratio of various fiber types in the structure of skeletal muscles is not constant in ontogenesis (Kornienko et al., 2005; Son'kin & Tambovtseva, 2011; Tambovtseva & Kornienko, 1986a,b, 1987).

Research primarily made on laboratory animals - Wistar rats and Guinea pigs - made possible a conclusion that at an early age the most part of mammals is non-differentiated fibers which further acquires features of red oxidative fibers. The share of quick fibers is rapidly increased during pubescence, which become predominant after pubescence (Tambovtseva & Kornienko, 1986a; 1987).

These studies continued on post mortem material of males within the age bracket from birth to adulthood (Tambovtseva & Kornienko, 1986b). On Fig. 6 there are results characterizing



the structure of large skeletal muscles in human extremities, achieved by the method of histochemical revelation of ATP myosin activity.

It turns out that all large human skeletal muscles are characterized by the same age tendency: undifferentiated embryo fibers are changed by fibers with a slow actomyosin ATP-ase, by 4-7 years an “aerobic profile” of mixed muscles is formed, which prevails up to 11-12 years. Then, with start of pubescence there is a two-phase transformation of the muscle structural-functional composition, which results in considerable reduction in a share of red oxidizing fibers (I type), some increase in a share of intermediate fibers (IIA type), and a considerable increase in presented glycolytic fibers (IIB type).

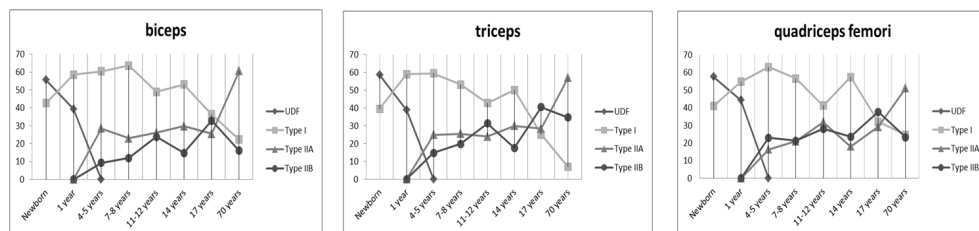


Fig. 6. Age changes of muscle fiber composition in men (% of each fiber type). By X-line – age from 4 months intrauterine development up to 70 years. By Y-line – fiber share (%): MB undifferentiated, MB I type, MB IIA type, MB IIB type. UDF – undifferentiated fibers.

Only by 17-18 years is a definite picture formed, which is characterized by predominance of anaerobic – glycolytic fibers in all large muscles. Such muscle structure is likely to be preserved up to the start of involutive processes at the old age, which might be connected with decreased activity of genital glands.

It should be noted that in the world literature there is no definite view on the age development of somatic muscle structural components. The relatively scarce researches of age features in human skeletal muscles provide conflicting results (Blimkie & Sale, 1998; Van Praagh, 2000). According to some authors, there is a relatively large share of undifferentiated fibers at birth (10-20%). Amount of I-type fibers grows rapidly after birth, and II-type fibers reduces. By the age of one year the structure which is similar to adults is formed (Bell et al., 1980; Colling-Saltin, 1980; Elder & Kakulas, 1993). The ratio of IIA-type and IIB-type fibers is also disputable (Colling-Saltin, 1980; du Plessis et al., 1985; Jansson, 1996). But, according to other authors, children until pubescence are more characterized by I type than adults (Eriksson & Saltin, 1974; Lexell et al., 1992; Lundberg et al., 1979). According to Jansson (1996), development of muscles from birth up to 35 years old for men corresponds to  $\Omega$ -model: from birth up to 9 years old a substantial increase in percent of I-type fibers is observed, at the age of about 9 there is a maximum, whereupon their share is reduced considerably by 19 years old. It is evident that this model is very close to results produced by the I.A.Kornienko laboratory.

### 4.3 Age changes of anaerobic metabolism ferments activity in muscles

In 1971 Swedish scientists demonstrated, by means of needle biopsy, that untrained boys at the age of 12 have a sharp (twofold) increase in the activity of phosphofructokinase (Eriksson et al., 1971). That was the first work where age changes in possible human

anaerobic - glycolytic source at the tissue level were discovered. Next by means of biochemical (Eriksson, 1980; Ferretti et al., 1994; Kornienko et al., 1980; Ratel et al., 2002), histochemical (Tambovtseva, 2003; Kornienko et al., 2000) and physiological (Kornienko et al., 2000; Pyarnat & Viru, 1975; Son'kin, 1988;) methods numerous confirmations of an abrupt activation of anaerobic - glycolytic energy production in the process of pubescence reconstructions were obtained, especially for boys (Boisseau & Delamarche, 2000; Van Praagh & Dore, 2002).

In ontogenesis of rats an activity of glycolysis key ferment - lactate dehydrogenase (LDG) was traced in detail (Musaeva, 1986; Demin et al., 1987). LDG molecule consists of 4 monomers and each of them can have one of two following isoforms: "H" - subunits which are typical for LDG from a cardiac muscle, "M" - subunits which are mainly in skeletal muscles of adult mammals (Lehninger, 1965). These isoferment forms differently participate in a cycle of glycolysis reactions, therefore the ratio of "H" and "M" activities - LDG subunits can be used as a sufficiently informative activity ratio index for aerobic and anaerobic - glycolytic sources.

In these studies it was proven that an age increase in "aerobic" ferment activity in muscles of male rates occurs generally parallel to increasing facilities of the oxidizing source and is complete by the start of pubescence, while total LDG activity rapidly grows in pubescence and even after it. Therefore, in process of pubescence qualitatively reconstructed is organization of energy metabolism in somatic muscle cells: an abrupt extension of facilities for anaerobic - glycolytic energy production in terms of stabilization and even some decrease in a relative capacity of aerobic energy production.

The given facts have proposed an important role of sex hormones in regulation of muscle energetics. Direct evidence of this hypothesis was obtained by Musaeva (1986) in tests on male rates with orchotomy at the age of 3 weeks or artificial androgenization: androgenization accelerates and orchotomy inhibits the formation of ferment systems, which are responsible for anaerobic mechanisms producing energy in somatic muscles, and practically does not have an effect on conditions of mitochondria (aerobic) energy production. Under the influence of exogenous testosterone, the fraction of muscle fibers with a high activity of ATP-ase in the structure of extremities considerably increased, meaning those, which are mainly characterized by anaerobic energy supply. Orchotomy has the opposite results (Musaeva, 1986; Son'kin & Tambovtseva, 2011).

Probably, male sex hormones play a role that is not less significant in formation of a morphological-functional status of human skeletal muscles (Boisseau & Delamarche, 2000; Ferretti et al., 1994; Jansson, 1996; Round et al., 1999; Tambovtseva & Kornienko, 1986; Van Praagh & Dore, 2002). It is remarkable that for girls the same effects of pubescence processes on the structure and function of their skeletal muscles are not revealed (Petersen et al., 1999; Tambovtseva, 2003; Treuth et al., 2001), which can be explained by various structural - metabolic consequences of androgen and estrogen effects. For boys testosterone content is increased 4 times at primary stages of pubescence and more than 20 times - at its last stages. For girls the testosterone is only 4 times increased from the primary to the last stages of pubescence (Blimkie & Sale, 1998).

In literature there are no data on creatine phosphokinase (CrK) activity in human muscles with age. In recent years, with development of magnetic resonance research methods (Ross et al., 1992), data on creatine phosphate (CrP) content in muscles in rest as well as under physical load and recreation have been obtained (Zanconato et al., 1993; Ferretti et al., 1994;

Boisseau & Delamarche, 2000; Van Praagh & Dore, 2002). Data available in press are contradictory.

At that same time, dynamics of these indices for various tissues in ontogenesis of rats was studied by Demin in detail (1983, 1985). According to these results, CrK activity in muscles of animal hind extremities in a nest life period makes 2.5 – 2.7  $\mu\text{mol}/\text{min}/\text{g}$  and it is practically unchanged in the first 2 weeks of life. At the same age CrK activity in cardiac tissue is somehow less than in leg muscles while in neck muscles, which perform the most thermoregulation function – it is 2 times more, than in leg muscles. With start of an active independent motion activity for young rats (3 weeks), CrK in leg muscles grows intensely reaching by pubescence (60 days) the level of 39  $\mu\text{mol}/\text{min}/\text{g}$ . This is 4.5 times more than in neck and cardiac muscles, 12 times more than in brain tissue and 50 times more than in the liver.

For this period CrP content in muscles is approximately increased by 3 times - from 5.4 up to 15.9  $\mu\text{mol}/\text{g}$  (in a 60-day rat's heart CrP content – 7.1  $\mu\text{mol}/\text{g}$ ; in brain – 5.7  $\mu\text{mol}/\text{g}$ ; in liver – 2.43  $\mu\text{mol}/\text{g}$ ).

CrP content and CrK activity are increased in skeletal muscles asynchronously with age and it provides age changes in potential duration of CrP expenditure at maximum activity. The most substantial increase in CrK activity is observed at the last stages of pubescence, which provides a considerable acceleration of ATP forming velocity in a creatine kinase reaction, meaning the capacity of an alactacide energy system. As a result, according to Demin (1985), ATP formation velocity in process of a creatine kinase reaction in muscles of rat extremities is increased from 20  $\mu\text{mol}/\text{g}/\text{min}$  at the age of 12 days up to 80  $\mu\text{mol}/\text{g}/\text{min}$  at the age of 40–45 days (an active phase of pubescence), and by the end of pubescence changes it grows up to 160  $\mu\text{mol}/\text{g}/\text{min}$ .

The given facts prove that the pubescence period is a “divide” between two qualitative conditions in energetics of somatic muscles. Prior to pubescence changes in muscles, like in other mammal tissues, the predominant role in energy supply is played by mitochondria oxidation. After pubescence changes, muscles acquire that colossal functional range and those specific features of organizing energy metabolism, which differentiates them from other tissues of an adult body, and the role of anaerobic energy sources is rapidly increased (Kornienko et al., 2000). Such reconstruction of energetics in skeletal muscles allows after some time the increase of the realized capacity of outer mechanical production, considerably extending the functional range, as well as promoting repeated growth of efficiency and reliable body function under strenuous muscle activity (Kornienko & Son'kin 1999). However, it should be noted, that the data of Demin, like most other similar results, were obtained for male rats. Sex differences in dynamics of energy facilities for skeletal muscles are studied insufficiently. According to the results of research made by means of up-to-date methods (Boisseau & Delamarche, 2000; Petersen et al., 1999; Treuth et al., 2001; Van Praagh, Dore, 2002), for girls at pre- and post-pubescent age such considerable differences in energy metabolism structure under muscular load were not revealed.

## 5. Conclusion

Energy metabolism, presenting the most integral body function, demonstrates logical age changes reflecting qualitative and quantitative redevelopments of a child's organism. The principle of functional economy is likely to be the most vivid of these changes with age development. This principle is implemented in age-related reduction of basal metabolism, in

slower rate of thermoregulatory reactions, decrease of food thermogenic effect with age, in change of daily energy expenditure structure with age. This is the structure of daily expenditure, where there are most vivid qualitative changes reflecting heterochronic development of most energy-intensive functions. If at an early age the energy metabolism priority is the brain and neural processes associated with it, with growth of the muscular system and formation of its functional facilities energy expenditure on kinesis starts taking a greater share in the daily energy balance.

This, together with the general tendency to fall in relative heat production, corresponding to the views of progressive functional economy in rising ontogenesis, with growth and development of skeletal muscles the maximum energy production is considerably increased, which is provided by activation of the least economic anaerobic – glycolytic source of energy production. In other words, by the example of age changes in energy metabolism the most important principle of development can be distinctly demonstrated – a principle of biological suitability, which is sometimes implemented due to the breach of other principles with lower value, to implement biosocial objectives of the corresponding ontogenesis stage.

For many decades the researchers of age changes in energy metabolism have been paying attention to reduction in the rate of exchange processes in rest with age. It was attempted to be explained by smaller relative surface of the body (Rubner, 1883), growth of relative muscular mass value (Arshavskii, 1967), lower relative mass of internal organs with a high rate of oxidizing metabolism (Holliday, 1971; Javed et al., 2010; Kornienko, 1979; Wang et al., 2010). But now we think that the most important age redevelopment is the combined reduction of basal and increased maximum energy expenditure (including expenditure pursuant to anaerobic ways to transform energy with realization of the intense muscle activity), which results in the considerable development of a functional range. That is the biological development objectives of energy production mechanisms, as a vast functional range provides implementation of a wide spectrum of social and biological problems facing the adult organism (Son'kin & Tambovtseva, 2011).

Theoretical views of the laws valid for age changes in energy metabolism can considerably effect the formation and implementation of practical methods and means, firstly in such directions as conditioning to the cold, organization of proper nutrition and rational physical activity of children and teenagers.

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# Role of Inorganic Polyphosphate in the Energy Metabolism of Ticks

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## 1. Introduction

Inorganic polyphosphates are long chains of a few to several hundred phosphate residues linked by phosphoanhydride bonds (Figure 1). Polyphosphates have been found in all cell types examined to date and have been demonstrated to play diverse roles depending on the cell type and circumstances (Kornberg et al., 1999; Kulaev & Kulakovskaya, 2000). The biological roles played by polyphosphates have been most extensively studied in prokaryotes and unicellular eukaryotes, where they have been shown to regulate many biochemical processes including the metabolism and transport of inorganic phosphate, cation sequestration and storage (Kornberg et al., 1999), and membrane channel formation (Reusch, 1989; Jones et al., 2003), and they have also been found to be involved in cell envelope formation and bacterial pathogenesis (Rashid et al., 2000; Kim et al., 2002), the regulation of gene and enzyme activities (McInerney et al., 2006), the activation of Lon proteases (Kuroda et al., 2001), and KcsA channel regulation (Negoda et al., 2009).

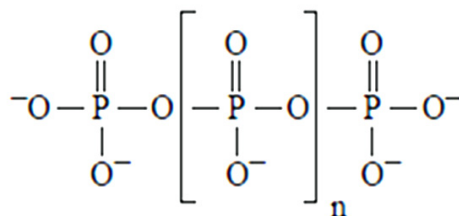


Fig. 1. Inorganic Polyphosphate

Conversely, polyphosphate functions have not been extensively investigated in higher eukaryotes; however, there is a good deal of interest in polyphosphates in mitochondria regarding two circumstances: polyphosphate as a macroenergetic compound with the same energy hydrolysis of the phosphoanhydride bond as an ATP and, according to the endosymbiotic theory, mitochondria originated from ancient prokaryotic cells (Clements et

al., 2009; Kulakovskaya et al., 2010), thus, it would be intriguing to discover whether or not mitochondria have preserved polyphosphate functions such as the regulation of energy metabolism and the participation in transport channel formation.

## 2. Polyphosphate mobilization during *Rhipicephalus (Boophilus) microplus* embryogenesis

The tick *Rhipicephalus microplus* is a one-host tick that causes major losses to bovine herds, especially in tropical regions. In this scenario, major efforts have been made to develop immunoprophylactic tick control tools (Guerrero et al., 2006). Ticks are also vectors of parasites that cause hemoparasitic diseases, which are endemic in many cattle production areas (Sonenshine et al., 2006). *Rhipicephalus microplus* only has one host throughout all three life stages, usually a bovine animal, and a long feeding period (approximately 21 days). The adult female, after becoming completely engorged, drops off of the host and initiates oviposition approximately three days later. Being an oviparous creature, embryogenesis occurs in the absence of exogenous nutrients, and maternal nutrients are packaged in oocytes and mostly stored as yolk granules. Hatching occurs around 21 days after oviposition, and the emerging larvae can survive for several weeks before finding a host, using the remaining yolk as the only source of energy (Fagotto, 1990).

Early *R. microplus* embryonic stages are similar to those of *D. melanogaster* and mosquitoes (Bate & Arias, 1991; Monnerat et al., 2002). Tick embryogenesis is characterized by the formation of a non-cellular syncytium up to day 4 (Campos et al., 2006). After this, the embryo becomes a multicellular organism and starts organogenesis (Campos et al., 2006).

The function of polyphosphate as a phosphate reserve is well known in prokaryotes and also in eukaryote microorganisms (Kulaev & Vagabov, 1983; Kornberg, 1995; Kulaev, 2004). The cells of higher eukaryotes also carry polyphosphate, but in smaller amounts than found in microorganisms. Therefore, as well as being a source of phosphate, these biopolymers probably participate in regulatory processes (Kornberg et al., 1999). Total polyphosphate levels were quantified throughout *R. microplus* embryogenesis and the levels were found to be higher during embryo cellularization and segmentation, from the fifth to the seventh day of development, and declined after that until a plateau was reached. The free phosphate content rapidly decreased during syncytial blastoderm formation on the third day of development, and remained low until the twelfth day of embryogenesis, when it rapidly increased thereafter (Figure 2A). Exopolyphosphatase splits phosphate off from the end of a polyphosphate chain and represents one of the main enzyme types responsible for polyphosphate hydrolysis (Kulaev et al., 2004). The activity of exopolyphosphatase was analyzed during embryogenesis and its activity was in agreement with total polyphosphate mobilization (Figure 2B).

It is interesting to note that in *R. microplus* the decline in total polyphosphate content after the seventh day of embryogenesis did not reflect the increase in the free phosphate content, since this only occurs after the twelfth day, suggesting that polyphosphate also plays roles other than being a phosphate reserve for embryo development. In this case, an alternative source of phosphate could be derived from the dephosphorylation of vitellin, a major yolk protein that is gradually dephosphorylated throughout embryogenesis (Silveira et al., 2006). This source could mainly be used until segmentation of the embryo, on the seventh day of development, because there is no total polyphosphate mobilization during this period.

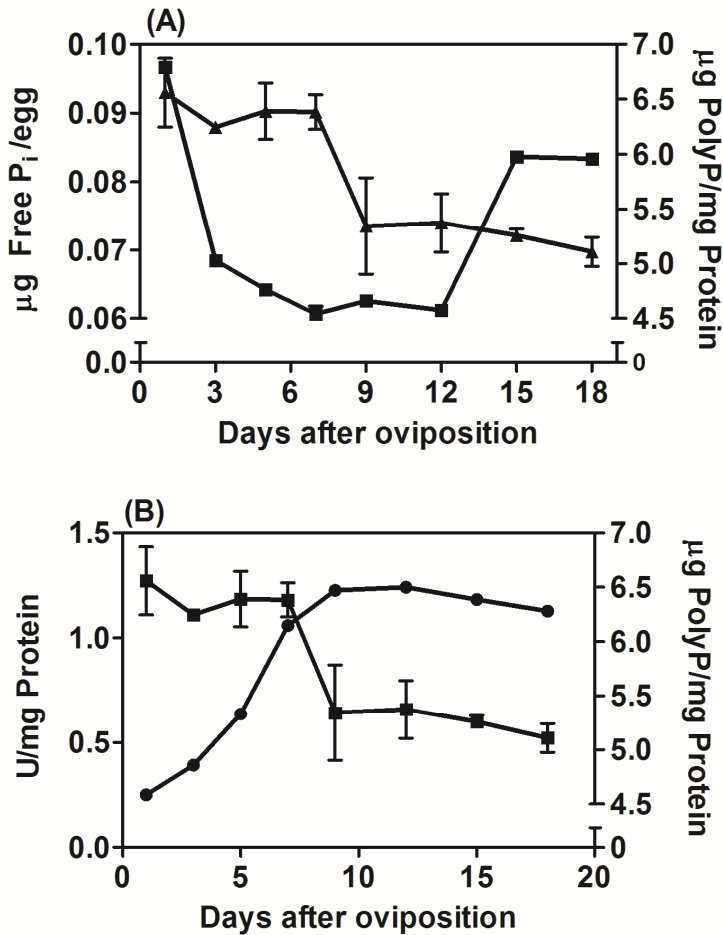


Fig. 2. Characterization of the total polyphosphate content during *R. microplus* embryogenesis. A) Total polyphosphate (▲) was extracted and quantified and free phosphate (■) was quantified in an egg homogenate on different days after oviposition. B) Total polyphosphate (▲) was extracted and quantified and exopolyphosphatase activity (●) was analyzed in an egg homogenate on different days after oviposition. Activity is expressed as units per milligram of total protein. The results represent the mean  $\pm$  SD of three independent experiments, in triplicate.

Quantification of the major energy sources in the egg over the course of *R. microplus* embryogenesis suggests that lipids and carbohydrates are the main energy source used during early development of the embryo. The total lipid contents remained stable until the fifth day, dropped on the seventh day, and remained roughly unchanged until hatching (Figure 3A). The total sugar contents exhibited a similar pattern, although slightly delayed: the values remained stable until the seventh day, dropped on the ninth day and remained

constant until hatching (Figure 3B). This pattern suggests the utilization of lipids during the course of cellularization, a maternally driven process (Bate & Arias, 1993). On the other hand, carbohydrates would be the major energy source for the quick segmentation of the embryo, of zygotic nature (Nusslein-Volhard & Roth, 1989; Bate & Arias, 1993).

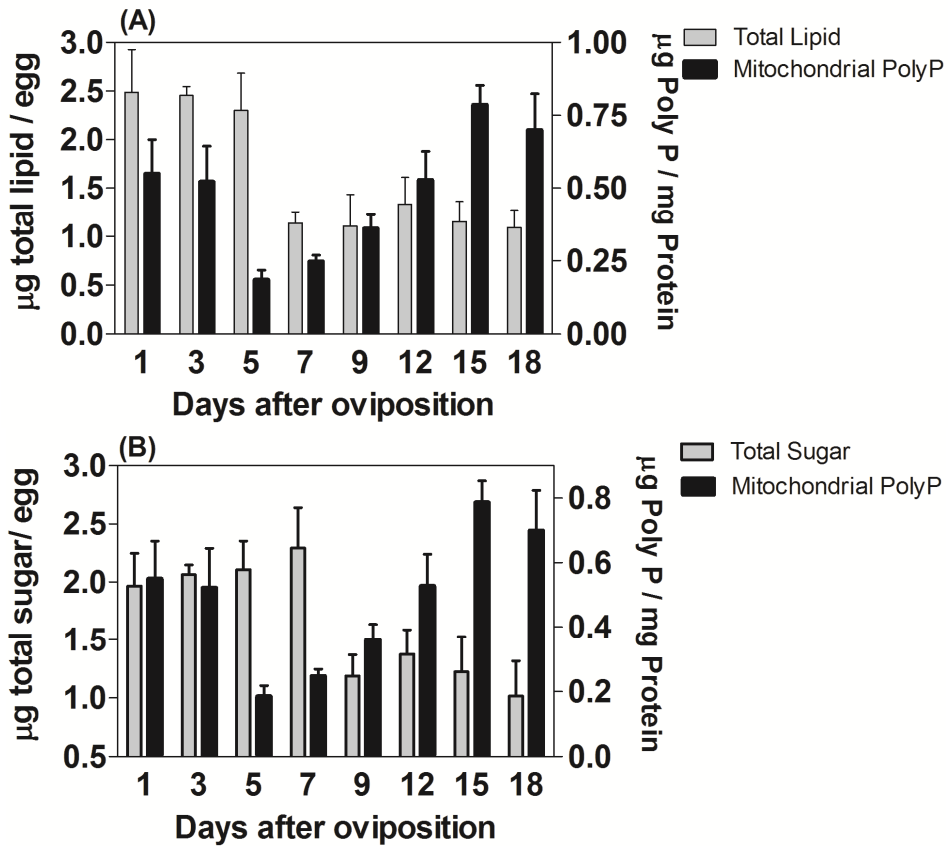


Fig. 3. Consumption of energetic sources. The major egg storage components of *R. microplus* were quantified on different days after oviposition. A) Lipid quantification, determined via the gravimetric method (Bligh & Dyer, 1959); B) total sugar concentration, measured using the method of Dubois (Dubois et al., 1956). The results represent the mean  $\pm$  SD of three independent experiments, in triplicate.

Interestingly, mitochondrial polyphosphate utilization occurred during blastoderm formation and segmentation of the embryo, between the fifth and seventh days of development, and higher total polyphosphate utilization occurred after blastoderm formation and segmentation of the embryo, after the seventh day of development (Figure 4). Thus, mitochondrial polyphosphate levels seemed to correlate with the energy demand of the embryo during these developmental stages, during which the embryo utilized a large part of its reserve lipids and sugars.

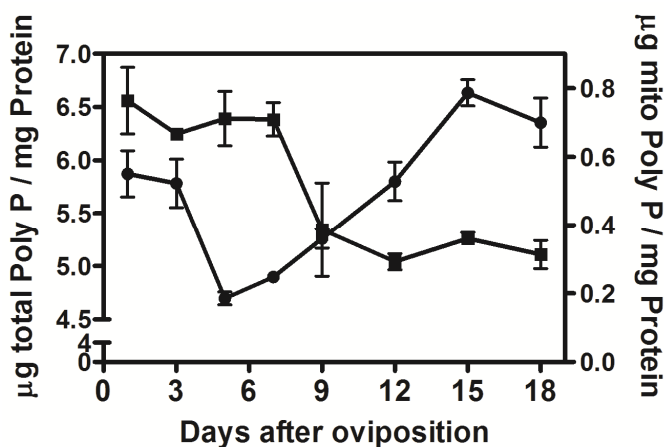


Fig. 4. Polyphosphate metabolism during *R. microplus* embryogenesis. Polyphosphate levels during embryogenesis in the mitochondrial fraction (●) and total polyphosphate (■) during embryogenesis. The results represent the mean  $\pm$  SD of three independent experiments, in triplicate.

### 2.1 Inorganic polyphosphate metabolism in tick mitochondria

Mitochondria from tick embryos in the segmentation stage (ninth day after oviposition) were isolated and respiration was measured using pyruvate as the substrate. The rate of oxygen consumption was 30 nmol/min/mg protein, and the respiratory control ratio (RCR) was 6.5. The process was KCN- and oligomycin-sensitive, his fraction exhibited an ATP hydrolyses azide sensitivity, a mitochondrial marker higher than 80%, and no activity of glucose-6-phosphate dehydrogenase, a cytosol marker, was detected (Table 1).

	State 3	State 4	RCR	% F - ATPase azide sensitive	G6PDH (U/mg protein)
Homogenate	---	---	---	49.50 %	2.9 $\pm$ 0.4
Mitochondrial fraction	30.2 $\pm$ 3.2	4.6 $\pm$ 0.7	6.5 $\pm$ 0.4	83.45 %	---

Table 1. Mitochondrial characterization

Once the mitochondria were characterized, mitochondria in eggs in the segmentation stage (ninth day after oviposition) were isolated and exopolyphosphatase activity was measured in order to evaluate the regulation of its activity. The influence of NADH, phosphate, and ADP was investigated in concentrations ranging from 0.1 to 2.0 mM. The activity of exopolyphosphatase was stimulated by a factor of two by NADH, whereas its activity was completely inhibited by 2 mM phosphate and slightly stimulated by ADP (Figure 5A). The activity of exopolyphosphatase was also measured during mitochondrial respiration using pyruvate as the substrate and polyphosphate as the only phosphate source. During this assay, the addition of a small amounts of ADP (0.2 mM) induced state 3 (phosphorylating respiratory rate) followed by state 4 (non-phosphorylating respiratory rate), when all of the ADP was converted to ATP.

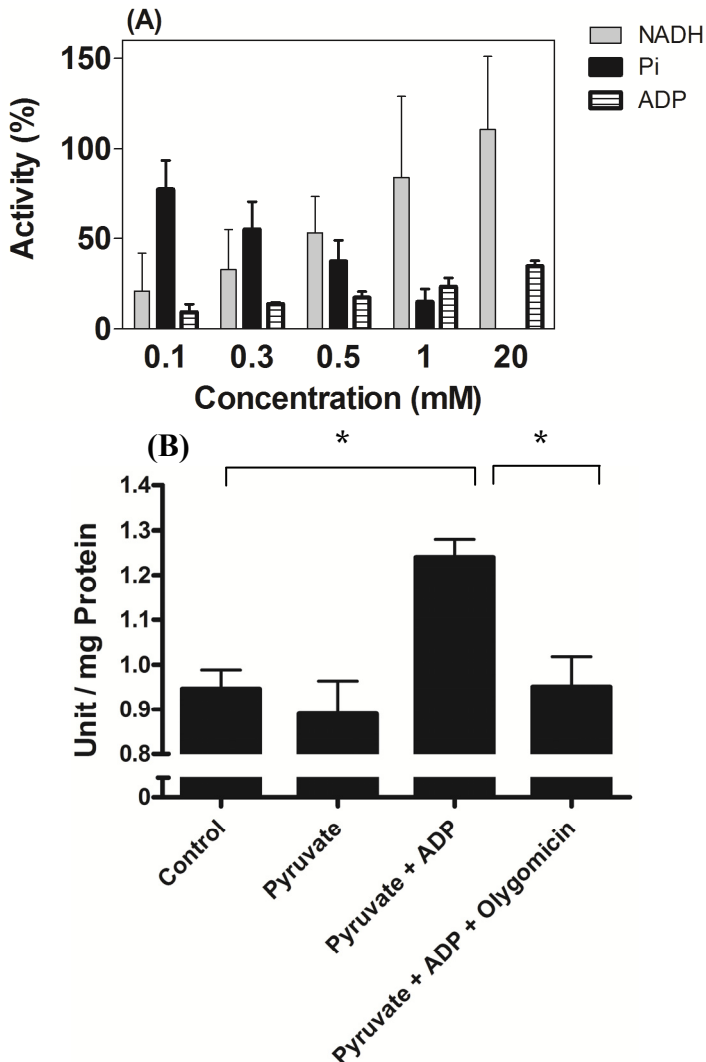


Fig. 5. In (A), Mitochondrial exopolyphosphatase activity in *R. microplus* embryos. Mitochondria from eggs on the ninth day of embryogenesis were isolated and exopolyphosphatase activity was determined using polyphosphate<sub>3</sub> in the presence of 0.1–2 mM NADH, ADP and Pi. The results represent the mean  $\pm$ SD of three independent experiments, in triplicate. B) Exopolyphosphatase activity was measured in the mitochondria of eggs on the ninth day of development during mitochondrial respiration with pyruvate as the oxidative substrate, polyphosphate<sub>3</sub> as the exopolyphosphatase substrate and olygomycin as ATP synthase. The activity is expressed as units per milligram of total protein and the results represent the mean  $\pm$  SD of three independent experiments, in triplicate. The asterisk (\*) denotes the difference between the populations and the significance was determined by a two-way ANOVA test (Kruskal-Wallis).



Thus, during state 3, a balance existed between the release of phosphate by exopolyphosphatase and ATP synthesis, since exopolyphosphatase activity was measured by the amount of phosphate present. The exopolyphosphatase activity increased during mitochondrial respiration when pyruvate and ADP were added. This increase did not occur without the addition of ADP, indicating that exopolyphosphatase is stimulated during state 3 and that the rate of phosphate release is higher than the rate of ATP synthesis. Indeed, the stimulatory effect was antagonized by oligomycin, an ATP synthase inhibitor (Figure 5B). These data suggest that mitochondrial exopolyphosphatase activity is regulated by phosphate and the energy demand.

Furthermore, it was possible to measure ADP-dependent mitochondrial oxygen consumption in the presence of polyphosphate and in the absence of any other phosphate source. This oxygen consumption was observed using polyphosphate<sub>3</sub> and polyphosphate<sub>15</sub>; however, the consumption was higher with polyphosphate<sub>3</sub>. On the other hand, heparin, an exopolyphosphatase inhibitor, blocked oxygen consumption, which was recovered when 5 mM phosphate was added and was again interrupted by the addition of oligomycin, an ATP-synthase inhibitor (Figure 6). These results suggest that polyphosphate was used as a phosphate donor for ATP synthesis due to the mitochondrial coupling observed when mitochondrial respiration was interrupted by oligomycin and the existence of membrane exopolyphosphatase in this process, due to the inhibition by heparin, which cannot cross the mitochondrial membrane and has its active site oriented toward the external face of the membrane. In fact, after mitochondrial subfractionation, the main exopolyphosphatase activity was recovered in the membrane fraction, supporting this hypothesis (Table 2).

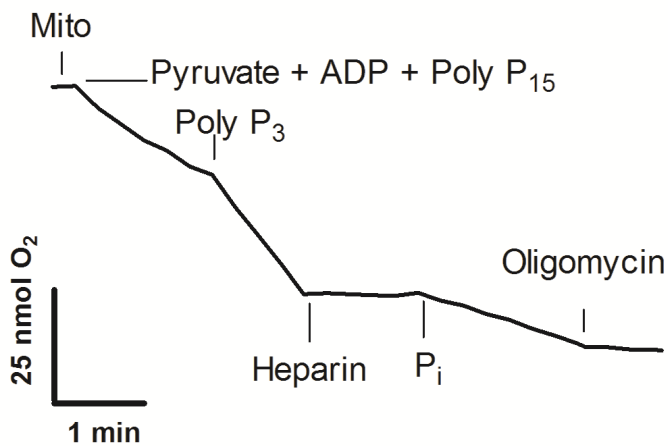


Fig. 6. Polyphosphate as a source for ATP synthesis. Oxygen consumption was monitored using a reaction buffer in the absence of a phosphate source in the eggs on the ninth day of development. The addition of 1 mM ADP, 5 mM pyruvate, 0.5  $\mu$ M polyphosphate<sub>3</sub> and <sub>15</sub>, 20  $\mu$ g/mL heparin, 5 mM phosphate and 0.5  $\mu$ M oligomycin is represented in the figure. This experiment was repeated at least three times with different preparations, and this figure shows a representative experiment.

	Exopolyphosphatase activity (U / mg protein)	Heparin (% inhibition)
Mitochondria	0.60 ± 0.19	98
Soluble fraction (intermembrane space and matrix)	0.35 ± 0.06	98
Membrane fraction (mixture of inner and outer membranes)	1.11 ± 0.16	98

Table 2. Exopolyphosphatase activity in mitochondrial preparations. Exopolyphosphatase activity was measured using eggs on the ninth day of development using polyphosphate<sub>3</sub> as the substrate. The activity is expressed as units per milligram of total protein and the results represent the mean ± SD of three independent experiments, in triplicate.

### 2.1.1 A mitochondrial membrane exopolyphosphatase

Exopolyphosphatases have been found in prokaryotes and eukaryotes and, although in bacteria these enzymes mostly hydrolyze high molecular weight polyphosphates (Kumble & Kornberg, 1996), at least some of the enzymes from *Saccharomyces cerevisiae* and *Leishmania major* are more active in hydrolyzing short chain polyphosphates, such as polyphosphate<sub>3</sub> (Kumble & Kornberg, 1996; Rodrigues et al., 2002). Exopolyphosphatase from *Escherichia coli* requires divalent cations and K<sup>+</sup> for maximum activity, while exopolyphosphatase from yeast only requires divalent cations (Lichko et al., 2003). Membrane mitochondrial exopolyphosphatase activity from the hard tick *R. microplus* was found to be stimulated by Mg<sup>2+</sup> and was insensitive to K<sup>+</sup>. Only a few compounds that inhibit exopolyphosphatase have been identified (Kornberg et al., 1999): treatment with molybdate (a common phosphohydrolase inhibitor) and fluoride (a pyrophosphatase inhibitor) showed that exopolyphosphatase present in the mitochondrial membrane fractions was insensitive to these compounds. However, heparin, a good inhibitor of other well-characterized exopolyphosphatases (Lichko et al., 2003), was effective in almost 100% (Figure 7). In order to obtain an insight into membrane exopolyphosphatase kinetics, the apparent *K<sub>m</sub>* was measured using polyphosphate<sub>3</sub> and polyphosphate<sub>15</sub> as substrates and the results were expressed as the average of three independent experiments. The membrane exopolyphosphatase affinity for polyphosphate<sub>3</sub> was 10 times stronger than for polyphosphate<sub>15</sub> (Table 3). These results are in contrast with those found in a mitochondrial membrane-bound exopolyphosphatase of *Saccharomyces cerevisiae*, in which case the affinity was stronger for long-chain polyphosphates (Lichko et al., 1998). However, the data demonstrated that membrane exopolyphosphatase kinetics were in agreement with the oxygen consumption rate, which was much higher for polyphosphate<sub>3</sub> than polyphosphate<sub>15</sub>. These results reinforce the theory of coupling between the activity of this enzyme and mitochondrial ADP phosphorylation (Figure 8).

Substrates	<i>K<sub>m</sub></i> (μM)	<i>V<sub>max</sub></i> (μmol min <sup>-1</sup> mg protein <sup>-1</sup> )
PolyP <sub>3</sub>	0.2	2.4
PolyP <sub>15</sub>	2.2	1.1

Table 3. Kinetics characterization of exopolyphosphatase activity in membrane preparations of mitochondria from *R. microplus* embryos on the ninth day of embryogenesis.

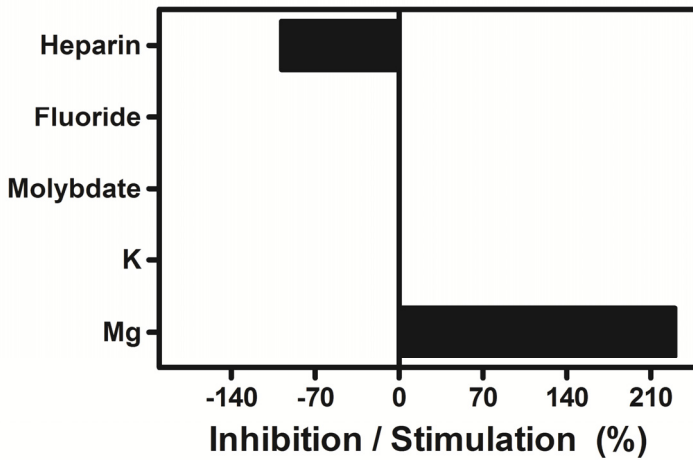
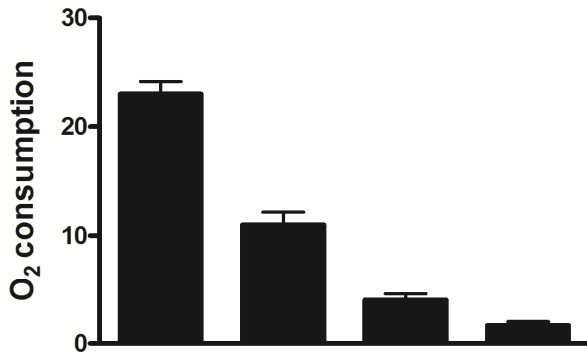


Fig. 7. The effect of some reagents on membrane exopolyphosphatase activity. Mitochondrial membrane fractions of *R. microplus* embryos in eggs on the ninth day of embryogenesis were isolated and the membrane exopolyphosphatase activity was determined using polyphosphate<sub>3</sub> as the substrate in the presence of 2.5 mM Mg<sup>2+</sup>, 50-200 mM K<sup>+</sup>, 10-100 μM molybdate, 1-10 mM NaF and 20μg/mL heparin.



Pyruvate	+	+	+	+
ADP	+	+	-	-
polyP <sub>3</sub>	+	-	+	-
polyP <sub>15</sub>	-	+	-	+

Fig. 8. Involvement of membrane exopolyphosphatase in mitochondrial respiration. Oxygen consumption was monitored using a reaction buffer in the absence of a phosphate source in the eggs on the ninth day of development in the presence of 1 mM ADP, 5 mM pyruvate, and 0.5 μM polyphosphate<sub>3</sub> and <sub>15</sub>. The results represent the mean ± SD of three independent experiments, in triplicate.

To further investigate the regulation of membrane exopolyphosphatase during mitochondrial respiration, the activity was measured using pyruvate as the substrate and polyphosphate as the only source of phosphate. Membrane exopolyphosphatase activity increased during mitochondrial respiration when pyruvate and ADP were added and the stimulatory effect was antagonized by potassium cyanide addition (decreased electron flux) and increased by protonophore carbonyl cyanide-p-trifluoromethoxyphenylhydrazone (increased electron flux), suggesting that membrane exopolyphosphatase could be modulated by the electron flux (Figure 9). These findings are consistent with those of Pavlov et al., 2010, who demonstrated that the production and consumption of mitochondrial polyphosphate depends on the activity of the oxidative phosphorylation machinery in mammalian cells. Furthermore, heparin completely inhibited exopolyphosphatase activity, reinforcing the role of membrane exopolyphosphatase during mitochondrial respiration, and the respiration activation by membrane exopolyphosphatase activity indicated that exopolyphosphatase could be close to the site of ATP production.

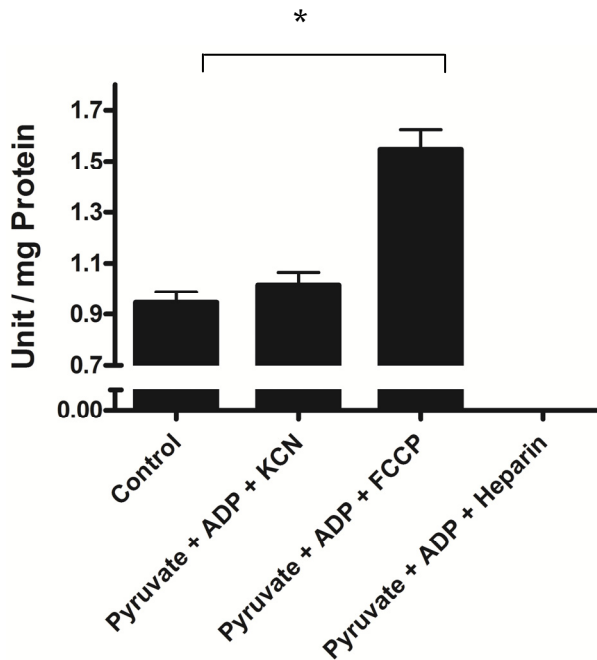


Fig. 9. Regulation of mitochondrial exopolyphosphatase activity during mitochondrial respiration. The activity of exopolyphosphatase was measured in the mitochondria of the eggs on the ninth day of development during mitochondrial respiration, using pyruvate as the oxidative substrate, polyphosphate<sub>3</sub> as the exopolyphosphatase substrate, KCN as the respiratory chain inhibitor, FCCP as the un-coupler and heparin as the exopolyphosphatase inhibitor. The activity was expressed as units per milligram of total protein and the results represent the mean  $\pm$  SD of three independent experiments, in triplicate. The asterisk (\*) denotes the difference between the populations and the significance was determined by a two-way ANOVA test (Kruskal-Wallis).

Despite the regulation of membrane exopolyphosphatase by an increased or decreased electron flux, the sensitivity of this enzyme according to the redox state using polyphosphate<sub>3</sub> as the substrate was evaluated. The influence of 1.0 mM dithiothreitol (DTT) and 1.0 mM hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) was investigated at different times and the exopolyphosphatase activity was stimulated and inhibited by 50% of both, suggesting that exopolyphosphatase is tightly regulated by the redox state (Figure 10).

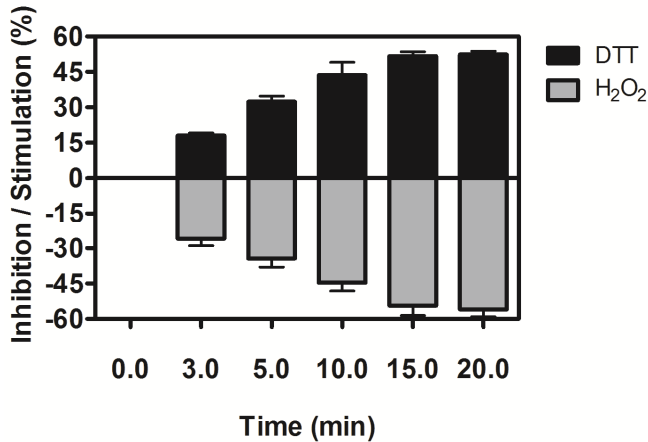


Fig. 10. The redox regulation of mitochondrial membrane exopolyphosphatase. Exopolyphosphatase activity was measured in the mitochondria of the eggs on the ninth day of development using polyphosphate<sub>3</sub> as the substrate. The mitochondria were treated with 1 mM DTT and 1 mM H<sub>2</sub>O<sub>2</sub> for 0–20 min. The results represent the mean ± SD of three independent experiments, in triplicate.

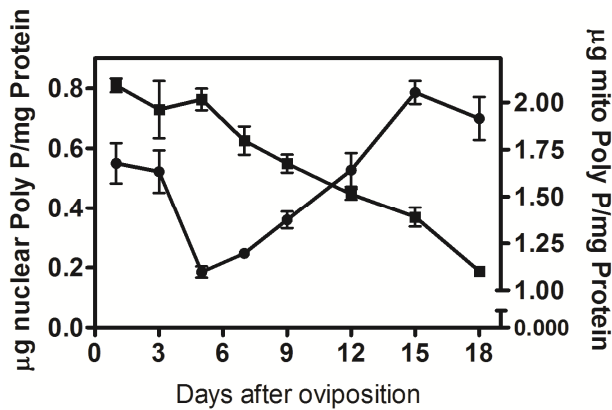


Fig. 11. Polyphosphate quantification in the nuclear and mitochondrial fractions. Polyphosphate levels during embryogenesis in the nuclear fraction (■) and mitochondrial fraction (●) during embryogenesis. The results represent the mean ± SD of three independent experiments, in triplicate.

Additionally, mitochondrial polyphosphate can form polyphosphate/ $\text{Ca}^{2+}$ /PHB complexes (Reusch, 1989) with ion-conducting properties similar to those of the native mitochondrial permeability transition pore (Pavlov et al., 2005). Polyphosphatases localized in the membrane can not only degrade, but they can also synthesize polyphosphate inside these complexes (Lichko et al., 1998). During the embryogenesis of *R. microplus*, the synthesis of polyphosphate occurs in mitochondria but not in the nuclei (Figure 11). As polyphosphate kinases have only been found in prokaryotes, the observation that polyphosphate synthesis in ticks only occurs in the mitochondrial fraction supports the possibility that such synthesis probably occurs via the action of these complexes, as already suggested for other organisms (Reusch and Sadoff, 1988; Lichko et al., 1998; Reusch et al., 1998; Abramov et al., 2007).

### 3. Conclusion

The ubiquity of polyphosphate and the variation in its chain length, location and metabolism indicate the relevant functions of this polymer, including those in animal systems. The present study showed that electron flux and the redox state may exert some influence on and be influenced by the activity of membrane exopolyphosphatase, and it describes a role for polyphosphate in the energy supply and ATP synthesis during embryogenesis of the hard tick *R. microplus*. In this sense, a more comprehensive understanding of polyphosphate biochemistry during tick embryo development may unravel additional targets that could be effective in the control of this ectoparasite and shed new light on polyphosphate metabolism.

### 4. Acknowledgment

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## **Part 2**

# **Reviews of Bioenergetics Applied to Performance Optimization**



# Bioenergetics Applied to Swimming: An Ecological Method to Monitor and Prescribe Training

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## 1. Introduction

Systematic assessments of athletes' physiological conditions are central to monitor and prescribe swimming training according to the needs and goals. Thus, it is possible to understand the current physiological state and follow its development in order to assess the effects of training, to identify the swimmer's skills profile and to predict athletic performance (Vilas-Boas & Lamares 1997). Specifically regarding swimmers and their skills, aerobic capacity is a major determinant of these athletes performance, and it is defined as the ability to maintain a high percentage of maximal oxygen uptake ( $VO_{2max}$ ) for a long period of time (DI PRAMPERO et al., 2011). Furthermore, the endurance is influenced by  $VO_{2max}$ , swimming economy (or energy cost, defined as the total energy expenditure required to move the body to a certain distance in a determined velocity) and anaerobic capacity (Dekerle & Pelayo 2011). In a group of swimmers with similar values of swimming economy and anaerobic capacity, those with greater aerobic potential ( $VO_{2max}$  and aerobic capacity) will be faster at distances of 400 m and longer. Four hundred meters, when swimming in front *crawl*, is usually suggested as a trial in which  $VO_{2max}$  is reached (Dekerle & Pelayo 2011). Thus, the longer events (800 m, 1500 m and open water marathon), which are covered primarily with energy from aerobic metabolism, are covered in a fraction of the  $VO_{2max}$ . The intensity will be lower the longer is the distance, reaching 60-65% of  $VO_{2max}$  on the 25 km open water marathon (Zamparo et al. 2005). In this sense, one of the objectives of the swimming training is to increase the aerobic capacity. Thus, a valid and reliable measure of the swimmer aerobic profile is essential to verify the benefits that the training program is or is not providing, and, also, to set training intensities according to the physiological profile of the athlete. Dekerle & Pelayo (2011) emphasize that the methodology used for this purpose cannot be considered valid unless it is reliable. Whenever possible, the degree of reliability should be assessed. The origin of the variability measurement (human error, equipment error, biological variation, or motivational factors when performing the test) needs to be taken into account. Thus, the aim of this chapter is to present a careful review of the bioenergetics contribution on the physiological assessment of the swimmer, especially related to aerobic profile.

## 2. Critical velocity (CV)

The performance achieved in competitions is an important setting information from training sessions in swimmers (Sweetenham & Atkinson, 2003). However, constant evaluations are necessities during the cycles and training sessions in order to verify the effectiveness of training and ensure the best performance in the competition (Sweetenham & Atkinson, 2003). Physiological and biomechanical swimmers conditions' knowledge is crucial to implement and/or to control the training processes that surround them (Pyne et al. 2001). These assessments can be applied in the field of competitive and / or recreational swimming. Tests used to evaluate and determine swimming speeds (SS) for the development of aerobic endurance training can be divided into invasive and noninvasive (Pyne et al. 2001), based on the relationship between oxygen consumption ( $\text{VO}_2$ ), blood lactate concentration ([La]), heart rate (HR) and SS (Vilas-Boas & Lamares 1997). Although the precision provided by some of these tests, which require invasive sampling, such as those using the [La], ethical conflicts may arise (Heck et al. 1985), especially when applied to children. Moreover, it is common a high number of athletes to be evaluated in a training session by only one coach, so that they may require a longer period for implementation. Another limiting factor is the high cost for each testing session (Heck et al. 1985).

Considering these difficulties, the tests that verify the SS in durations of 30 ( $T_{30}$ ) and 60 ( $T_{60}$ ) minutes (Olbrecht et al. 1985; Madsen 1982) or even over distances of 2000 m ( $T_{2000}$ ) (Touretski 1993) and 3000 m ( $T_{3000}$ ) (Madsen 1982), the perceived exertion (PE) (Lima et al. 2006), the critical velocity (CV) (Ettema 1966) and 400 m testing ( $T_{400}$ ) (Wakayoshi et al. 1993a; Dekerle et al. 2006; Alberty et al. 2006; Pelayo et al. 2007) have been widely disseminated in swimming. However,  $T_{30}$ ,  $T_{60}$ ,  $T_{2000}$  and  $T_{3000}$  can provide very subjective information to determine training intensities in young and/or low level of experience swimmers. These protocols require the maintenance of a given SS for a long time require psychological and physiological capacity compatible with the demands of the test (Zacca & Castro 2008, 2009). Regarding the PE, the athlete needs good training base to swim extensive sets with minimal adjustments in intensity between each repetition (Zacca & Castro 2008, 2009). In this sense, determination of SS for swimming training through the CV (Dekerle et al. 2006; Greco et al. 2008; Leclair et al. 2008; Vandewalle et al. 2008) seems to correspond to these swimmers profiles. CV's use is also justified due to the low cost and facility to apply in various populations. Another advantage is that CV is able to be gotten even during competitions (Vilas-Boas & Lamares 1997).

Since Hill (1927), it is accepted that the relationship between power output and time to exhaustion is a hyperbole. The asymptote of this relationship of power (critical power or PC) is equivalent to the slope of the regression line related to the work and time to exhaustion (time limit or *tlim*) (Monod & Scherrer 1965). Since then, CP represents, at least theoretically, the largest power that could be sustained, whose energy would be derived preferably by the aerobic metabolism without fatigue, and is suggested as a good performance index in events of long duration (Vandewalle et al. 1997).

Ettema (1966) applied the CP concept in cyclists, swimmers, speed skaters and runners. Instead of power and work, the author used speed (S) and distance limit (*dlim*), respectively. The hyperbolic relationship between S and *tlim* (Hill 1927) and the linear relationship between *dlim* and *tlim* (Equation 1), usually called critical velocity (CV), have the same physiological meaning of CP (Pepper et al. 1992; Housh et al. 2001).

In Equation 1, the slope of the regression line corresponds to CV (obtained through a two-parameter model,  $CV_{2par}$ ), the y-intercept (second parameter) is mathematically defined as a finite stock of reserve power available pre-exercise (Ettema 1966; Wakayoshi et al. 1992), usually referred as "anaerobic distance capacity" ( $ADC_{2par}$ ).

$$dlim = CV_{2par} \cdot tlim + ADC_{2par} \tag{1}$$

The non-linear SS-time limit to exhaustion ("SS-*tlim*"), the linear relationship between distance limit and time limit (*dlim-tlim*) and the linear relationship between SS and the inverse of *tlim* (Equation 2) are two-parameter models commonly used to estimate the VC (Billat et al. 1999; Housh et al. 2001; Whipp et al. 1982).

$$SS = \frac{ADC_{2par}}{tlim} + CV_{2par} \tag{2}$$

Equation 2 shows that the CV can be obtained by expressing SS as a function of *tlim* (Ettema 1966). In order to revise the statement that in the hyperbolic model SS is infinite when time approaches zero, Morton (1996) proposed a mathematical model including an additional parameter representing the maximum instantaneous velocity ( $V_{max}$  obtained from a three-parameter model,  $V_{max3par}$ ).

$V_{max3par}$  allows a time asymptote (*tlim*) which is below the x-axis where *tlim* is zero, thus providing a  $V_{max}$  in the y-intercept (Morton 1996). Equation 3 expresses SS as a function of *tlim* (Zacca et al. 2010; adapted from Morton 1996).

$$SS = \frac{ADC_{3par}}{tlim + \frac{ADC_{3par}}{V_{max3par} - CV_{3par}}} + CV_{3par} \tag{3}$$

Where SS is the swimming speed, *tlim* is the time limit and  $ADC_{3par}$ ,  $V_{max3par}$  and  $CV_{3par}$  are the parameters. The fact that two-parameter model assumes that there is no upper limit for power output or SS (Morton et al. 1996; Dekerle et al. 2006) leads some authors choose three-parameter models (Gaesser et al. 1995; Bull et al. 2000; Hill et al. 2003).

However, both (two and three parameters) models have an important limitation: they do not take into account the "aerobic inertia" ( $\tau$ ) (Wilkie 1980; Vandewalle et al. 1989), regarding to the cardio respiratory adjustments for the  $VO_2$  reaches the steady state or maximum value. Thus, a four-parameter model ( $CV_{4par}$ ,  $CDA_{4par}$ ,  $V_{max4par}$  and  $\tau$ ) as proposed by Zacca et al. (2010) could provide more information on bioenergetics in sports (Equation 4).

$$SS = \frac{ADC_{4par}}{tlim + \frac{ADC_{4par}}{V_{max4par} - CV_{4par} \left( 1 - e^{-\frac{tlim}{\tau}} \right)}} + CV_{4par} \left( 1 - e^{-\frac{tlim}{\tau}} \right) \tag{4}$$

Zacca et al. (2010) proposed to plot *tlim* and SS values using a four-parameter model (Equation 4). The CV was corrected on this model by an exponential factor, proposed by Wilkie (1980). This exponential factor represents the time constant of the increased aerobic

involvement, called "aerobic inertia" ( $\tau$ ), understood as a temporary delay in the response of  $\text{VO}_2$ , caused by dissociation of  $\text{O}_2$  absorbed in lungs and used especially by skeletal muscle. The use of CV in swimming training is suggested since 1966 (Ettema 1966). Studies by researchers about its use continue to be published (Dekerle & Pelayo 2011).

### 3. Intensity domains (training zones)

Some authors (Gaesser et al. 1996; Greco et al. 2008) suggest a range of intensities of three domains (sometimes referred as training zones) and others (Dekerle & Pelayo 2011) a scale of five domains and their physiological effects. According to Table 1, exercise can be conducted in three different intensity domains, resulting in very distinctive physiological effects in each of these domains (Gaesser et al. 1996; Greco et al. 2008).

Intensity domains	Effects
SEVERE	<ul style="list-style-type: none"> <li>• There is no variable metabolic stabilization;</li> <li>• Accumulation and increase of lactate / pyruvate relationship and increase of protons concentration <math>[\text{H}^+]</math>;</li> <li>• <math>\text{VO}_2</math> increases toward the maximum.</li> </ul>
HEAVY	<ul style="list-style-type: none"> <li>• <math>[\text{La}]</math> stabilizes at high values of concentration</li> <li>• The efficiency appears to be lower;</li> <li>• High <math>\text{VO}_2</math> values (development of a slow component);</li> <li>• It is still possible to maintain a stable physiological state and perform the exercise for a longer period.</li> </ul>
MODERATE	<ul style="list-style-type: none"> <li>• <math>[\text{La}]</math> stabilizes quickly;</li> <li>• <math>\text{VO}_2</math> has a quick adjustment;</li> <li>• The individual can maintain this intensity for hours without exhaustion.</li> </ul>

Table 1. Intensity domains and their physiological effects (Gaesser et al. 1996; Greco et al. 2008)

#### 3.1 Moderate intensity domain

$[\text{La}]$  stabilizes quickly and can be maintained almost similar to resting levels. Similarly,  $\text{VO}_2$  shows a quick set (1-3 min) before stabilization, and the individual can maintain the intensity for hours without exhaustion. The main explanation for the "end" of the exercise refers to substrate depletion (muscle and liver glycogen), changes related to hydration and electrolytes or problems related to the process of thermoregulation (Greco et al. 2008).

#### 3.2 Heavy intensity domain

Production and removal rates of lactate levels are high due to a high metabolic demand. Consequently,  $[\text{La}]$  tends to stabilize at higher concentrations when compared to exercise at moderate intensity. Moreover, the efficiency of the specific motor gesture seems to be smaller, generating higher  $\text{VO}_2$  values than the linear relationship between  $\text{VO}_2$  and exercise intensity that characterizes the Moderate intensity domain (development of a slow

component of  $VO_2$ ). Although the metabolic stress is high, it is possible to maintain a state of physiological balance and to perform the exercise for a long period (Greco et al. 2008). However, Baron et al. (2008) found exercise performed at maximum intensity possible to maintain the stabilization of the  $[La]$ , i.e., in the maximal lactate steady state (MLSS), depletion occurred while physiological reserve capacity still existed, but in association with an increase in PE assessments, as predicted by the central regulator model (Noakes & St Clair Gibson 2004; Noakes et al. 2005). The end of the exercise could then be induced by an integrative homeostatic control of peripheral physiological system to ensure specifically the maintenance of homeostasis.

**3.3 Severe intensity domain**

There is no stabilization in metabolic variables. Specifically, the rate of lactate production is greater than the rate of removal, with a consequent increase in the accumulation and the relationship between lactate and pyruvate and the concentration of protons ( $[H^+]$ ) (Greco et al. 2008). At the same time,  $VO_2$  increases towards to its maximum ( $VO_{2max}$ ) and the amplitude of the slow component is much higher than those that characterize the heavy intensity exercise (Xu & Rhodes 1999). This reduces exercise tolerance, with *tlim* related to the cellular level of disturbance (metabolites production and removal rates), caused by high demand of muscle adenosine 3-phosphate (ATP) (Greco et al. 2008).

**3.4 Scale of five intensity domains proposed by Dekerle & Pelayo (2011)**

Dekerle & Pelayo (2011) propose a scale of five domains and their physiological effects. On this scale, lactate threshold (LT), MLSS and  $CV_{2par}$  can be understood as boundaries that demarcate some intensity domains. Figure 1 shows the five intensity domains proposed by Dekerle & Pelayo (2011), in which the behavior of  $[La]$  and  $VO_2$  is illustrated in each domain.

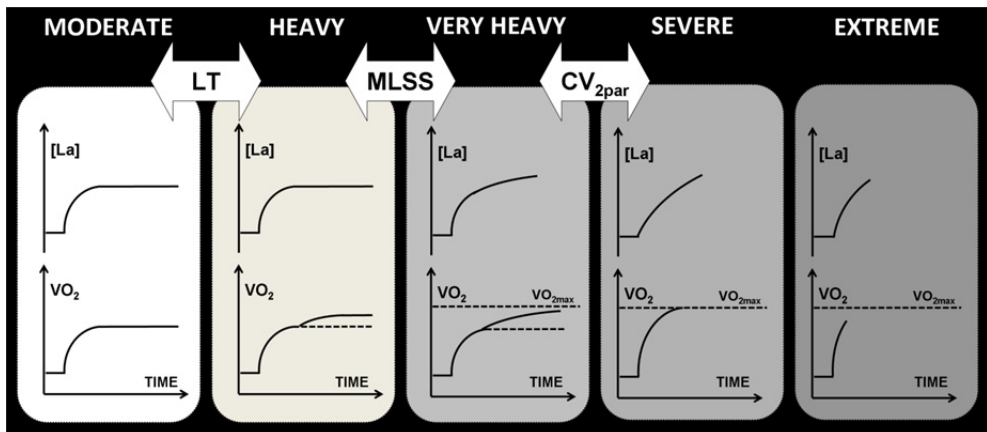


Fig. 1. Intensity domains (adapted from Dekerle & Pelayo 2011) and the response of each to  $[La]$  and  $VO_2$  kinetics during exercise in different SS.

Each of the five intensity domains (Dekerle & Pelayo, 2011) is characterized by acute specific physiological responses. Dekerle & Pelayo (2011) establish the lactate threshold (LT) as the boundary between moderate and heavy domain. The LT is defined as the first increase in lactate response to an incremental test (Wasserman et al. 1990).

#### 3.4.1 Heavy intensity domain

The exercise is performed in intensity very close to the LT, but a little higher, which causes a small increase in [La] (no more than 1 mmol·l<sup>-1</sup>) in the first minutes, with subsequent stabilization close to resting levels ( $\approx 2.1$  mmol·l<sup>-1</sup>). The maximum exercise intensity at which [La] stabilization occurs is defined as maximal lactate steady state (MLSS,  $\approx 3$ -5 mmol·l<sup>-1</sup>) (Beneke, 1995). The MLSS is the heavy intensity domain upper limit (Barstow 1994). The intensity corresponding to LT can be maintained for a very long period (e.g. aquatic marathons) and occurs at a slower speed when compared to MLSS ( $t_{lim} \approx 60$  min). MLSS is located in the smaller SS than CV<sub>2par</sub> ( $t_{lim} \approx 14.3$  to 39.4 min). Importantly, for being difficult to detect the MLSS through the curve obtained in [La] and SS, and also to avoid any misinterpretation, the term "anaerobic threshold" should not be associated to the MLSS. Swimming in a very low SS is a difficult task ( $<0.4$  to  $0.5$  m·s<sup>-1</sup> or 50-60% of V<sub>400</sub> -average speed of 400 m front *crawl* in maximal effort). Thus, the lowest speed that can be adopted by swimmers using a good technique, it is almost equal to LT (Dekerle & Pelayo 2011).

#### 3.4.2 Severe intensity domain

In SS above the MLSS (heavy intensity domain upper limit) there is an increase in [La], HR and VO<sub>2</sub> (occurrence of the slow component). Initially, it was suggested that the increase in VO<sub>2</sub> in these intensities reach the maximum (VO<sub>2max</sub>) before exhaustion, which characterizes the severe intensity domain). This statement is controversial and difficult to investigate because of the low reliability of time to exhaustion obtained in constant intensity tests (variability of  $t_{lim}$ ) (Hinckson & Hopkins, 2005). The SS equivalent to the Severe intensity domain includes performances of approximately 2 to 60 minutes (VO<sub>2max</sub> reaching the end of the exercise) with the performance of 400 m in front *crawl*, the maximum aerobic speed (MAS) and CV<sub>2par</sub> lying within that domain (Lavoie & Montpetit et al 1981; Lavoie et al. 1983; Lavoie & Leone 1988; Rodrigues 2000; Pelayo et al. 2007; Billat et al. 2000; Dekerle et al. 2010).

#### 3.4.3 Extreme intensity domain

This domain includes performances of very short duration ( $< 2$  min). Due to the limited response of VO<sub>2</sub>, VO<sub>2max</sub> is not reached during exercise, although the task is performed to exhaustion.

#### 3.4.4 Very heavy intensity domain

Dekerle & Pelayo (2011) suggest the subdivision of Heavy intensity domain. According to these authors, the range of effort associated to this area is wide (performances of  $\approx 2$  to 60 min) and associated with many chronic responses to training, i.e., the physiological adaptations of a training period in SS near the MLSS are different from the training adaptations induced by a training period in MAS or above.



In addition, the physiological responses to swimming at intensities equal to or above the MLSS are still unclear, since it is not certain that  $VO_{2max}$  is reached. Thus, it is justifiable to establish at least one domain between the MLSS and  $CV_{2par}$ : the “very heavy intensity domain”. Thus, exercise performed in this domain (very heavy) suggests an increase in [La] and the occurrence of the  $VO_2$  slow component, but without reaching  $VO_{2max}$  in the end of the exercise (Dekerle et al. 2010).  $VO_{2max}$  would only be achieved if the exercise was conducted in intensity above  $CV_{2par}$  and continued until exhaustion (featuring the severe domain). Thus,  $CV_{2par}$  represents the boundary between very heavy and severe intensity domain. However, Dekerle & Pelayo (2011) suggest that more experiments are needed in these models of training zones. As a result, coaches and swimmers will be able to use them with a greater degree of reliability.

Based on the information presented, it is believed that the model of five intensity domains proposed by Dekerle & Pelayo (2011) best describes the physiological responses to exercise in different intensities.

## 4. Physiological meaning of each parameter

### 4.1 Two-parameter model

#### 4.1.1 Critical Speed ( $CV_{2par}$ )

PC was used initially to determine exercise intensity that could be theoretically maintained for a long period of time without exhaustion (Monod & Scherrer 1965). CP (or CV in running or swimming) proved to be valid for aerobic capacity prediction (Dekerle et al. 2005a) and sensitive to physiological changes from aerobic training programs (Jenkins & Quigley, 1991). CP or CV determined by two-parameter model ( $CP_{2par}$  or  $CV_{2par}$ ) represents the lower boundary of the severe intensity domain (Poole et al. 1990; Hill & Ferguson 1999). Poole et al. (1990) found that when subjects performed exercise intensity on  $CP_{2par}$ ,  $VO_2$  stabilized around 75% $VO_{2max}$ . In addition, studies have investigated the hyperbolic relationship between power and time to achieve  $VO_{2max}$ . The results also suggest that this relationship is the lower boundary of the severe intensity domain, or  $CP_{2par}$  (or  $CV_{2par}$ ) (Hill & Smith 1999; Hill & Ferguson 1999). Thus,  $CV_{2par}$  can determine the exercise intensity equivalent to the lower boundary of the severe intensity domain.

#### 4.1.2 Anaerobic distance capacity ( $ADC_{2par}$ )

The physiological meaning of  $ADC_{2par}$  is still subject of many studies (Moritani et al. 1981; Green et al. 1994; Miura et al. 2000; Heubert et al. 2005). Evidence trying to suggest the  $ADC_{2par}$  anaerobic nature was observed in cyclists (Green et al. 1994). Also in cyclists, Heubert et al. (2005) found a decrease of 60 to 70% in  $ADC_{2par}$  values as a result of a 7 s maximal effort performed before a protocol of four exercises at constant intensity (95, 100, 110 and 115% $VO_{2max}$ ) and to determine the  $ADC_{2par}$  and  $CP_{2par}$ .  $CP_{2par}$  values did not change. Moritani et al. (1981) also found no differences in  $ADC_{2par}$  values in response to ischemia, hypoxia and hyperoxia. In relation to prior depletion of glycogen, Miura et al. (2000) found a decrease in  $ADC_{2par}$  values (in cycle ergometer). Jenkins & Quigley (1993) found an increase in  $ADC_{2par}$  values in response to high-intensity training in untrained individuals, but the  $CP_{2par}$  values did not change.  $ADC_{2par}$  values also showed increases in response to creatine supplementation (Miura et al. 1999) and demonstrated good correlation with predominantly anaerobic exercises (Vandewalle et al. 1989; Jenkins & Quigley 1991; Hill 1993; Dekerle et al. 2005b).

## 4.2 Three-parameter model

### 4.2.1 Critical Velocity ( $VC_{3par}$ )

The oxygen supply spends a period of time to reach a steady state or maximum. This has led some researchers (Vandewalle et al. 1989; Morton 1996) questioned the "immediate" availability of CV in two-parameter models ( $CV_{2par}$ ). As a result of this lapse of time, probably  $CV_{2par}$  was being overestimated. In addition, studies found that  $CV_{2par}$  could be sustained only by 14.3 to 39.4 min by swimmers (Dekerle et al. 2010). These results suggest that the concept of  $CV_{2par}$  as a speed that could be sustained infinitely would not be appropriate.

There is little information on CV and the type of mathematical model used to obtain it in sports. Morton (1996) suggests that  $CV_{2par}$  values may be overestimated. Gaesser et al. (1996) also found that three-parameter model generated CP values ( $CP_{3par}$ ) significantly lower, and the subjects were able to resist in a continuous work for a long period. Thus,  $CV_{3par}$  seems not to be at the lower boundary of the severe intensity domain, requiring further investigation. Probably  $CV_{3par}$  is below the lower boundary of the severe intensity domain.

### 4.2.2 Anaerobic distance capacity ( $ADC_{3par}$ )

Vandewalle et al. (1989) question the assumption that at exhaustion all  $ADC_{2par}$  is used, as theoretically is suggested by two-parameter models. Thus,  $ADC_{2par}$  may be underestimated (Vandewalle et al. 1989; Morton 1996).

### 4.2.3 Maximum instantaneous velocity ( $V_{max3par}$ )

As a result of the lapse of time ("immediate" availability of  $CV_{2par}$ ), Morton (1996) proposed a three-parameter model (Equation 3) which the "maximum instantaneous speed" ( $V_{max3par}$ ) was included (third parameter). With the addition of the parameter  $V_{max3par}$ , the three-parameter model is more accurate in estimating the CV (and therefore ADC) surpassing the initial concept of the relationship velocity-*tlim*, that when *tlim* approaches zero, velocity is infinite (Morton 1996).  $V_{max3par}$  allows a time asymptote below the x-axis, where time = zero, and provides a  $V_{max3par}$  value in the intercept-x (MORTON 1996).

## 4.3 Three-parameter model

### 4.3.1 Critical velocity ( $CV_{4par}$ )

Both models (two and three-parameter models) have an important limitation: do not predict the "aerobic inertia" ( $\tau$ ) (Wilkie 1980; Vandewalle et al. 1989), related to cardio respiratory adjustments so that the  $VO_2$  reach steady state or maximum. Thus, a four-parameter model ( $CV_{4par}$ ,  $ADC_{4par}$ ,  $V_{max4par}$  and  $\tau$ ) proposed by Zacca et al. (2010) could provide more information on bioenergetics in cyclic sports. The four-parameter model proposed by Zacca et al. (2010) was based on the three-parameter model, and  $CV_{4par}$  was corrected by an exponential factor, first proposed by Wilkie (1980). This exponential factor is theoretically defined as the time constant that describes the increased aerobic involvement, the "aerobic inertia" ( $\tau$ ). Zacca et al. (2010) suggest that CV is sensitive to additional parameters in young swimmers (93% of the variation was explained by the mathematical model used). The effect of the models showed that  $CV_{2par}$  was higher than  $CV_{3par}$  and  $CV_{4par}$ .  $CV_{3par}$  and  $CV_{4par}$  were similar (and therefore the physiological meanings of both models are also similar). Thus, future studies are necessary to understand the physiological meaning of  $CV_{3par}$  and  $CV_{4par}$  in young swimmers and probably in other sports. Figure 2 shows the plot of the data using two, three and four-parameter models with speed and *tlim* data of 50, 100, 200, 300, 400, 800

and 1500 m from swimmers (adapted from Zacca et al. 2010). It is easy to see that the data fits more appropriately in three and four-parameter models. Thus,  $CV_{2par}$  was higher than  $CV_{3par}$  and  $CV_{4par}$ , as previously described.

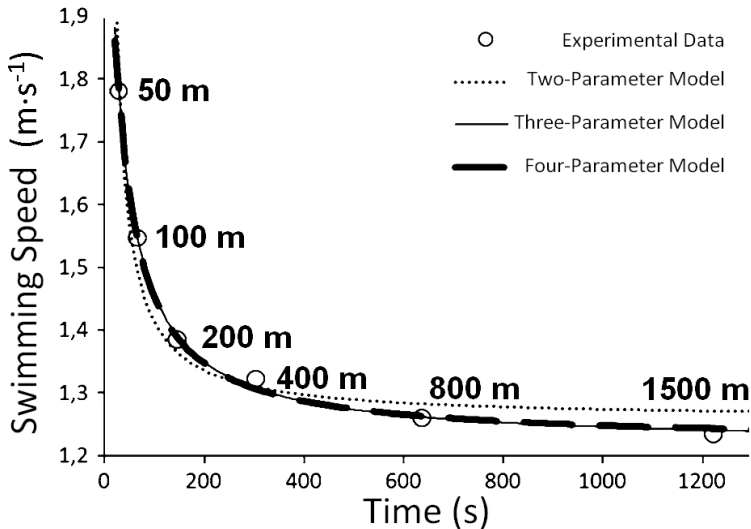


Fig. 2. Swimming speed and time of 50, 100, 200, 300, 400, 800 and 1500 m from sprint swimmers and fitted curves through two, three and four-parameter models (adapted from Zacca et al. 2010).

#### 4.3.2 Anaerobic distance capacity ( $ADC_{4par}$ )

$ADC_{2par}$  was originally defined as the maximum distance (m) that could be covered anaerobically (Ettema 1966). However, Costill (1994) conceptualized  $ADC_{2par}$  as the total work that can be performed by a set of limited power of the human body (phosphagen, anaerobic glycolysis and oxygen reserves) suggesting that the anaerobic energy system is predominant but not exclusive (Gastin 2001). Zacca et al. (2010) compared  $ADC_{2par}$ ,  $ADC_{3par}$  and  $ADC_{4par}$  values. The results showed that  $ADC_{2par}$  ( $13.77 \pm 2.34$  m) was lower than  $ADC_{3par}$  and  $ADC_{4par}$  ( $30.89 \pm 1.70$  and  $27.64 \pm 0.03$  m respectively). Moreover,  $ADC_{3par}$  and  $ADC_{4par}$  values were similar. These results are consistent with others that also observed an overestimation of the parameter ADC in two-parameter model (Billat et al. 2000). Dekerle et al. (2002) evaluated ten well-trained swimmers, when the objective was to verify the possibility of determining  $ADC_{2par}$ . They concluded that  $ADC_{2par}$  is not perfectly linear and is very sensitive to variations in performance. Thus, according to the authors, it is impossible to estimate the anaerobic capacity by two-parameter models. Toussaint et al. (1998) also suggest that the anaerobic capacity in swimming obtained by two-parameter model does not provide an accurate estimate of the real anaerobic capacity. It seems clear that three and four-parameter models seem more suitable to predict ADC.

### 4.3.3 Maximum instantaneous velocity

There are gaps in the literature regarding the prediction of  $V_{\max}$  by mathematical models. Billat et al. (2000) found that  $V_{\max 3\text{par}}$  was not different from the maximum speed obtained in 20 m at maximal effort. However, Bosquet et al. (2006) suggest that  $V_{\max 3\text{par}}$  is smaller than the real  $V_{\max}$  (obtained by the average speed of the last 10 m of a maximal 40 m effort). Zacca et al. (2010) found that  $V_{\max}$  was higher in sprint than endurance swimmers ( $2.53 \pm 0.15 \text{ m s}^{-1}$  and  $2.07 \pm 0.19 \text{ m s}^{-1}$  respectively) independent of the mathematical model used (three or four parameters). In addition,  $V_{\max 4\text{par}}$  was greater than  $V_{\max 3\text{par}}$  ( $2.42 \pm 0.29 \text{ m s}^{-1}$  and  $2.18 \pm 0.34 \text{ m s}^{-1}$  respectively), suggesting future studies to compare  $V_{\max}$  and real  $V_{\max}$ .

### 4.3.4 Aerobic inertia

The two-parameter model given by the relation "SS-*tlim*" (or "D*lim*-*tlim*") and three-parameter model given by the relation "SS-*tlim*" have an important limitation: they do not take into account the "aerobic inertia" ( $\tau$ ) (Wilkie 1980; Vandewalle et al. 1989). The " $\tau$ " is a temporary delay in  $\text{VO}_2$  response because of dissociation between  $\text{O}_2$  absorbed in the lungs and the mainly used by skeletal muscle, lasting approximately 15 to 20 s. " $\tau$ " is associated to vasodilatation, i.e., the time it takes for the body to increase heart rate and redirect blood flow. Studies regarding oxygen kinetics during exercise with children and adolescents is limited to few articles and until recently was based on data collected with adults (FAWKNER & ARMSTRONG 2003). Invernizzi et al. (2008) suggest that the time to reach steady state in  $\text{VO}_2$  after the beginning of the exercise depends on the characteristics of the subject: endurance swimmers reach this balance sooner than sprint swimmers, and children reach earlier than adults. Thus, " $\tau$ " could be a good tool for evaluating cardiovascular and pulmonary performance in athletes (Kilding et al. 2006; Duffield et al. 2007).

## 5. Swimming speeds prescription through a 400 m front *crawl* maximum effort ( $T_{400}$ )

Although many distances used in swimming competition does not exceed 2 min (50, 100 and 200 m), the zone related to  $\text{VO}_2$ , commonly referred as aerobic power, is relevant in swimming (Di Prampero 2003), perhaps because  $T_{400}$  is performed in similar SS reach  $\text{VO}_{2\max}$  (Rodrigues 2000). The concept of aerobic power refers to the rate of oxidative energy synthesis (i.e., the maximum power at which the oxidative system can operate, also known as maximum aerobic speed, MAS), available to the muscle work, which can be measured by  $\text{VO}_{2\max}$ . Measuring  $\text{VO}_{2\max}$  in swimming is always a great challenge (PELAYO et al. 2007). This is due to the fact that conventional techniques interfere in swimming biomechanics (Keskinen et al. 2003; Barbosa et al. 2010), which performs the side breathing impossible, changes can occur in hydrodynamics, and most of the times the turns are not performed (Montpetit et al. 1981). Training programs, in order to develop aerobic power in swimmers, are related to the increase in  $\text{VO}_{2\max}$  and the ability to use a high percentage of  $\text{VO}_{2\max}$  for a long time. Maximal aerobic power is widely used to assess aerobic fitness and training intensities prescription (Lavoie & Montpetit 1986).

In an attempt to find alternatives and make the evaluation of athletes swimming closer to reality applied in swimming pools, several studies have been conducted in order to verify the possibility to prescribe training intensities through a single test, but not so extensive such as  $T_{30}$  (Lavoie et al. 1981; Lavoie et al. 1983; Lavoie & Montpetit 1986; Rodrigues 2000; Takahashi et al. 2002; Takahashi et al. 2003, 2009). The attainment of  $\text{VO}_{2\max}$  values from the

recovery curve of  $VO_2$  (the back extrapolation method proposed by Di Prampero et al. 1976) was first tested on swimmers by Lavoie et al. back in 1983. Lavoie et al. (1983) found a high correlation between  $VO_{2max}$  and  $tlim$  of  $T_{400}$ . The possibility to prescribe training intensities using a single test has renewed expectations of swimming coaches and researchers. The attainment of  $VO_{2max}$  values trough the back extrapolation involves obtaining  $VO_2$  after swimming and applying a simple regression curve between the time and the values of consumption in order to predict the value of  $VO_2$  in time zero (Lavoie & Montpetit 1986).

It is believed that the high correlation between  $VO_{2max}$  and  $tlim$   $T_{400}$  m found by Lavoie et al. (1983) is probably the first indication of the  $T_{400}$  as a non-invasive alternative. Since then,  $T_{400}$  is a reference to verify the MAS and prescribe swimming training intensities (Montpetit et al. 1981; Lavoie et al. 1983; Rodrigues 2000; Pelayo et al. 2007). However, despite many studies reporting the use of  $T_{400}$  by swimming coaches (Wakayoshi et al. 1993b; Dekerle et al. 2005a; Alberty et al. 2006; Dekerle et al. 2006; Pelayo et al. 2007), we did not find a reliable protocol for prescribe more than one swimming training zone through the  $T_{400}$ , i.e., a protocol not only able to predict aerobic power, but also another training zone.

By questioning some brazilian coaches, we find that some of them use a protocol (of unknown origin) based on the  $T_{400}$  to monitor and to prescribe three different SS for swimmers and triathletes. Table 2 presents a summary of the equations used to calculate the SS for "aerobic threshold", "anaerobic threshold" and " $VO_{2max}$ ".

OBJECTIVE	DISTANCE	EQUATION
$VO_{2max}$ ( $I_{VO2}$ )	400 m ( $t_{400}I_{VO2}$ )	$= 400 / (400 / tlim\ 400\ m) \cdot k$
	800 m ( $t_{800}I_{VO2}$ )	$= t_{400}I_{VO2} \cdot 2 + 3\ s$
	200 m ( $t_{200}I_{VO2}$ )	$= t_{400}I_{VO2} / 2 - 3\ s$
	100 m ( $t_{100}I_{VO2}$ )	$= t_{200}I_{VO2} / 2 - 2\ s$
	50 m ( $t_{50}I_{VO2}$ )	$= t_{100}I_{VO2} / 2 - 1,5\ s$
ANAEROBIC THRESHOLD ( $I_{LA}$ )	400 m ( $t_{400}I_{LA}$ )	$= 400 / ((400 / tlim\ 400\ m) \cdot k) \cdot 0,95$
	800 m ( $t_{800}I_{LA}$ )	$= t_{400}I_{LA} \cdot 2 + 3\ s$
	200 m ( $t_{200}I_{LA}$ )	$= t_{400}I_{LA} / 2 - 3\ s$
	100 m ( $t_{100}I_{LA}$ )	$= t_{200}I_{LA} / 2 - 2\ s$
	50 m ( $t_{50}I_{LA}$ )	$= t_{100}I_{LA} / 2 - 1,5\ s$
AEROBIC THRESHOLD ( $I_{LAe}$ )	400 m ( $t_{400}I_{LAe}$ )	$= 400 / (((400 / tlim\ 400\ m) \cdot k) \cdot 0,95) \cdot 0,93$
	800 m ( $t_{800}I_{LAe}$ )	$= t_{400}I_{LAe} \cdot 2 + 3\ s$
	200 m ( $t_{200}I_{LAe}$ )	$= t_{400}I_{LAe} / 2 - 3\ s$
	100 m ( $t_{100}I_{LAe}$ )	$= t_{200}I_{LAe} / 2 - 2\ s$
	50 m ( $t_{50}I_{LAe}$ )	$= t_{100}I_{LAe} / 2 - 1,5\ s$

Table 2. Equations used to calculate the SS for "aerobic threshold", "anaerobic threshold" and " $VO_{2max}$ ". K is a constant: K = 0.94 if  $tlim$  is between 3 min 50 s to 4 min 40 s, K = 0.95 if  $tlim$  is between 4 min 41 s to 5 min 40 s, K = 0.96 the  $tlim$  is between 5 min 41 s to 6 min 40 s, K = 0.97 if  $tlim$  is above 6 min 41 s, t = time prescribed for a given distance;  $I_{VO2}$  = intensity prescribed to increase  $VO_{2max}$ ,  $I_{LA}$  = intensity for anaerobic threshold and  $I_{LAe}$  = intensity prescribed for aerobic threshold.

In this protocol, the coach just needs that your athletes swim 400 m in front *crawl* under maximum intensity (in training situation, but preferably in competitive situation).

According to the protocol, the  $T_{400}$  is able to prescribe SS in three different intensities for training in swimming called (1) "aerobic threshold" ( $I_{LAe}$ ) (2) "anaerobic threshold" ( $I_{LA}$ ) and (3) "increased  $VO_{2max}$ " ( $I_{VO2}$ ) (Olbrecht 2000; Maglischo 1999). For each intensity, the protocol suggests the time prescription for distances of 50, 100, 200, 400 and 800 m. SS prescribed by  $T_{400}$  for  $I_{VO2}$  is between 94 and 97% from the SS of 400 m ( $V_{400}$ ). SS prescribed for  $I_{LA}$  is proposed as approximately 90% of the  $V_{400}$ . SS prescribed for  $I_{LAe}$  stands at approximately 84% of the  $V_{400}$ .

It can be seen throughout this review that the literature presents a wide naming to explain the [La] response to exercise. However, despite being related to the same phenomenon, the physiological responses are often different, such as LT and MLSS mentioned above, and  $I_{LAe}$  and  $I_{LA}$  used in this protocol. This means that it cannot be used interchangeably.

As Maglischo (1999) and Olbrecht (2000) suggest, sets on  $I_{LAe}$  are swum in SS ranging from an intensity which is observed in the first rise in [La] above the resting level to the SS that sits comfortably below the  $I_{LA}$  of the swimmer. The total distance can vary between 2,000 and 10,000 m for adult swimmers or 20 to 120 min for young swimmers. Any distance can be used in the interval sets. Regarding the rest intervals between each repetition, it is suggested 5 to 30 s (Olbrecht 2000). Still, in  $I_{LA}$  sets, the total distance of the set can range from 2,000 to 4,000 m for adults, or approximately 30 min for younger athletes (Maglischo 1999; Olbrecht 2000). Distances between 25 and 4,000 m can be used in the interval sets (Maglischo 1999; Olbrecht 2000), with rest intervals between 10 to 30 s (Olbrecht 2000). Series aimed to increase  $VO_{2max}$ , Maglischo (1999) suggests SS slightly above the  $I_{LA}$  until 95% of best performance (Maglischo 1999) (Severe intensity domain). It is suggested distances between 25 to 2,000 m, with intervals of rest of 30 s to 120 s between each repetition (Maglischo 1999). However, the SS percentage suggested for training zones prescription have not been observed in constant speed tests until exhaustion. However, similarities were observed in *tlim* and percentage of training zones prescription between the  $T_{400}$  and the 1 mile running applied by Daniels (2005). Daniels's concepts (Daniels 2005) were based on "velocity at  $VO_{2max}$ " ( $vVO_{2max}$ ).

## 6. Velocity at $VO_{2max}$ ( $vVO_{2max}$ )

Although  $VO_{2max}$  is accepted as the physiological variable that best describes cardiovascular and respiratory capacities (Hill & Lupton 1923; Billat & Koralsztein 1996),  $vVO_{2max}$  was measured only five decades later in order to provide a practical method to measure aerobic fitness in runners (Billat & Koralsztein 1996). In the 80's there was a growth interest in the physiological assessments in order to monitor athletic training (Billat & Koralsztein 1996). However, it is known that protocols for  $VO_{2max}$  measurement, for example, require trained professionals, special equipment and need to be conducted in a controlled environment.

The first field test used to measure  $vVO_{2max}$  was intended to replace the 12 min test Cooper (Cooper 1968) as an alternative to predict  $VO_{2max}$  in a unique effort to simplify procedures and reduce costs. Cooper (1968) reported a correlation of 0.9 between  $VO_{2max}$  and the distance covered in a 12 min test running or walking. However, the motivation and rhythm was mentioned as critical to achieve good reliability in a 12 min test (Cooper 1968). Importantly, when prescribing training intensities based on the performance test, is also considered the psychological characteristic of the race, because instead of applying laboratory tests to monitor training status of the athlete, we use the performance obtained in competitive events, which is directly affected by the willingness to deal as discomfort. Tests

based on test performances reflect everything that an athlete recruited to travel any distance in a competitive situation (Daniels, 2005).

The Cooper test (1968) was based on the linear relationship between running speed and  $\text{VO}_2$  when, while driving the subject until exhaustion, it was possible to determine  $\text{VO}_{2\text{max}}$ . Billat & Koralsztein (1996) suggest that the accuracy of prediction of  $\text{VO}_{2\text{max}}$ , or also its inaccuracy, depends on the energy cost inter-individual variation, i.e., the total energy expenditure required to move the body to a certain distance.

Daniels et al. (1984) introduced the term "velocity at  $\text{VO}_{2\text{max}}$ " ( $v\text{VO}_{2\text{max}}$ ) suggesting that it is a useful variable that combines  $\text{VO}_{2\text{max}}$  and movement economy (Conley & Krähenbühl 1980) on a single factor that identifies aerobic differences among various runners or group of runners. According to Daniels (2005),  $v\text{VO}_{2\text{max}}$  explains individual differences in performance that  $\text{VO}_{2\text{max}}$  or running economy alone could not identify, i.e. individuals with the same  $\text{VO}_{2\text{max}}$  for example, may have different performance times.

Daniels et al. (1984) found in female runners who had various combinations of  $\text{VO}_{2\text{max}}$  and running economy (submaximal  $\text{VO}_2$ ), that  $v\text{VO}_{2\text{max}}$  was similar to the average speed required to run 3,000 m (maintained approximately for 9 min). In a study with sub-elite distance runners, Billat et al. (1994a) measured a *dlim* at  $v\text{VO}_{2\text{max}}$  of  $2,008.7 \pm 496$  m. However the authors suggest that there is a need to distinguish total run at  $v\text{VO}_{2\text{max}}$  and time run at  $\text{VO}_{2\text{max}}$  race only. Daniels et al. (1984) calculated  $v\text{VO}_{2\text{max}}$  extrapolating through a regression curve relating running speed and  $\text{VO}_2$ . When  $\text{VO}_{2\text{max}}$  was reached, the running speed corresponding to  $\text{VO}_{2\text{max}}$  was identified. Sub-maximal  $\text{VO}_2$  was calculated from efforts of 6 min at speeds of 230, 248 and 268  $\text{m}\cdot\text{min}^{-1}$  at intervals of 4 to 7 min between each effort.  $\text{VO}_{2\text{max}}$  was measured separately in a test based on the incremental pace of 5,000 m, adding 1% for the treadmill speed every minute until the test is terminated, where subjects reported that they would not be able to run more than 30 s. The highest  $\text{VO}_2$  achieved during the maximal test was considered as  $\text{VO}_{2\text{max}}$ .

## **7. *tlim* that swimmers are able to keep at $v\text{VO}_{2\text{max}}$ ( $t\text{lim}-v\text{VO}_{2\text{max}}$ )**

For several years, many studies have remained focusing on measuring  $v\text{VO}_{2\text{max}}$  during swimming. However, few investigations in order to determine the  $t\text{lim}-v\text{VO}_{2\text{max}}$  were carried out. This training tool which requires the swimmer to keep the exercise intensity corresponding to its  $v\text{VO}_{2\text{max}}$  has been studied mainly by the Billat et al research group. Based on the pioneering work of Hill and Lupton (1923), Billat & Koralsztein (1996) defined this parameter as the maximum time that the  $v\text{VO}_{2\text{max}}$  is maintained until exhaustion ( $t\text{lim}-v\text{VO}_{2\text{max}}$ ).

The difficulties of measuring  $\text{VO}_2$  in the aquatic environment hindered the swimming research and related modalities. The first studies were conducted in "swimming flume" (Faina et al. 1997; Demarie et al. 2001). To our knowledge, the first study in the pool, i.e., under normal swimming conditions, was performed by Renoux (2001). However, Renoux (2001) did not present results for cardio respiratory parameters such as  $\text{VO}_2$  and ventilation. The main results obtained in studies with "swimming flume" suggested that: a) the  $t\text{lim}-v\text{VO}_{2\text{max}}$  has low inter-individual variability in swimming, unlike other sports such as running (Billat et al. 1994b), and the values are between 4 min 45 s and 6 min 15 s; b) There is an inverse relationship between  $t\text{lim}-v\text{VO}_{2\text{max}}$  and  $v\text{VO}_{2\text{max}}$ , similar to running (Billat et al. 1994c); c) There was an inverse relationship between  $t\text{lim}-v\text{VO}_{2\text{max}}$  and anaerobic threshold.

Studies carried out in swimming pool with both genders and different levels of performance showed some results that agreed with "swimming flume" studies. Fernandes et al. (2003a, 2003b) suggest little variability in  $\text{tlim-vVO}_{2\text{max}}$  between subjects at the same level of performance (Fernandes et al. 2006c), genders (Fernandes et al. 2005), or swimming techniques (Fernandes et al. 2006a). Still, there was an inverse relationship between  $\text{tlim-vVO}_{2\text{max}}$  and  $\text{vVO}_{2\text{max}}$  (Fernandes et al. 2003b, 2005, 2006a), and between  $\text{tlim-vVO}_{2\text{max}}$  and anaerobic threshold corresponding blood concentrations of 3,5 mmol l<sup>-1</sup> (Fernandes et al. 2003b).

The method for obtaining  $\text{vVO}_{2\text{max}}$  of swimmers in swimming pool proved to be valid by Fernandes et al. (2003a). First, each subject performed an intermittent and individualized protocol, with increments of 0.05 m.s<sup>-1</sup> at each stage of 200 m and with 30 s intervals between each stage, until exhaustion. The  $\text{VO}_2$  was measured directly with a ergospirometer (K4b2, Cosmed, Rome, Italy) connected to the swimmer through a snorkel and a valve system (Keskinen et al. 2003). The concentrations of expired gases were measured *breath-by-breath*. A speed controller (*visual pacer*, TAR. 1.1, GBK-electronics, Aveiro, Portugal) with lights in the pool, was used to help the swimmers to keep their pre-determined SS.  $\text{VO}_{2\text{max}}$  was considered to be reached according to primary and secondary physiological criteria: (HOWLEY et al. 1995):

- a. Occurrence of a  $\text{VO}_2$  plateau independent of the increase in SS;
- b. [La] level ( $\geq 8\text{mmol l}^{-1}$ );
- c. High respiratory exchange ratio ( $r \geq 1,0$ );
- d. High HR ( $\geq 90\%$  of  $[220-\text{age}]$ );
- e. High value of PE (visually controlled).

Thus,  $\text{vVO}_{2\text{max}}$  is equal to the SS corresponding to the first stage at which  $\text{VO}_{2\text{max}}$  is reached. If a plateau lower than 2.1ml min<sup>-1</sup> kg<sup>-1</sup> could not be observed, the  $\text{vVO}_{2\text{max}}$  was then calculated by the equation proposed by Kuipers et al. (1985):

$$v\dot{V}O_{2\text{max}} = SS + \Delta S \cdot (n \cdot N^{-1}) \quad (5)$$

where SS is the speed corresponding to the last completed stage,  $\Delta S$  is the increment of speed,  $n$  indicates the number of seconds that the subjects were able to swim during the last stage, and  $N$  is the preset time (in seconds) to that stage. After determining the  $\text{vVO}_{2\text{max}}$  of each swimmer, followed by an adequate recovery period, applies the test of  $\text{tlim-vVO}_{2\text{max}}$  when each swimmer trying to stay in your swimming  $\text{vVO}_{2\text{max}}$  (speed control) to exhaustion.

The main studies in swimming suggest that  $\text{tlim-vVO}_{2\text{max}}$ :

- a. Correlates inversely with the energy cost, ie, it has a direct relationship with swimming economy (Fernandes et al. 2005);
- b. Correlates inversely with the speed of the individual anaerobic threshold (Fernandes et al. 2006a);
- c. Presents negative correlation values with the delta lactate ( $\Delta[\text{La}]$ ), ie, the difference found between [La] at the end and [La] at the beginning of exercise ( $\Delta[\text{La}]$ ) (Fernandes et al. 2008);
- d. Presents negative correlation with maximum values of [La]. (Fernandes et al. 2008);
- e. Shows no significant correlation with  $\text{VO}_{2\text{max}}$  (Fernandes et al. 2003a; 2003b; 2005; 2006a; 2006b; 2006c);



- f. Depends on the biomechanical parameters, correlating inversely with the strokes frequency and directly with the distance traveled per stroke cycle and the swimming index (product of the average SS and average distance traveled per stroke cycle) (Fernandes et al. 2006b);
- g. During the protocol to obtaining  $t_{lim-vVO_{2max}}$  there is a significant increase in stroke frequency and a great decline in the distance per stroke cycle (Marinho et al. 2004, 2006).

Studies in runners and cyclists (Billat & Koralsztein 1996) found that the  $t_{lim-vVO_{2max}}$  is less than 12 minutes, and the average is about 6 minutes.

Study	n	$t_{lim}$ (s)	$vVO_{2max}$ ( $m \cdot s^{-1}$ )	$d_{lim}$ (m)
FERNANDES et al. (2003a)	10 Males (students)	<b>325±76.5</b> (4min8s to 6min41s)	<b>1.19±0.08</b>	<b>295.7 to 477.79</b>
FERNANDES et al. (2003b)	15 Males (athletes)	<b>260.2±60.73</b> (3min19s to 5min21s)	<b>1.46±0.06</b>	<b>279.26 to 487.8</b>
FERNANDES et al. (2006a)	8 (athletes)	<b>243.17±30.49</b> (3min33s to 4min34s)	<b>1.45±0.08</b>	<b>308.38 to 396.80</b>
FERNANDES et al. (2006b)	13 Males	234.49±57.19 (4min17s to 4min51s)	1.45±0.04	257.08 to 422.93
	10 Females	231.90±52.37 (3min to 4min44s)	1.35±0.03	242.36 to 383.76
	<b>Total = 23</b> (athletes)	<b>233.37± 53.92</b> ( <b>3min to 4min47s</b> )	<b>1.40±0.06</b>	<b>240.44 to 419.42</b>
FERNANDES et al. (2008)	3 Males	217.67±20.84 (3min17s to 3min58)	1.55±0.02	301.15 to 374.47
	5 Females	258.46 ± 25.10 (3min53s to 4min44s)	1.39±0.02	319.70 to 399.82
	<b>Total = 8</b> (athletes)	<b>243.20 ± 30.50</b> (3min32s to 4min34s)	<b>1.45±0.08</b>	<b>291.54 to 418.76</b>

Table 3. Studies that measured  $t_{lim-vVO_{2max}}$  in swimmers.

Despite these results, is not only the complexity of measuring  $vVO_{2max}$  that affect the application of this concept by coaches. Because it is an abstract goal, the use of  $vVO_{2max}$  and  $t_{lim-vVO_{2max}}$  in swimming training would be more attractive if a " $d_{lim}$ " was associated with  $t_{lim-vVO_{2max}}$ . The studies presented in Table 3 suggest that efforts related to aerobic power ( $vVO_{2max}$ ) have very similar  $d_{lim}$  of 400 m front crawl, ranging from 4min01s (3min17s to 5min21s, elite swimmers) and 5min25s (4min8s to 6min41s, recreational swimmers). Fastest swimmers endure less time  $vVO_{2max}$  likely for two reasons:

- a. Higher SS imply higher energy cost (Fernandes et al. 2008);
- b. Higher  $v\text{VO}_{2\text{max}}$  in best swimmers require more strenuous levels of exercise, more anaerobic system request (Fernandes et al. 2008).

## 8. Conclusion

Is well justified that  $\text{CV}_{2\text{par}}$  seems to be higher than  $\text{CV}_{3\text{par}}$  and  $\text{CV}_{4\text{par}}$ .  $\text{CV}_{3\text{par}}$  and  $\text{CV}_{4\text{par}}$  better represent the relationship between “SS-tlim” due to its better fit.  $\text{CV}_{3\text{par}}$  and  $\text{CV}_{4\text{par}}$  are similar and probably are located below the lower boundary of the severe intensity domain. However, its applicability to swimming training is questioned because of the need to conduct many maximum efforts to obtain the CV.

In this sense, obtaining  $v\text{VO}_{2\text{max}}$  through the  $T_{400}$  seems to be an interesting ecological non-invasive protocol. tlim- $v\text{VO}_{2\text{max}}$  relationship should be considered during swimming training, specifically in the evaluation sessions of the training status. This parameter, together with other indicators, such as LT, MLSS, PE and general biomechanical parameters allow improving the assessment and intensity prescription of training programs. In this sense, assuming some limitations that bring non-invasive tests,  $v\text{VO}_{2\text{max}}$  can be obtained through a single effort of 400 m front *crawl* at maximum intensity ( $T_{400}$ ), with the advantage of being easy to use, low cost, and have great ecological validity (i.e., reflect the real swimming condition, as it is applied in the training environment. Thus, evaluations and prescriptions for training swimmers would be more practical and accessible, not only for the shortest time spent (i.e, collected even in a competitive situation) but also because do not impact cost. The ability to prescribe more than one training zone through  $T_{400}$  still deserves further studies.

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# Invertebrates Mitochondrial Function and Energetic Challenges

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## 1. Introduction

The term “invertebrate” recalls all animal species lacking a backbone or a bony skeleton. Although “invertebrate” is not a scientific term that encloses a taxonomic rank, this group includes animal species represented by over 30 phyla and it includes the first animals that successfully inhabited the earth, an event that – according to the fossil evidence – dates back to around 600 million years ago. This group is composed of several different phyla, such as annelids, molluscs, sponges, cnidarians, echinoderms, and all species from the phylum Arthropoda – which is the largest among invertebrates and is comprised by insects, arachnids and crustaceans (nearly reaching 1,033,160 species).

Since they appeared for the first time during the Cambrian period, invertebrates have played an important ecological role since they are frequently the key constituents of many trophic chains and they occupy virtually every available ecosystem on Earth, being characterised by notable variations in temperature, oxygen concentrations, food availability and food quality. Also, many species occupy highly specific and important roles in nature as pollinators, parasites or vectors for parasitic diseases affecting human and animal health.

It is clear that the ability of invertebrates to inhabit almost every ecosystem – as well as the diverse array of morphological and behavioural strategies used to obtain nutrients from the environment – is an accurate reflection of the enormous ability of these organisms to solve their most basic energetic requirements. From blood-suckers such as mosquitoes, intestinal nematodes and leeches (hirudin), to small plankton marine feeders such as cnidarians and marine benthic bivalves, all species face changes in food availability throughout their life cycle which affect their energy stores and growth rates (Peck, 2002; Popova-Butler & Dean, 2009). A beautiful example of highly specific energy stores – crucial during invertebrates’ life cycle and important to human health – is that of the female mosquito (*Anopheles gambiae*), which usually feeds on sugar to gain energy to fly and to cope with metabolic

requirements; however, anautogenous mosquitoes require the energy resulting from blood digestion in order to produce eggs, and it is during blood sucking that *Plasmodium vivax* (the parasite from infected females) enters into the vertebrate host to produce Malaria, a major health problem around the world (Das et al., 2010).

Large energetic demands during external work are observed throughout the life of several invertebrate species, and a clear example may be found in insect flight, which is considered to be one of the most energetically demanding processes of animal locomotion (Harrison & Roberts, 2000). Besides this, being an aerobic process that requires a permanent oxygen supply and depends upon ATP cellular production, the high energetic cost of flying is related to the frequency of the flight muscles' contraction (Vishnudas & Vigoreaux, 2006). In vertebrate species, the existence of high-energetic molecules in the muscle (phosphocreatine) during its exercise has been well documented (Jubrias et al., 2001); however, in invertebrate species, the presence of phosphagen-kinases that catalyse the synthesis of these high-energetic phosphorylated molecules has not been widely distributed (Ellington & Hines, 1991). The insect flight muscle seems to lack such molecules, but some flying species are able to surpass such energy needs by the proximity of mitochondria to muscle myofibrils, thus facilitating the export of energy rich nucleotides – such as ATP – to myofibrils (Vishnudas & Vigoreaux, 2006).

Some other invertebrate phyla – such as crustaceans – are able to synthesise phosphagens differently from that of vertebrates, like phosphocreatine. Phosphoarginine – a phosphagen of L-arginine found in the tail muscle of shrimp and crabs as well as in the flight muscle of flying insects – is the chemical energy storage system of these tissues, and thus animals are able to rapidly produce ATP when it is required (Wegener, 1996; Kotlyar et al., 2000). The enzyme responsible for the synthesis of phosphoarginine from ATP and L-arginine in invertebrates is named 'arginine kinase' and it is also considered to be a major allergen protein for shrimp-allergic individuals (Garcia-Orozco et al., 2007).

Since energetics are considered to be a key factor in limiting organisms' adaptation to extreme temperatures, several invertebrate species inhabiting marine polar environments are known to show a remarkable plasticity as regards their cellular system. Such adaptations may include an increasing number of mitochondria per cell as the temperature decreases as well as differences in the mitochondrial characteristics relating to the species' lifestyle, from motile species to sedentary ones (Peck, 2002). Studies in the mitochondrial function of the eurythermal polychaete *Arenicola marina* have concluded that invertebrates inhabiting higher latitudes – and consequently exposed to cold temperatures – showed higher oxygen consumption, mitochondrial densities and mitochondrial capacities when compared with those organisms living at lower latitudes with higher temperatures (Sommer & Portner, 1999; Peck, 2002). This adaptation of cold-acclimatised organisms is thought to occur in order to equate the level of metabolic activity present at warmer temperatures.

Among other important environmental factors affecting the bioenergetic state of organisms, marine invertebrates face large daily fluctuations in the dissolved oxygen concentrations of water, as well as wide salinity changes between open ocean and coastal waters – where many species live at least during one specific stage of their life cycle – (Dall et al., 1990). Such variations can adversely affect some species whose physiological mechanisms usually do not allow them to cope with low oxygen levels (as oxyregulators) or to handle salinity changes (as osmoregulators). However, several species are able to swim or move from one place to other, searching for a suitable site to grow, reproduce and survive (Hochachka &

Somero, 2002; Abele et al., 2007). Nevertheless, other invertebrate species are highly adapted to live in extreme conditions such as those living in hypoxic or even anoxic environments, like the brine shrimp *Artemia franciscana* (Eads & Hand, 1999; 2003).

As has previously been stated, this chapter reviews the current state of knowledge of the mitochondrial function of invertebrate species. It asks two central questions: 1) How are invertebrates able to adapt to such diverse environmental conditions by using a common set of structures and mechanisms - their mitochondrial machinery - to fulfil their energy requirements along their entire life cycle? 2) Is it really important to understand the role of mitochondria in the life history of invertebrates? This chapter also includes original data on crustacean responses to the external factors affecting such mitochondrial functions as hypoxia, starvation and the energetically expensive molt cycle.

## **2. The highly conserved mitochondrial machinery of invertebrates: Same functions, different challenges**

Following the endosymbiotic origin from primitive bacteria - at least 2 billion years ago - when atmospheric oxygen levels rose and subsequently remained relatively steady, mitochondria have experienced large changes among species, from  $\alpha$ -proteobacteria to mammals. During the adaptation process of organisms to their new dynamic environment, some mitochondrial characteristics have remained highly conserved even among distantly related species, such as their rod shape - the overall structure including two phospholipid membranes - and, with some exceptions, their conserved characteristic genome content of 22 tRNAs, 2 rRNAs, and 13 genes encoding protein subunits of the enzymes from the oxidative phosphorylation system (OXPHOS) (Boore, 1999; Gray et al., 1999).

Besides mitochondrial encoded proteins, a significant fraction of the original mitochondrial genes have moved to the nucleus. Thus, in the mammalian mitochondria, approximately 76 subunits - which are part of the respiratory chain - are encoded by nuclear genes, and all of them must be imported into the mitochondria. The complete protein machinery involved in mtDNA replication, transcription and translation (including all of the ribosomal protein subunits) is encoded by nuclear genes (St. John et al., 2005; Falkenberg et al., 2005). Furthermore, several of these imported proteins are highly conserved among species, some of them accomplishing key roles as subunits alpha and beta of the ATP-synthase, which are part of the catalytic sites of the enzyme (Martinez-Cruz et al., 2011).

In addition to those key proteins that maintain a conserved function, hundreds of new proteins have been described among invertebrate species as being imported to mitochondria, each presumed to participate in at least one of the large number of metabolic pathways occurring in this organelle. However, its major conserved function allows mitochondrion to produce - from food assimilated compounds via oxidation - the proton motive force that drives ATP synthesis (Rich & Marechal, 2010). This complex process produces 95% of the cellular ATP that cells need for biosynthesis, transport and motility (Wilson et al., 1988; Dudkina et al., 2008; Diaz, 2010), and any significant change in the system could result in deleterious consequences for the whole cell metabolism and - consequently - reduce its efficiency or provoke its death (Mayevsky & Rogatsky, 2007).

Throughout the years (and mostly based in the study of human pathologies) researchers have found that mitochondria are involved in various critical functions - such as thermoregulation - in the synthesis of essential molecules - such as phospholipids and heme - in the programmed cell death or apoptosis of mediating multiple cellular signalling

pathways (Ryan & Hoogenraad, 2007). Mitochondria are also essential in the cholesterol metabolism and the detoxification of ammonia in the urea cycle. In addition, there is a close relationship between mitochondria and different cell types. It is well known that the number of mitochondria in individual cell types varies according to their function and energy requirements (St. John et al., 2005; Chen & Chan, 2009). Thus, highly energetic tissues as the flight muscle of flying insects and the midgut gland of crustaceans are known to contain a large number of mitochondria, just as occurs in the skeletal muscles of vertebrates during endurance training (Harrison & Roberts, 2000).

Mitochondria are known as dynamic organelles that cannot be made *de novo*, and instead they divide through a highly regulated process called mitochondrial fission, mediated by a defined set of new proteins recruited from the cytoplasm, which are added to pre-existing sub-compartments and protein complexes to a point whereby the organelle grows and divides (Ryan & Hoogenraad, 2007). Furthermore, mitochondria are now seen as a set of organelles that are able to migrate throughout the cell, to fuse and divide regulating mitochondrial function (Chen & Chan, 2009).

Recent findings have also confirmed the existence of dynamic mitochondrial supercomplexes - defined as the association of protein complexes distributed along the inner mitochondrial membrane - on mammals, plants, yeasts (*Yarrowia lipolytica*), and bacteria (Nübel et al., 2009; Wittig & Schägger, 2009; Dudkina et al., 2010). Complexes I, III and IV are able to associate in order to promote electron transport as single OXPHOS complexes or else as a supercomplex called respirasome (I + III<sub>2</sub> + IV<sub>1-2</sub>) both of which can autonomously carry out respiration (Wittig et al., 2006). Furthermore, complex V - the mitochondrial F<sub>1</sub>F<sub>0</sub>ATP-synthase - is associated to form dimeric, trimeric and tetrameric organisations (Dudkina et al., 2008). Unfortunately, to our knowledge, there are no reports confirming the existence of these mitochondrial protein associations from invertebrate species.

A general description of the most recent advances covering mitochondrial enzymes participating in the electron transport chain and the OXPHOS, including some particular findings on the enzymes of some invertebrate species, is presented below:

### **2.1 Complex I, NADH: Ubiquinone-oxidoreductase (EC. 1.6.5.3)**

Is an enzyme which provides the input to the respiratory chain by catalysing the transfer of two electrons from NADH from - glycolysis - to ubiquinone, and which utilises the free energy released in this redox reaction for the translocation of four protons across the membrane, from the matrix to the intermembrane space. The proton translocation from the mitochondrial matrix generates the proton-motive force required for ATP synthesis at the end of the respiratory chain during oxidative phosphorylation (Friedrich & Weiss, 1997; Dudkina et al., 2008). However, this proton-pumping enzyme is the largest, most complicated and least-well understood of the respiratory chain (Zickermann et al., 2008). Another unconventional function of complex I is the generation of reactive oxygen species (ROS) - such as the superoxide ion (O<sub>2</sub><sup>-</sup>) - and, even if it is not a strong oxidant, it is a precursor of most other ROS and, consequently, contributes significantly to cellular oxidative stress. In mammalian mitochondria, the superoxide production is predominantly produced by complex I (Turrens, 2003).

The scarce information available concerning mitochondrial complex I from invertebrates includes basic descriptive reports of the nucleotide sequences of the NADH subunits - most

of them from the mitochondrial genome-, their proteins, and an interesting study of site-directed mutagenesis aiming to understand the subunits' function in model insect species such as *Drosophila* spp. (Tovoinen et al., 2001; Sanz et al., 2010).

In addition, the existence of an alternative oxidase (AOX) in the animal mitochondria has been confirmed. Previously, this enzyme - which catalyses the O<sub>2</sub>-dependent oxidation of ubiquinol, producing ubiquinone and H<sub>2</sub>O - was thought to be limited to plants, some fungi and protists. The major difference between complex I and AOX is that the electron flow from ubiquinol to AOX is not coupled to the generation of a proton motive force, decreasing energy conservation in oxidative phosphorylation. The complementary DNA sequence that encodes AOX in invertebrate species from the phyla Porifera, Cnidaria, Nematoda, Anellida, Mollusca, and Echinodermata, has been characterised and it has been suggested that it may contribute on the acclimation of animals to stress conditions, mainly when the cytochrome pathway is inhibited (McDonald et al., 2009).

## 2.2 Complex II, Succinate: Ubiquinone- Oxidoreductase (EC 1.3.99.1)

Also called Succinate Dehydrogenase (SDH), is a functional member of the Krebs cycle and the aerobic respiratory chain, and it couples the oxidation of succinate to fumarate with the reduction of quinone to quinol (QH<sub>2</sub>). Most probably, this enzyme presents the most striking differences among the mitochondrial complexes in the electron transport chain and OXPHOS (Rich & Marechal, 2010). It must be noticed that the oxidation of succinate to fumarate is the only Krebs reaction that takes place in the mitochondrial inner membrane itself; this reaction does not participate in proton translocation from one side to the other of the inner mitochondrial membrane. The energy carrier flavin adenine dinucleotide (FAD) forms a part of complex II, and succinate oxidation begins after the binding of succinate to the enzyme. This covalent binding of FAD to the enzyme increases the redox potential to a level that allows succinate oxidation (Rich & Marechal, 2010).

Contrary to the four human and yeast mitochondrial complexes, which include subunits that are encoded by the mitochondrial genome, the four subunits of SDH are encoded in the nuclear genome (SDH1 to SDH4; Figueroa et al., 2002).

Early studies of complex II (SDH) from invertebrates reported the isolation of mitochondrial fractions from the body muscles of the worm *Nereis virens* and from the tail muscle of the lobster *Homarus gammarus*, and reported high activity in both enzymes (Mattisson, 1965). Unfortunately, there is scarce new information available concerning complex II in invertebrates. However, the study of mitochondria from parasite species - used as animal models - can be considered a framework that has guided our knowledge in the understanding of such critical endogenous processes as aging, mitochondrial dysfunction and the role of the organelle in apoptosis (Grad et al., 2008; Wang & Youle, 2009). Thus, it has been suggested that mitochondria may influence the longevity of the nematode *Caenorhabditis elegans* through the rate of ROS production and by the stress-evoked signals that are known to act in a cell-non-autonomous manner during mitochondrial protein regulation (Durieux et al., 2011). Furthermore, *C. elegans* has been used as a model to investigate the mitochondrial mechanisms of human aging and tumourigenesis by studying the catalytic effects of mutation in the genes encoding the SDH iron-sulphur subunit. Promising results suggest that the SDH ubiquinone-binding site can become a source of superoxide and that the pathological consequences of SDH mutations can be diminished with antioxidants, such as ascorbate and N-acetyl-L-cysteine (Huang & Lemire, 2009).

### **2.3 Complex III, Ubiquinol: Cytochrome C Oxidoreductase or Cytochrome BC<sub>1</sub> (EC 1.10.2.2)**

Is a multimeric enzyme complex involved in the transfer of electrons from ubiquinol to cytochrome C, and it is also coupled to electrons' transfer across the inner mitochondrial membrane. This bovine enzyme is formed by 10 nuclear encoded subunits, with only one encoded in the mtDNA (Xia et al., 1997). The catalytic mechanism of the enzyme includes the complex mechanism of the protonmotive Q-cycle that provides the additional efficiency of the energy conservation of the electrons transferred (Mitchell, 1976; Rich & Marechal, 2010).

In such species as mammals and yeasts it has been observed that as the rate of electron transfer is reduced, the enzyme may leak electrons to molecular oxygen, promoting the formation of the superoxide ion. This mitochondrial dysfunction has been widely studied, and its role in the O<sub>2</sub> sensing pathway has been investigated because the increasing production of reactive oxygen species (ROS) is the result of organisms in hypoxic/anoxic conditions (Guzy et al., 2007). New evidence suggests that ROS generated by the mitochondrial complex III are required for the hypoxic activation of transcription factors such as HIF (Hypoxia Inducible Factor); however, this topic will be more extensively discussed below.

The mitochondrial complex III from invertebrates has been poorly studied, but recent reports about these species confirm the importance of studying its basis and applications. An interesting example is the study about the control of Chagas disease, which severely affects the health of the human population in Latin America and which is caused by the protozoan parasite *Trypanosoma cruzi*. Genes et al. (2011) reported such bacteria species as *Serratia marcescens* biotype A1a, which is regularly found in the gut of the vector insect *Rhodnius prolixus*, and which demonstrates the trypanolytic activity conferred by prodigiosin. Prodigiosin is a potent bacterial tripyrrolic compound with various biological activities. This study suggests the abnormal mitochondrial function of *T. cruzi* since prodigiosin inhibits the mitochondrial complex III, affecting subsequent oxidative phosphorylation.

### **2.4 Complex IV, Cytochrome C oxidase (EC 1.9.3.1)**

Is the terminal enzyme of the electron transport chain and it catalyses the reduction of molecular oxygen to water. The reduction of oxygen by this enzyme - which is responsible for biological energy conversion in mitochondria (Belevich et al., 2010) - is also linked to the translocation (pumping) of four protons across the membrane. This movement of electrons is subsequently coupled to ATP synthesis by the ATP-synthase (Khalimonchuk & Rödel, 2005). The cytochrome C oxidase (CO) has been described as one of the electron transport chain elements which is highly affected by changes in oxygen levels - since cytochrome C reduction is oxygen-dependent - and becomes more reduced when oxygen levels increase (Wilson et al., 1988).

The CO from eukaryotes consists of 11-13 subunits, depending on the species. It belongs to the family of heme-cooper enzymes, some of them suggested as hypoxia sensors. The enzyme is highly regulated by transcription factors, hormones, lipid membranes and the second messengers that control its activity (Ripamonti et al., 2006; Semenza, 2007; Fontanesi et al., 2008). As observed in other mitochondrial complexes, CO also includes mitochondrial encoded genes as subunits CO1, CO2, and CO3 which form the functional core of the enzyme; the rest are nuclear-encoded subunits and their functions - even in the most studied animal models - remain unclear, although they are assumed to participate in the

assembly, stability and regulation of the enzyme (Rich & Marechal, 2010). Moreover, CO is also regulated by the existence of various isoforms from each nuclear-encoded subunit which is known to be tissue- and specie-specific (e. g. CO5a and CO5b, CO6a, CO6b and CO6c, and CO7a, CO7b, CO7c, etc.; Diaz, 2010).

The CO genes' expression and the activity of the enzyme are known to be affected by external factors. In crustacean species, such as the grass shrimp *Palaemonetes pugio*, the gene expression of subunits CO1 and CO2 is positively or negatively regulated by low dissolved oxygen concentrations in water (Brouwer et al., 2008). References and further reading may be available for this article.

In insects, as with the sweet potato hornworm *Agrius convolvuli*, diapause - the delay in development in response to regularly and recurring periods of adverse environmental conditions - is induced by low temperatures. During this physiological state, the neurological activity, oxygen consumption rate and metabolic levels are low compared to undiapaused animals; and it has been found that the genetic expression of the CO1 subunit is down-regulated. When the organism terminates diapause, CO1 is up-regulated and the enzyme activity also increases (Uno et al., 2004). Other insect species, such as the cotton boll worm *Helicoverpa armigera*, show diverse responses during diapause: the levels of CO1 mRNA and enzyme activity are low, suggesting that the diapause state is different in each species (Yang et al., 2010).

In some species, CO participates in organism detoxification, as observed in the polychaetes *Hediste diversicolor* and *Marenzelleria viridis* which inhabit eutrophicated regions with low oxygen levels and high sulphide concentrations - where CO functions as an alternative pathway of oxidation - (Hahlbeck et al., 2000). In addition, when sulphide becomes hydrogen sulphide (HS) - a weak acid that occurs in marine and aquatic environments such as hydrothermal vents, mudflats and marshes - HS is known to reversibly inhibit CO activity, affecting the aerobic metabolism of certain species, such as the worm *Urechis caupo* (Julian et al., 1998).

### 2.5 Complex V, ATP synthase (EC 3.6.3.14)

Is a multimeric enzyme that transforms the kinetic energy of the protons' electrochemical gradient to synthesise the high energy phosphate molecule ATP. Nowadays, it is well-known that the enzyme can also hydrolyse ATP, functioning as an ATPase (Boyer, 1997; Tuena de Gomez-Poyou et al., 1999). This mitochondrial enzyme comprises a catalytic sector  $F_1$  (composed by  $\alpha_3\beta_3\gamma\delta\epsilon$  subunits), and a transmembrane hydrophobic sector  $F_0$  (composed of at least three subunits:  $a$ ,  $b_2$  and  $c_{10-12}$ ), both linked by a central and a peripheral stalk (Mueller et al., 2004). As in other mitochondrial complexes, this enzyme includes subunits encoded in both the nuclear and mitochondrial genomes, in a tightly coordinated process to assemble this multimeric complex (Itoi et al., 2003; Muhlia-Almazan et al., 2008).

During the oxidative phosphorylation process in mitochondria, the electron transport chain generates a proton gradient that is proposed to drive the rotation of  $F_0$ , a central rotor located in the inner mitochondrial membrane. This rotation movement is believed to reverse the rotation of the  $F_1$  nanomotor, inducing - via a conformational change - the sequential release of ATP from three identical catalytic sites followed by the sequential synthesis of newly formed ATP from  $P_i + ADP$  at these sites (Cardol et al., 2005). Biochemical and structural studies of the  $F_1$  sector from bovine enzymes have demonstrated that catalytic sites are integrated mainly by three  $\beta$  subunits that alternate with three  $\alpha$  subunits. The

three catalytic sites formed by these three pairs of  $\alpha/\beta$  subunits are grouped in segments forming a sphere, which is connected to the  $\gamma$  subunit which connects  $F_1$  to  $F_0$  (Lai-Zhang & Mueller, 2000).

Due to its complex structure and the dual role that the ATP synthase plays in cells, the current state of research concerning this mitochondrial enzyme is both abundant and relevant; however, for the majority of invertebrate taxa, the information regarding this enzyme appears to be almost non-existent, restricted to some insect species for the more studied models. Analyses of the mitochondrial transcriptome and proteome from these species – which have been exposed to different environmental conditions – have shown that the ATP-synthase subunits can be affected in their expression, and that specific subunits of this multimeric complex can also play additional roles in the mitochondrial function. These findings suggest that invertebrates are able to respond by changing their metabolism to maintain cell homeostasis.

In the fruit fly *Drosophila melanogaster* and the California purple sea urchin *Strongylocentrotus purpuratus* the gene expression of the ATP-synthase subunit alpha (*atp $\alpha$* ) was measured at early developmental stages, and it was found that the amount of mRNA varies throughout development in both species. Contrary results showed that during the larval stage the nuclear and mitochondrially encoded ATP synthase genes appear to be temporally co-regulated in *Drosophila*, although in the sea urchin this development pattern was not observed (Talamillo et al., 1998). In 2005, Kidd et al. analysed null mutants of the ATP-synthase subunit  $\epsilon$  in *Drosophila* spp., and a dramatic delay in the growth rate of the first instar larvae that finally died was reported. In addition, in fly embryos the ATP-synthase activity had a six-fold reduction.

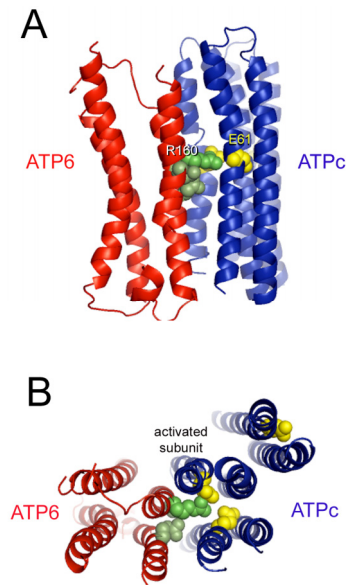
Most likely, the first two studies concerning the ATP synthase of crustacean species were published in 2001. The authors characterised the enzymatic properties of  $F_1$  and evaluated its sensitivity to specific inhibitors and modulators in the gills of the freshwater crayfish *Orconectes virilis*; they included, as an important contribution, the standardised methods for isolating mitochondria from crustacean tissues and some results about their enzyme stability at different temperatures and pH conditions (Li & Neufeld, 2001a, 2001b).

Recent reports on the most-studied shrimp species – *Litopenaeus vannamei* – have characterised and studied several mitochondrial and nuclear encoded subunits from tissues such as muscles, gills, pleopods and the midgut gland (Muhlia-Almazan et al., 2008; Martinez-Cruz et al., 2011). The complementary DNA sequences of the *atp6* subunit encoded in the mtDNA and the *atp9* (a nuclear encoded subunit) were characterised and their deduced proteins, as major components of the  $F_0$  sector, were included in a molecular model which predicted that in the shrimp  $F_0F_1$  ATP synthase the *atp9* oligomeric ring may contain 9-10 proteins (Figure 1; Muhlia-Almazan et al., 2008).

Over the last decade, the effects of a viral agent which provokes shrimp death have been deeply studied. The white spot syndrome virus (WSSV) is perhaps the most devastating shrimp disease, causing massive mortalities in global aquaculture systems (Sanchez-Paz, 2010). In 2006, Wang et al. analysed the gene expression profile of the fleshy prawn *Fenneropenaeus chinensis* in response to WSSV infection through cDNA microarrays. Genes including the ATP-synthase A chain and arginine kinase were found to be down-regulated during WSSV infection. Additional studies in other shrimp species, reported thirty additional genes which are involved in the antiviral process as part of the shrimp's defence system. One of the most interesting findings of these studies was that the interferon-like



protein (IntIP) – known as an antiviral factor – showed increased expression in virus-resistant shrimp (He et al., 2005). Later, Rosa & Barraco (2008) suggested that the shrimp interferon-like protein (IntIP) is rather a region of the insect mitochondrial b subunit of the ATP-synthase, due to the high identity between both proteins (60–73%). Recently, Liang et al. (2010) have suggested the ATP-synthase subunit  $\beta$  (*atp*  $\beta$ ) – earlier called BP53 – as a protein involved in the WSSV binding to shrimp cells that may play an important role in the antiviral defence system of shrimp against WSSV.



A) Ribbon lateral view, and B) Ribbon front view of the subunit ATP6 complex with three ATP9 subunits. The predicted functional residues are marked in both subunits, R160 from ATP6, and E99 from ATP9. (Taken from Muhlia-Almazan et al., 2008).

Fig. 1. Molecular Model of the ATP9- ATP6 Subcomplex from the Shrimp *L. vannamei*.

Transcriptomes and proteomes have provided a lot of information, not only about the characteristics of specific sequences of nucleotides or amino acids, but also about the proteins' structure and function in invertebrate organisms under diverse environmental conditions (Clavero-Salas et al., 2007). Moreover, novel proteins have been reported as accessories to the mitochondrial protein complexes in invertebrates species, such as the ticks *Ornithodoros moubata* and *O. erraticus*, where six novel proteins similar to the ATP synthase subunit 6 (*atp6*) were identified in the salivary glands. These proteins are attractive targets for controlling ticks and tick-borne pathogens (Oleaga et al., 2007).

Actually, and based in the mitochondrial highly conserved function, generic models of the electron transport chain in mitochondria have been constructed using bioinformatic tools to predict how the rate of oxygen consumption through the system – and the redox states of some intermediates such as NAD/NADH, ubiquinone, and cytochromes – respond to physiological stimuli such varying oxygen levels and other rapid energy demands (Banaji, 2006).

Ultimately, it is remarkable that the mitochondrial function has remained in all animal species through its long and peculiar evolutionary history and under the influence of variable selective pressures. Moreover, structural and biochemical adaptations promoting highly effective mitochondrial functions have allowed organisms to inhabit unusual environments.

### 3. The Invertebrates mitochondrial genome

The study of the mitochondrial genome has provided enormous amounts of information from which it has become feasible to infer the origin of species by using comparative and evolutionary genomics (Jiang et al., 2009) in order to understand the ancient phylogenetic relationships among species, to comprehend population genetics (Boore et al., 1995; Boore, 1999), and to recognise the mechanisms coordinating the nuclear and mitochondrial genomes so as to synthesise a large number of functional proteins located in this organelle.

To date, the mtDNA of several invertebrates has been sequenced and characterised, including ascidians (Yokobori et al., 1999), echinoderms (Jacobs et al., 1988; Asakawa et al., 1995), insects (Clary & Wolstenholme, 1985), nematodes (Okimoto et al., 1992), molluscs (Yu & Li, 2011; Cheng et al., 2011), and various crustacean species such as shrimp and crabs (Staton et al., 1997; Shen et al., 2007; Peregrino-Uriarte et al., 2009). Several reports have shown that the mitochondrial genome of invertebrate species varies, and ranges between 12 and 20 kbp. This may be due to contrasting ecological habitats or it may be a response to different selective pressures (Table 1).

Phylum	Species	mtDNA size (bp)	GenBank Acc. No.	References
Porifera	<i>Plakinastrella sp.</i>	19,790	NC_010217	Lavrov et al., 2008
	<i>Negombata magnifica</i>	20,088	NC_010171	Belinky et al., 2008
	<i>Aphrocallistes vastus</i>	17,427	NC_010769	Rosengarten et al., 2008
Cnidaria	<i>Hydra oligactis</i>	16,314	NC_010214	Kayal & Lavrov, 2008
	<i>Aurelia aurita</i>	16,937	NC_008446	Shao et al., 2006
	<i>Fungiacyathus stephanus</i>	19,381	NC_015640	---
Platyhelminthes	<i>Symsagittifera roscoffensis</i>	14,803	NC_014578	Mwinyi et al., 2010
	<i>Clonorchis sinensis</i>	13,877	JF729304	Cai et al., 2011
	<i>Taenia taeniaeformis</i>	13,647	NC_014768	Liu et al., 2011
Rotifera	<i>Brachionus plicatilis</i>	12,672	NC_010484	Suga et al., 2008
Acanthocephala	<i>Leptorhynchoides thecatus</i>	13,888	NC_006892	Steinauer et al., 2005

Phylum	Species	mtDNA size (bp)	GenBank Acc. No.	References
<b>Nematoda</b>	<i>Caenorhabditis elegans</i>	13,794	NC_001328	Wolstenholme et al., 1994
	<i>Necator americanus</i>	13,605	AJ417719	Hu et al., 2002
<b>Onychophora</b>	<i>Oroperipatus sp.</i>	14,493	NC_015890	Segovia et al., 2011
<b>Brachiopoda</b>	<i>Laqueus rubellus</i>	14,017	AB035869	Noguchi et al., 2000
<b>Echinodermata</b>	<i>Acanthaster planci</i>	16,234	NC_007788	Yasuda et al., 2006
	<i>Strongylocentrotus purpuratus</i>	15,650	NC_001453	Qureshi & Jacobs, 1993
	<i>Cucumaria miniata</i>	17,538	NC_005929	Arndt & Smith, 1998
<b>Mollusca</b>	<i>Crassostrea gigas</i>	18,225	EU672831	Ren et al., 2010
	<i>Cepaea nemoralis</i>	14,100	NC_001816	Terrett et al., 1996
	<i>Octopus minor</i>	15,974	HQ638215	Cheng et al., 2011
<b>Annelida</b>	<i>Platynereis dumerilii</i>	15,619	AF178678	Boore & Brown, 2000
	<i>Lumbricus terrestris</i>	14,998	NC_001673	Boore & Brown, 1995
<b>Arthropoda</b>				
<b>Subphylum Chelicerata</b>	<i>Centruroides limpidus</i>	14,519	NC_006896	Davila et al., 2005
<b>Subphylum Crustacea</b>	<i>Litopenaeus vannamei</i>	15,989	DQ534543	Shen et al., 2007
<b>Subphylum Myriapoda</b>	<i>Scutigera coleoptrata</i>	14,922	NC_005870	Negrisoló et al., 2004
<b>Subphylum Hexapoda</b>	<i>Apis mellifera</i>	16,343	NC_001566	Crozier & Crozier, 1993

Table 1. Invertebrates' mitochondrial genome size of the species of different phyla.

Because of the wide variability of environmental conditions in which a large number of invertebrate species are distributed, several specific mtDNA-rearrangements have been found when compared with those observed in the mtDNA of mammals. Such novel arrangements include the mitogenome from the blue mussel *Mytilus edulis* (Hoffmann et al., 1992), and that of the fruit fly *Drosophila melanogaster* (Clary & Wolstenholme, 1985; Garesse, 1988) and the horseshoe crab *Limulus polyphemus* (Staton et al., 1997).

Also, some species - or groups of species - may lack some genes, such as nematodes whose mtDNA lacks a gene for ATP8 (Keddie et al., 1998), or cnidarians like the coral *Sarcophyton glaucum* which includes an unusual gene encoding an extra tRNA (Beaton et al., 1998). Moreover, major changes have been found in invertebrates' mtDNA, such as the mitochondrial genes of *Lumbricus terrestris*, which are all known to be encoded in the same strand and, unlike others, the genes coding A8 and A6 are separated by a long 2700 nucleotides fragment (Boore & Brown, 1995).

In 2006, the description of the mtDNA of the moon jellyfish (*Aurelia aurita*) was reported. It was surprising to find that mitochondria of this organism contain a linear genome, which became the first non-circular genome described in a Metazoan. Besides its linearity, its organisation involves two additional sequences of 324 and 969 nucleotides, the last (ORF969) encodes a putative family B-DNA polymerase, tentatively identified as *dnab*, which was previously only reported in algae mtDNAs (Shao et al., 2006). Subsequently, the linear mitogenome of Cnidarians of the genus *Hydra* was also reported, although it was found that it is fragmented as two linear mitochondrial “chromosomes” (mt1 and mt2) where all genes are unidirectionally-oriented (Voigt et al., 2008).

In addition, the invertebrate’s mitochondrial genetic code differs from the universal/standard genetic code, and it is suggested that this is species-specific since several studies have identified some changes in animal mitochondrial code, as shown by Table 2 (taken from Watanabe, 2010). As observed in this table, invertebrate mtDNAs are largely represented by different changeable codons - depending upon the species. This is the case for the AUA codon which usually codes Ile in the standard genetic code but in the mitochondria of some species of Nematoda, Mollusca, Platyhelminthes and Vertebrata it encodes a Met (Himeno et al., 1987; Bessho et al., 1992). Also, in several species, the start codon differs from the AUG but still codifies a methionine, and in most of the species the stop codon is an incomplete codon, such as UA or U (Watanabe, 2010).

<b>Codon</b> <b>(Universal code)</b>	<b>AUA</b> <b>(Ile)</b>	<b>AAA</b> <b>(Lys)</b>	<b>AGA</b> <b>(Arg)</b>	<b>AGG</b> <b>(Arg)</b>
<b>Vertebrates</b> (human, bovine, rat, mouse, chicken, frog)	<b>Met</b>	Lys	<b>Term</b>	<b>Term</b>
<b>Prochordates</b> (ascidian, asymmetron)	<b>Met</b>	Lys	<b>Gly</b>	<b>Gly</b>
<b>Echinoderms</b> (sea urchin, starfish)	Ile	<b>Asn</b>	<b>Ser</b>	<b>Ser</b>
<b>Arthropods</b>	<b>Met</b>	Lys	<b>Ser</b>	<b>Ser</b>
Most (shrimp, daphnia)	<b>Met</b>	Lys	<b>Ser</b>	<b>Ser</b>
Insect ( <i>Drosophila</i> )	<b>Met</b>	Lys	<b>Ser</b>	-
<b>Molluscs</b> (squid, octopus, Liolophura, Mesogastropoda)	<b>Met</b>	Lys	<b>Ser</b>	<b>Ser</b>
<b>Nematodes</b> (nematodes, ascaris)	<b>Met</b>	Lys	<b>Ser</b>	<b>Ser</b>
<b>Platyhelminthes</b>	<b>Met</b>	<b>Asn</b>	<b>Ser</b>	<b>Ser</b>
Most (Echinostomida, Trematoda)	Ile	<b>Asn</b>	<b>Ser</b>	<b>Ser</b>
Rhabditophora ( <i>Planaria</i> )	Ile	Lys	Arg	Arg
<b>Coelenterates</b> (jellyfish, coral, sea anemone, hydrozoa)	Ile	Lys	Arg	Arg

Table 2. The relationships between the genetic codes of animal mitochondria. Modified from: Watanabe, 2010. Bold letter: non-universal codon; Term: termination codon.

Although, to date, the mitochondrial genes expression mechanisms are not fully understood, and the evolutionary processes by which the mitogenome suffers a rearrangement are not clear. It is proposed that a new order in genes' arrangements must preserve or facilitate those signals or mechanisms required for the transcription and processing of RNAs to accomplish the mitochondrial function in animal species (Boore, 1999).

The mitochondrial DNA from animal cells is known to be easily affected, since it is not protected by DNA-binding proteins or histones such as nuclear DNA. Several studies have found that mtDNA can be affected by aging, hypoxia and random events of mutation or insertion/deletion (rates of mutation for mitochondrial genomes are known to be much higher than those in the nuclear DNA) that can produce increased oxidative stress and high levels of ROS in this organelle. Defective proteins which result from altered mtDNA molecules cause defective mitochondrial function, as an impaired respiratory chain and increased electron leaks so as to finally generate larger amounts of ROS (Wei et al., 1998).

Insects' mitogenomes are known to be affected at the transcriptional level by chemicals, since the mtDNA copy number has been shown to increase to meet the bioenergetic demands of the organism, as observed in the fly *D. melanogaster* when exposed to tetracycline. Treatment with this antibiotic causes an energetic deficiency, promoting an up-regulation of the mtDNA copy number (Moraes, 2001; Ballard & Melvin, 2007).

#### **4. Invertebrate challenges and how marine species spend energy**

In most animal species, high energy levels in their bodies reveal fast growth, adequate energy storage, effective reproduction strategies and viable descendants with characteristic short life spans; however, reduced energy levels in a biological system results in affected gene expression, low survival rates and reduced metabolic rates and, therefore, a need on the part of physiological mechanisms to slow the ageing rate until environmental conditions are enhanced and higher energy levels are again reached (Stuart & Brown, 2006). In their natural habitat, many invertebrate species must undergo endogenous physiological processes during their life cycle, such as molting, starvation, quiescence and metamorphosis, among others. Many of these processes imply high energetic expense, causing a low energy status that reduces their ability to reach the adult stage (Hochachka & Somero, 2002).

The role of metamorphosis - one of the most amazing physiological endogenous processes in nature - becomes strikingly important when considering the large number of animal species that undergo metamorphic changes. Frequently, the energetic balance of holometabolous insects during metamorphosis is negative, because there is no energy gain and species must face all these changes by using any energetic reserves previously stored (Nestel et al., 2003).

During their larval stages, insects - such as Lepidopterans - show fast growth rates, as observed in the tobacco worm larvae of *Manduca sexta* which increases its mass 10,000-fold in just 16 days at the final larval instar (Goodman et al., 1985). The midgut epithelium of this species is a highly aerobic tissue that digests and absorbs nutrients, and transports ions at high rates. During metamorphic changes, the midgut epithelium is programmed to die and the larval midgut should maintain structural and functional integrity until the pupal epithelium is formed. During this process, ATP synthesis and mitochondrial function must be obligatorily maintained. Thus, organisms resolve this by reducing mitochondrial

substrate oxidation, a clear indication that the electron transport chain may be a site of modulation during metamorphosis (Chamberlin, 2004).

Quiescence and estivation are also two responses that some species may display during unfavourable environmental conditions in which insufficient energy is available to grow and breed. These dormant states allow species to survive by reversibly down-regulating their metabolism to low levels for up to several years. Among invertebrates, many species show quiescent states at stress conditions, including nematodes, crustaceans such as the brine shrimp *Artemia franciscana* (Hand, 1998), the estivating pulmonate snail *Helix aspersa* (Pedler et al., 1996), and various insect species entering in diapause, such as *Helicoverpa armigera*. Studies have proposed that a coordination mechanism is required when animals enter into the dormant state so as to maintain cellular homeostasis by both energy-consuming and energy-producing pathways. During quiescence, *A. franciscana* can reduce its metabolism essentially to zero, this metabolic-rate suppression affects the mitochondrial respiratory capacity and the rates of ATP-consuming processes (Barger et al., 2003). In the embryos of *Artemia franciscana*, anoxia provokes the organism to enter into a quiescent state. During experimental gradual oxygen removal, various biochemical responses are observed, such as a pH decrease, the reduction of heat production and the depression of ATP levels. Also, genetic responses, such as the down-regulation of RNA transcription, are observed during quiescence (Hand, 1998).

Often, metabolic rates have been inversely related to the life span of mammals. Moreover, when mitochondrial respiration has been inhibited by RNAi techniques, the life span extends in *C. elegans* (Lee et al., 2003), and long-lived mutants of this nematode concomitantly show decreased metabolic rates (Stuart & Brown, 2006).

The process by which mitochondrial respiration affects or extends life span has been studied in several organisms, including yeasts, worms, flies and mice (Lee et al., 2010). Electron transport in mitochondria is the main producer of superoxide anion (O<sup>-</sup>), which in turn generates several types of reactive oxygen species (ROS), as has been mentioned (mitochondrial Complex III). In fact, according to various studies, ROS are not only undesirable toxic metabolites promoting organism oxidative stress, but they are also molecules that participate in the mitochondria-nucleus's signalling pathways (Storz, 2006). Emerging data on *C. elegans* suggests a new described pathway where superoxide serves as an intracellular messenger, whereby with increasing superoxide concentration a signal transduction pathway is triggered, resulting in changes in the pattern of gene expression of nuclear proteins and which finally results in an increased life span (Yang & Hekimi, 2010). However, different mechanisms have also been proposed as being implicated in the aging process, such as diet restriction, ubiquinone deficiency and the hypoxic response (Klimova & Chandel, 2008).

At this point, this chapter would not be complete if the energetic costs of flying for insect species were to be omitted. This activity is probably the most expensive process recorded in nature. It is by now a well-known and remarked-upon fact that the metabolic rate during insect flight increases over 50-100 fold above the resting rate (Ellington, 1985). Thus, it is clear that the flight muscle of insects is the model tissue that many researchers have adopted in order to understand mitochondrial function since it is capable of effectively producing and hydrolysing large amounts of ATP (Sherwood et al., 2005). Insect flight is a highly oxygen-dependent process, and the flight muscle metabolism is fully aerobic; thus, it has

been suggested that the amazing aerobic capabilities of insects are based on a highly efficient mode of oxygen delivery that includes their oxygen transport system in a well distributed system of tracheae and tracheoles (Wegener, 1996).

In addition, several studies have demonstrated that the function and energy needs of certain tissues are highly correlated with the number of mitochondria per cell (Robin & Wong, 1988). This agrees with the large quantities of mitochondria with pronounced cristae and large surface areas that are found in the flight muscle cells of the honey bee *Apis mellifera* (Suarez et al., 2000). To date, it is well-known that oxygen uptake rates in mitochondria cristae are much higher in the flying muscle of *A. mellifera* than that observed in mammals' mitochondria - this can explain the higher electron transport rates observed in such enzymes as cytochrome c oxidase, whose maximum catalytic capacity was recorded in this species during flight - (Suarez et al., 2000).

Besides the increase on the ATP hydrolysis rate during flight, other mitochondrial adaptations to the highly and continuous energy requirements of flying species have been reported, such as the remarkable dependence on the synthesis of energy-rich phosphate compounds like phosphoarginine. Phosphoarginine, as mentioned above, constitutes a usable pool of high energy phosphate (Hird, 1986) so as to maintain the high rate of ATP turnover in flying insects (Wegener, 1996).

In addition to the various metamorphic changes in their life, crustaceans undergo a frequent and cyclic process: molting. During the molt cycle, crustaceans are exposed to a temporary scarcity of food since they lack the ability to handle food until their new exoskeleton is synthesised. Several adaptive strategies have been recognised as being employed by these organisms so as to avoid the adverse effects of starvation, such as the storage of fuel compounds in their midgut gland (Sanchez-Paz et al., 2007), changes in locomotor activity (Hervant & Renault 2002), and a decrease in oxygen consumption (Morris et al., 2005). However, little attention has been paid to the bioenergetic consequences of starvation in shrimp; since the composition of food plays an important role in oxidative phosphorylation, the nutritional status of shrimp species, such as *Litopenaeus vannamei*, may affect its major bioenergetic functions.

In our lab, we have hypothesised that, due of its central role in the cell energy metabolism, the expression of genes encoding the different polypeptide subunits that compose ATP synthase during unpredictable episodes of food shortage may ultimately be modulated. Thus, we experimentally evaluate the effect of starvation in the gene expression of subunits *atp $\alpha$* , *atp $\beta$*  and *atp9* in the shrimp midgut gland, during a period of short-term food deprivation (5 days). Our results (Figure 2) show that the mRNA amounts from subunits *atp $\alpha$*  and *atp $\beta$*  which directly participate during ATP synthesis decreased as starvation time increased; however, no significant changes were observed in the mRNA amounts of *atp9*, which forms the oligomeric ring from Fo in the shrimp ATP-synthase.

Sanchez-Paz et al., (2007) reported a gradual decrease of glycogen in the midgut gland of the white shrimp as starvation progressed. After a 24 h starvation period, the glycogen content dropped by about 50%, which correlates with an increase of the *atp9* subunit after 24 h of starvation, suggesting that glycogen may be used as fuel to generate ATP and pyruvic acid. As glycogen stores become depleted, the organism must increasingly rely on fatty acid catabolism as a source for ATP synthesis. In general, starved shrimp showed a sharp decrease in their midgut gland lipidic constituents for up to 120 h (more noticeable in acylglycerides).

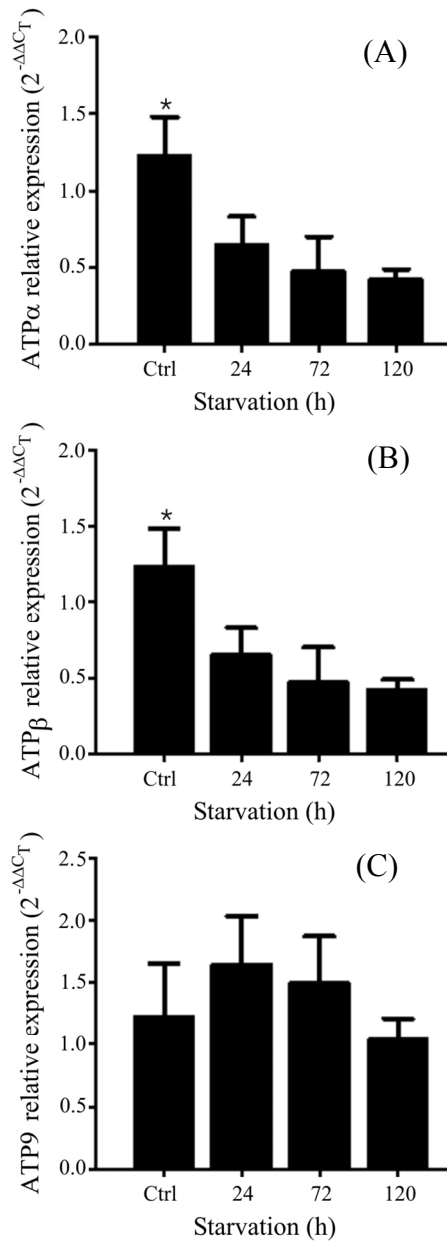


Fig. 2. The relative expression of A) ATP $\alpha$ , B) ATP $\beta$  and C) ATP9 mRNA in the midgut gland of the white shrimp *Litopenaeus vannamei* in response to a short-term starvation period. Expression values are given based on normalisation to L8. The data is represented as the mean and standard deviation of triplicate determinations. (\*) Statistical significance was considered at  $P < 0.05$ .



Various studies have shown that during starvation-induced lipolysis there is a decrease in the amount of ATP, which was accompanied by a fall in some subunits of the FoF<sub>1</sub>-ATP synthase (Vendemiale et al., 2001). It is well-known that starvation tampers with cellular detoxification systems and may expose cells to oxidative injury (Di Simplicio et al., 1997; Vendemiale et al., 2001), leading to an impaired production of ATP and a reduced uptake of substrates for mitochondrial metabolism. The results from our study, together with results from previous studies, prompt us to suggest that shrimp are capable to satisfy their energy demands through a complex combination of mechanisms that enables them to survive the adverse effects of food scarcity.

Due to its density, viscosity (800 times more dense and 50 times more viscous than air) and low oxygen solubility, water - as a respiratory medium - imposes difficulties for aquatic breathers in obtaining the necessary supply of oxygen from their surrounding environment so as to keep breathing and bringing oxygen into their systems. This process becomes more complicated when considering additional parameters (such as temperature, salinity and depth) affecting the dissolved oxygen concentration of seawater, causing additional constraints on marine species' development (Sherwood et al., 2005). All the species inhabiting marine environments should face these dynamic environmental conditions, which in over the last few decades have been seriously affected by a wide variety of anthropogenic activities, such as industrial and agricultural runoffs (Wu, 2002).

Several studies have found that marine invertebrates may respond to stress conditions by changes at the transcriptional level. In crustacean species such as the crab *Eriocheir sinensis*, different gene expression profiles from gills were characterised during acclimation to high cadmium concentrations in water. Analyses have revealed over-expressed genes, such as disulphide isomerase, thioredoxin peroxidase and glutathione S-transferase. Under the same conditions, ATP synthase beta, alpha tubulin, arginine kinase, glyceraldehyde-3-phosphate dehydrogenase and malate dehydrogenase were down-regulated. The results demonstrated that acute and chronic exposure to waterborne cadmium induced a decreased abundance of the transcript-encoding enzymes involved in energy transfer; this suggests that chronic metal exposure induced an important metabolic reorganisation (Silvestre et al., 2006).

Some other species which face high cadmium concentrations are marine intertidal molluscs, such as oysters, which live in estuaries where fluctuating temperatures and levels of trace metals are known to directly affect mitochondrial function. Isolated mitochondria from the oyster *Crassostrea virginica* which were exposed to low cadmium concentrations (1 µmol·L<sup>-1</sup>) resulted in a progressive uncoupling that increased with the increasing dose of cadmium; this response agrees with that observed in mammals. However, unlike mammals, molluscs are ectotherms and the exposure to the combined effects of high temperatures and cadmium concentrations severely affected mitochondrial function since elevated temperatures increased the sensitivity of this organelle to cadmium and promoted an increase in the rate of ROS production (Sokolova, 2004). These results highlight the key role of temperature in the mitochondrial system of ectotherm species.

Most invertebrates are described as ectotherm species because their body temperatures vary with the environment. At very low temperatures, polar marine invertebrates were expected to show low metabolic rates, as previously observed in Antarctic fish; however, in 1999 Sommer & Portner found important intra-specific differences in the mitochondrial function of the polychaete *Arenicola marina* from the North Sea and the colder White Sea. Their results

concluded that invertebrate life is more costly at higher latitudes, where oxygen uptake, tissues mitochondrial densities and mitochondrial capacities were higher.

Remarkable abilities have been recorded in invertebrate species inhabiting extreme environments. The term “metabolic plasticity” perfectly describes such organisms as the intertidal periwinkle snail *Littorina littorea*, which has the ability to deal with very low temperatures and also to tolerate the changing environmental conditions imposed by the tidal cycle, implying continuous oxygen deprivation (Storey, 1993). Besides the biochemical and physiological mechanisms previously identified in this species, the over-expressed gene encoding a metallothionein (MT) was recently found during the exposure to low temperature and anoxic conditions of the tissues of *L. littorea*. Since thermogenesis is a process that requires high oxygen consumption and since it is also accompanied by a sharp rise in reactive oxygen species (ROS) generation, the authors describe the ability of MT to function as an antioxidant and as a reservoir of essential metals that contributes to survival under these conditions (English & Storey, 2003).

The deep sea hydrothermal vents are a different type of extreme environment where thermophilic species such as the Pompeii worm *Alvinella pompejana* inhabit. Shin et al. (2009) studied the structure and biochemical characteristics of the Cu,Zn-superoxide dismutase (SOD) of this species and found striking similarities between this enzyme and that of humans, but with an enhanced stability and catalysis – characteristics that may mean that this enzyme is potentially suitable for scientific and medical application. Other mitochondrial proteins have been proposed as a part of gene therapy for devastating human diseases by preventing the cell damage caused by oxidative stress. AOX – the mitochondrial alternative oxidase previously mentioned – is suggested to work in any cell, becoming chemically active only when it is required. AOX is provided to the cell by engineering a gene from a marine invertebrate snail *Ciona intestinalis*; this protein is under analysis as a therapeutic tool tested in mammalian disease models (Hakkaart et al., 2006).

## 5. How do invertebrates face hypoxia?

Hypoxia is probably one of the most studied factors affecting the central metabolic pathways of living organisms, including invertebrates. Aquatic species usually face hypoxic events in freshwater or marine environments as a daily cyclic routine in the shallow waters of lagoons, estuaries and mangroves during the dark hours, when plants and algae do not produce oxygen and organic matter is continuously oxidised (Dall et al., 1990). However, nowadays the frequency, abundance and severity of hypoxic events in coastal waters have increased due to anthropogenic activities resulting in deteriorating environments affecting marine organisms (Diaz, 2001). It is well known that hypoxia depresses the growth rate of marine animals, as it disturbs metabolic pathways and promotes the reallocation of energy resources (Wei et al., 2008; Wang et al., 2009).

Several studies have examined the physiological responses of invertebrate species to hypoxia, such as growth, stress resistance and even behaviour patterns in aquatic species able to vertically and horizontally migrate through the water column to reach more oxygenated zones (Eads & Hand, 2003; Burgents et al., 2005; Abe et al., 2007; Seibel, 2011). In fact, among invertebrates there are hypoxia-tolerant species, such as bivalve molluscs and annelids, with highly adapted structures and mechanisms to deal with hypoxia, and some others, such as crustaceans, whose tolerance to hypoxia depends on their habitat, food, and energy needs. Unfortunately, the responses to hypoxic conditions – at the molecular and

biochemical levels - of the mitochondrial proteins and enzymes that participate in the respiration process are still poorly studied for most invertebrate species.

The main physiological responses from invertebrates to hypoxia are somewhat similar to those from vertebrates since in the reduction or absence of oxygen, animal cells are not able to produce enough energy to survive. Such general responses are clearly a legacy of the evolutionary past from ancestral forms and they serve adaptive ends. In marine species, such as crustaceans and molluscs, reduced oxygen consumption and metabolic rates have been confirmed during hypoxia; in addition, glucose utilisation and lactate accumulation as indicators of a switch to anaerobic metabolism have been detected at low oxygen concentrations in water (Racotta et al., 2002; Martinez-Cruz, 2007; Soldatov et al., 2010). In the brine shrimp *A. Franciscana*, the intracellular pH falls at anoxia, heat production is reduced and ATP concentrations are also depressed to low levels (Hand, 1998; Eads & Hand, 2003).

A large amount of information is now available about the changes at the transcriptional level promoted by hypoxia in invertebrates, most of it concerning aquatic species. In our lab, we have evaluated the effects of hypoxia in the gene expression of F<sub>0</sub>F<sub>1</sub> ATP synthase subunits, such as *atp9*, *atp6*, *atpα*, *atpβ*, *atpγ*, *atpδ*, and *atpε*, in different tissues of the white shrimp *L. vannamei*. Results show a general trend towards increase the amount of mRNA as oxygen concentrations decrease (Martinez-Cruz, 2007; Martinez-Cruz et al., 2011; Martinez-Cruz et al. in preparation). Also, significant changes in the amount of mRNA from the mitochondrial- and nuclear- encoded subunits of the ATP synthase were detected at different molt stages and tissues, according to the energy requirements of each stage and the specific requirements of the function of each tissue (Muhlia-Almazan et al., 2008). Chronic exposure to severe hypoxia (1.5 mg/mL during 7 days) also causes the increased transcription of mitochondrial-encoded genes, such as the 16S, CO1, and CO2 subunits from the cytochrome C oxidase in the grass shrimp *Palaemonetes pugio* (Brouwer et al., 2008). To date, microarray technologies have revealed a set of genes that are up- and down-regulated in *P. pugio* during chronic, acute and moderate hypoxia; the results revealed that various genes encoding mitochondrial proteins were affected (Li & Brouwer, 2009).

In the absence of oxygen, animal cells activate transcription factors - such as the well-studied vertebrates hypoxia-inducible factor (HIF) - which has been reported in invertebrates from worms to flies (Semenza, 2007). When activated, HIF leads the organism to exhibit metabolic adaptation to hypoxia by regulating the genetic expression of some proteins and enzymes involved in central biological processes such as glycolysis, erythropoiesis, breathing and angiogenesis so as to maintain cell homeostasis (Klimova & Chandel, 2008). In the shrimp *P. pugio*, a homolog protein to HIF- $\alpha$  called gsHIF was found in this hypoxia-tolerant species. It includes all the conserved domains of vertebrates' HIF proteins, and an additional polypeptide sequence of 130 residues that has not been found in databases, and its participation in the functional properties of the protein has not yet been determined (Li & Brouwer, 2009). In the white shrimp *L. vannamei*, HIF-1 is a heterodimer formed by two subunits: HIF-1 $\beta$ , which is constitutively expressed in shrimp cells and HIF-1 $\alpha$ , which is differentially expressed in hypoxic conditions. HIF-1 is suggested in crustaceans to be the master regulator that senses decreased oxygen availability and transmits signals promoting the physiological responses mentioned above (Soñanez-Organis et al., 2009). Additional functions have been attributed to HIF in coral species, such as *Acropora millepora*, where the diel cycle in the central metabolism appear to be governed by the circadian clock and regulated by the HIF system operating in parallel (Levy et al., 2011).

As a part of the HIF-regulated metabolic responses to hypoxia in invertebrates, the activities of specific enzymes – most of them part of the central metabolism – are known to increase. In bivalves such as *Anadara inaequivalvis*, the increased activities of enzymes – such as malate and lactate dehydrogenases – were detected at hypoxia (Soldatov et al., 2010). Also, increases in the catalase and GST activities during anoxia in the estuarine crab *Chasmagnathus granulata* have been observed. It has been suggested that such responses may be a strategy to prepare the organisms for oxidative stress in an effort to protect tissues against oxidative damage during re-oxygenation. An important decrease in SOD activity (which occurred after aerobic recuperation) was also detected; and it could have been caused by the accumulation of hydrogen peroxide production during re-oxygenation (de Oliveira et al., 2005).

At normoxia, the small levels of ROS produced by the metabolism in normal animal mitochondria come from carrying electrons along the mitochondrial complexes I, II, and III (Turrens, 2003). However, when oxygen levels are reduced, the presence of the final electron acceptor in the mitochondrial respiratory chain fails, producing a reduction in the rate of electron transport and a decrease in oxygen consumption. Under these conditions, the membrane potential increases as does ROS production (Guerrero-Castillo et al., 2011).

It has been reported that in invertebrate species considered to be hypoxia-tolerant, the absolute rate of H<sub>2</sub>O<sub>2</sub> production is at least an order of magnitude less per mg of mitochondrial protein than that measured on mammalian species (Abele & Puntarulo, 2004). However, some other species which are not tolerant to hypoxia tend to produce higher levels of ROS at low oxygen levels; thus, it is suggested that they display alternate pathways in order to maintain the mitochondrial respiratory rate and avoid an over-production of ROS (Guerrero-Castillo et al., 2011).

Nowadays, the alternative mechanism of proton sinks has been evidenced in invertebrates since uncoupling proteins (UCPs) have been identified in these species (Abele et al., 2007). Such proteins have been involved in various functions, including thermoregulation, body composition, antioxidant defence and apoptosis. UCPs are thought to dissipate the proton gradient across the inner mitochondrial membrane and may help in controlling ROS production (Yu et al., 2000).

In *Drosophila*, an UCP5 protein over-expressed in a heterologous system has shown to have similar functional abilities to an uncoupling protein (Fridell et al., 2004), while in the marine eastern oyster, *Crassostrea virginica*, UCP5 is represented by two transcript forms: UCP5S (small) and UCP5L (large). However, their function has not been determined since its gene expression is not affected by hypoxia, cadmium exposure or different temperatures (Kern et al., 2009). In addition, a novel protein (UCP6) in invertebrates is considered to be an ancestral form of the vertebrates UCP1, UCP2, and UCP3 (Sokolova & Sokolov, 2005).

In mammals, it is known that less-severe hypoxia induces protective mechanisms. This phenomenon – called hypoxic preconditioning (HP) – appears in two forms: immediate preconditioning (which occurs only a few minutes after a sub-lethal hypoxic episode and declines after 4 h) and delayed preconditioning (which requires gene expression changes and takes place 12 to 24 h later and can last for days) (Dirnagl et al., 2009). In the nematode *C. elegans*, the delayed form of HP has been found to induce unfolded protein response pathways – at this point, misfolded proteins serve as early hypoxic sensors that trigger signalling pathways to induce a hypoxia protective response (Mao & Crowder, 2010).

## 6. The role of mitochondria in invertebrate programmed cell death (Apoptosis)

Besides the various functions just described, mitochondria also acts as the arsenal of the cell. Numerous and complex processes, still poorly understood, can trigger the release of mitochondrial components into the cytoplasm and subsequently induce cellular apoptosis of the organelle (Hengarter, 2000). It is not our intent here to provide exhaustive coverage of all the issues relating to apoptosis in great detail, but rather to give the reader a basic description of the process – to highlight its importance and to show the challenges that those interested in this topic will face.

As has been mentioned, studies in invertebrate biology are paramount to an understanding of biodiversity and to the search for potential uses for their metabolic capabilities and products for biotechnologies. Besides, comparative sciences may facilitate the use of invertebrate models in understanding the biology and pathology of farmed animals and humans. This is due – in spite of differences in the biochemical, physiological, and cellular characteristics that make invertebrates and vertebrates so obviously different – to the fact that most parts of such grades of their biology have remained similar in both groups through their evolution. For example, invertebrate cells – whether wounded by harsh environments or by the expression of abnormal proteins – die as do vertebrate cells, indicating that the powerful advantages of invertebrate molecular genetics might be successfully used for testing specific hypotheses about human diseases, for the discovery of drugs and for non-biased screens for suppressors and enhancers of maladies (Driscoll & Gerstbrein, 2003). The same criteria apply for all cellular functioning, as for apoptosis.

Apoptosis (from the Greek: “falling off”) – or programmed and regulated cell death and elimination – is a pivotal process in embryogenesis, the orderly elimination of wounded or infected cells, and the maintenance of tissue homeostasis. The process is so important that it is estimated that on a daily basis the human body must get rid of approximately  $10^{10}$  cells. Through apoptosis, cells die quietly in a controlled, regulated fashion; while in another forms of cell death – such as in necrosis – a series of uncontrolled events occur leading to serious and irreversible damage. Given the proper conditions, apoptosis destroys the cell swiftly and neatly. In contrast, necrosis causes the rupture of the cell, releasing its content into the surrounding tissue. Tampering with apoptosis may result in devastating health problems, such as cancers, immune diseases, neurodegenerative disorders and the proliferation of viruses. Apoptosis is executed by a variety of membrane, organelle, cytoplasmic and nucleus signalling, and initiator and effector molecules, including a subfamily of cysteine proteases known as caspases (Jiang & Wang, 2004).

In mammals, the active role of mitochondria in apoptosis induction has been well-established. In invertebrate models of apoptosis, such as the fly *Drosophila melanogaster* and the worm *C. elegans*, the role that mitochondria play during apoptosis and, in particular, during apoptosis initiation is less clear (Rolland & Conradt, 2006). While key regulators of apoptosis in *Drosophila* and *C. elegans* have been found in association with mitochondria, the significance of these associations has not been rigorously tested.

The regulated destruction of a cell is a basic process in Metazoa, as multicellular animals are obligated to remove damaged or harmful cells. During apoptosis, cells die in an orderly, regulated sequence of molecular, biochemical, and cellular processes. According to the endosymbiotic theory, the origin of apoptosis is currently regarded as the result of molecular interactions in which some components of a signal transduction pathway affects

other pathways through interaction of some initiator and effector proteins. Accordingly, apoptosis could have arisen simultaneously with – and as a by-product of – endosymbiosis (Kroemer, 1997). However, it has also been proposed that apoptosis may be the result of the acquisition of the aerobic metabolism by early eukaryotes (Frade & Michaelidis, 1997).

Apoptosis is a unique phenomenon of tissue kinetics as it can be said that life is critically controlled by the operational centre of cell, the nucleus. Instead, death is a process controlled by the power house of the cell, the mitochondria. Thus, even cells lacking nucleus commit apoptosis. In general, the two-step membrane depolarisation and free radical release taking place in the mitochondria may trigger apoptosis. This in fact is not so peculiar if we understand that mitochondria were once free-living bacteria which did not need an external gene control for achieving their functions. Once each came into symbiosis forming a eukaryotic cell, it retained some capacity to operate partially independently.

There are several major apoptotic pathways, but the most well-known and studied are the extrinsic and the intrinsic pathways, which respond to different environmental and cellular challenges in vertebrates. The intrinsic pathway is also called the mitochondrial pathway because of the involvement of mitochondria. There are mitochondrial proteins that induce this process (proapoptotic) and others that limit cell death (antiapoptotic). Both proteins interact so as to cooperate and govern the cell's fate. Also, the origin of the activation signals of apoptosis taking place on the mitochondria is a clue molecule, cytochrome C (Cyt C), which is released from the mitochondria to form the apoptosome complex. The intrinsic pathway – with some differences – is a mostly conserved pathway among metazoans (for a comprehensive review look at Wang & Youle, 2009). Cyt C is a key component of the apoptosome complex for activating the initiator caspase-9 after its release from mitochondria. Under non-apoptotic conditions, Cyt C is kept inside the respiratory chain. Against some cellular challenges, like the alteration of the DNA in the mitochondria or the nucleus, Cyt C is released from its membrane, crossing the external membrane and initiating the formation of the apoptosome complex. In essence, mitochondrial proteins – like Cyt C and caspases – are not hired guns and during non-apoptotic conditions they are responsible for various basic mitochondrial roles for normal cell functioning. The compartmentalisation of such mitochondrial proteins isolates them from interacting with partners or targets, a mechanism to prevent the unwanted activation of apoptosis in normal cells. Only after their appropriate release into the cytoplasm do such proteins play the role of triggers to initiate the cell's suicide.

The classical invertebrate model organisms for the study of apoptosis are *C. elegans* and *Drosophila*. In spite of the fact that the regulators of apoptosis have been found in such model organisms, the involvement of mitochondria in apoptosis is not conclusive. So far, no irrefutable evidence of the release of Cyt C from the intermembrane space has been found. Also, the involvement of Cyt C in the apoptosome formation in *Drosophila* is controversial, and some evidence suggests that Cyt C is not necessary (Rolland & Conradt, 2006).

The current evidence indicates that the whole process of apoptosis -including the involved proteins and the regulation mechanisms- in crustaceans is far more diverse than has been assumed from the studies with model organisms. Recent studies have shown that several proteins in the apoptotic network are quite conserved between mammals and arthropods; however, it is clear that the integration of such homologous proteins in the physiology and pathophysiology of crustaceans needs further experimental assessment. Some unresolved questions regarding this topic are: how does the regulation of the process occur? Is

crustacean apoptosis transcriptionally regulated, as in *Drosophila* (RHG 'killer' proteins)? Or is it controlled by pro- and anti-apoptotic Bcl-2 family proteins, as in vertebrates? The issues that should be investigated in the short-term are whether the calcium-induced opening of the mitochondrion permeability transition pore (MPTP), commonly found on vertebrate species, also occurs in crustaceans. Furthermore, the study of the differences in the regulation of the intrinsic pathway of crustacean apoptosis will lead to an understanding of their adaptation to challenging environments; this is because marine organisms have to deal with seasonal as well as circadian changes in environmental variables. Some examples are UV radiation, temperature and dissolved oxygen, and even some biological stresses such as toxins that may vary over time. But this is not all: other variables that may inhibit apoptosis must be considered. "Characterisation of the players, pathways, and their significance in the core machinery of crustacean apoptosis is revealing new insights for the field of cell death" (Menze et al., 2010).

Apoptosis is a key host response to viral infection. Viruses that can modulate a host's apoptotic responses are likely to gain important opportunities for transmission. Here, we review recent studies that demonstrate that the particles of Invertebrate Iridescent Virus6 (IIV-6) (Iridoviridae, genus Iridovirus), or an IIV-6 virion protein extract, are capable of inducing apoptosis in lepidopteran and coleopteran cells, at concentrations 1000-fold lower than that required to shut-off the host's macromolecular synthesis (Williams et al., 2009). Throughout the process of pathogen-host coevolution, viruses have developed a battery of distinct strategies to overcome the biochemical and immunological defences of the host. Thus, viruses have acquired the capacity to subvert host cell apoptosis, control inflammatory responses, and evade immune reactions. Since the elimination of infected cells via programmed cell death is one of the oldest defence mechanisms against infection, disabling host cell apoptosis might represent an almost obligatory step in the viral life cycle. Conversely, viruses may take advantage of stimulating apoptosis, either to kill uninfected cells from the immune system or else to induce the breakdown of infected cells, thereby favouring viral dissemination (Galluzzi et al., 2008).

## 7. Conclusion and future perspectives

As stated by Van der Giezen in 2009 "over the last 5-10 years, it has become apparent that the organelle known as the mitochondrion is a much more fluid entity than generally believed," so "why should mitochondrion be the same in all eukaryotes while other cellular structures show such great evolutionary malleability?"

It is our belief that since natural selection has given invertebrates the opportunity to evolve in quick steps, a large window is opening in the field of mitochondrial research among these species, giving an outstanding opportunity to researchers to contribute to an increase in knowledge, not only because there is scarce information, but also because many species have shown special and unique characteristics that need to be explained.

At this point, the information reviewed clearly shows that invertebrates display remarkable physiological capabilities, including highly specialised mechanisms for adjusting mitochondrial functions to solve their energetic demands under the stressful conditions they usually face. These species also include within their systems ancient and novel molecules and structures acting to reach an adaptive state, from the increasing number of mitochondria per cell to the highly complex function of the HIF system.

It is also remarkable that the number of invertebrate species considered as potential models in the study of mitochondrial function has increased. New data on marine invertebrates, such as molluscs and crustaceans and non-*Drosophila* species, are emerging. Since there is still an immense lack of knowledge about invertebrates, important efforts in new animal models should focus on i) the description of mitochondrial systems in species inhabiting extreme environments, ii) the recognition and understanding of the causes and effects of mitochondrial disorders, and iii) the development of unsolved phylogenetic relationships among species and phyla. This may also open important opportunities for new biotechnological applications to better face the effects of global changes such as warming, hypoxic conditions and chronic stressors that specifically affect the central metabolic pathways in such species.

If the regulation of apoptosis in crustaceans is as varied as their diversity as a species, or at least their Families, then the potential for discovering novel biomolecules is immense. Such molecules may find uses in biotechnologies across diverse industries, including pharmacology. We endorse the hypothesis that an advanced knowledge in apoptosis will provide some clues about how crustaceans deal with viral infections and enable the proposal of feasible strategies to protect farmed crustaceans.

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# Optimisation of Cell Bioenergetics in Food-Associated Microorganisms

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## 1. Introduction

Microorganisms display a considerable versatility, with mechanisms that govern cell bioenergetics and a large number of redox active molecules being used as electron donors or acceptors. We will not review the basis of microbial bioenergetics here, but instead focus attention on the metabolic systems that microorganisms have evolved to optimise the efficiency of cell catabolism and cell energy homeostasis. The mechanisms that act in the regulation of cell bioenergetics belong to the complexity of biological systems in which large networks of metabolic pathways interact to govern the life and responsiveness of cells towards environmental fluctuations. During growth, all microorganisms determine considerable changes in the environmental concentration of nutrients, organic acids and other molecules generated by cell catabolism. As a consequence, microorganisms are constantly faced with different environmental stimuli and stresses. The natural habitats of some microorganisms may fluctuate erratically, whereas others which are more predictable offer the opportunity to prepare in advance for the next environmental change. In this context, microorganisms may have evolved the bioenergetic machinery to anticipate environmental fluctuations by adapting to their temporal order of appearance. Food matrixes represent an example of 'predictable' fluctuating environments, generated by anthropic activities and able to drive the speciation of several microorganisms. The nutrient's richness, and specifically the abundance of mono- and disaccharides that characterise several food matrixes (such as milk and grape juice), have allowed the speciation of lactic acid bacteria (LAB) and yeasts with a high fermentation capacity. The bakers' yeast *Saccharomyces cerevisiae* degrades sugars to two-carbon components - in particular, ethanol - even in the presence of excess oxygen, thus using a fermentation metabolism instead of the energetically favourable respiration metabolism (2 mol versus about 32 mol of ATP per mol of glucose respectively). *S. cerevisiae* alcoholic fermentation has been exploited for several millennia throughout the world in a variety of food processes of crucial importance for humans, such as the making of beer, wine and bread. Moreover, LAB species have partially lost the genetic information need in order to carry out a respiratory metabolism on behalf of a homofermentative pathway in which lactic acid is the primary product, or a heterofermentative pathway in which lactic acid, CO<sub>2</sub>, acetic acid and/or ethanol are produced (Kandler, 1983). The seemingly simplistic metabolism of LAB has been exploited throughout history for the preservation of foods and beverages in nearly all societies, and dates back to the origins of agriculture. The domestication of LAB strains passed down through various

culinary traditions and the continuous passage of food stuffs has resulted in modern-day cultures that are able to carry out these fermentations (Makarova *et al.*, 2006).

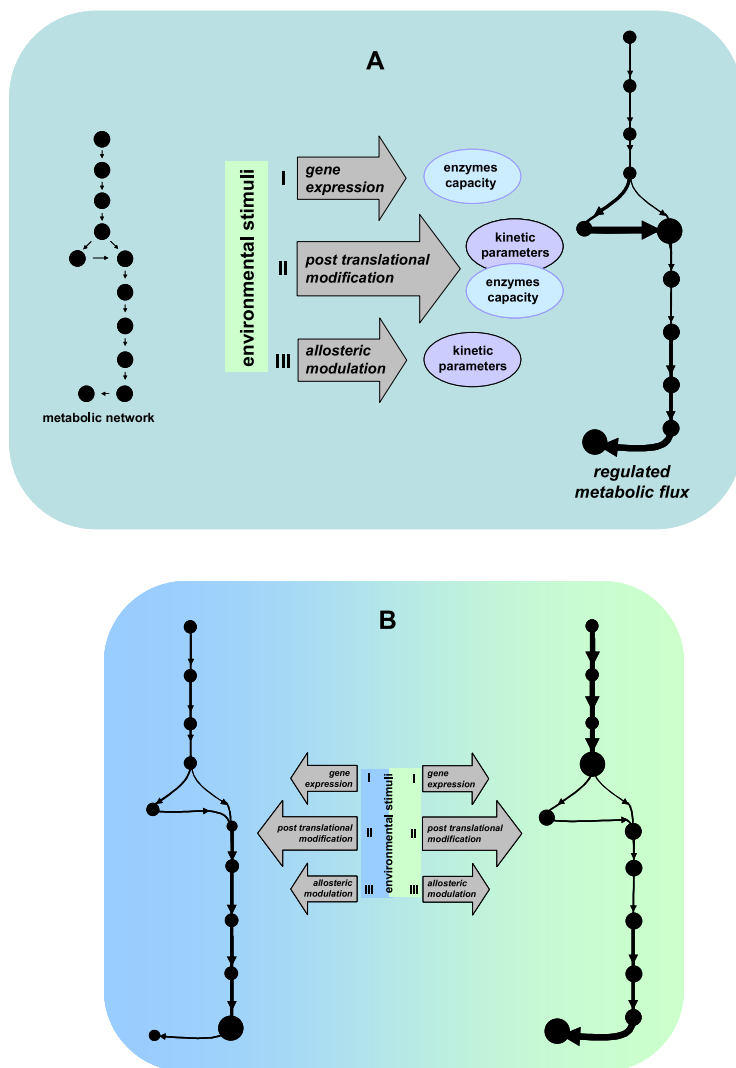


Fig. 1. View of the overlapping regulatory mechanisms modulating metabolic fluxes. A) Example of a metabolic network and schematic representation of the three layers of cellular regulatory mechanisms. The metabolic flux and metabolite pools' concentrations are subjected to the three layers of regulation. The regulation mechanisms act as a response to environmental stimuli. B) Different environmental stimuli (blue and green areas) affect the metabolic fluxes thereby determining the accumulation or depletion of intermediate metabolites.



Both LAB and *S. cerevisiae* have definitely evolved their energetic metabolism to reach maximum fitness in a defined environmental niche characterised by a high carbohydrates concentration. Milk, the proposed evolutionary environmental niche for the LAB *Streptococcus thermophilus*, *Lactobacillus delbrueckii* subsp. *bulgaricus*, and the "domesticated" strains of *Lactococcus lactis* (Bolotin *et al.*, 2004; van de Guchte, 2006; Passerini *et al.*, 2010), and the man-made niches, grape juice, has driven the evolution of the domesticated strains of *S. cerevisiae* (Martini, 1993, Fay & Benavides, 2005). These two are environments in which mono- and disaccharides resources are both large and dense. In these environmental contexts, fast sugar consumption, lactic acid or ethanol production, accumulation and tolerance, and the ability to propagate without oxygen are some of the 'winning' traits, and they have apparently evolved and become specialised to perfection in these fermenting microorganisms. In other words, energetic limitation is an important factor for organisms in their natural environment and therefore the ATP-production pathways have been under strong selection pressure during evolution (Pfeiffer *et al.*, 2001). Similarly, we can hypothesise that all mechanisms acting in the regulation and optimisation of the ATP-production pathways are subjected to the same selection pressures.

The complexity of the understanding of how metabolic fluxes are modulated arises from multiple overlapping regulatory mechanisms and metabolic feedback into regulatory networks (Figure 1). The *in vivo* capacity of an enzyme to govern and modulate a metabolic flux is a function of its abundance and kinetic properties. Both abundance and the kinetic properties of enzymes are governed by three layers of cellular regulatory mechanisms: i) *gene expression*, acting on enzyme abundance, ii) *post-translational modification*, modulating enzyme abundance and kinetic parameters, and iii) *allosteric modulation*, exclusively affecting the kinetic parameters. Moreover, the *in vivo* metabolic flux depends also on the *in vivo* reactant concentrations (Gerosa & Sauer, 2011) which are function of thermodynamics and reaction kinetics, i.e. parameters that a cell may modulate only indirectly.

This chapter examines the mechanisms regulating the primary metabolism by using as model organisms the dairy species *L. lactis* among prokaryotes, and the bakers' yeast *S. cerevisiae* among eukaryotes. Moreover, some enzymatic activities and metabolic pathways are described and their physiological role is revisited, taking into consideration the optimisation of the cellular bioenergetics as a result of an environment-dependent selection pressure.

## 2. The regulation of the energetic metabolism in lactic acid bacteria

Despite the wide use of LAB in food production and the role of some species for their health benefits for the human gastro intestinal tract, the regulatory mechanisms that govern the main energetic metabolism of these bacteria have still not been completely disclosed. Most of the studies have been carried out on the 'domesticated' *L. lactis* species, a member of the LAB widely used in the industrial manufacture of milk-fermented products. The most important industrial application of *L. lactis* is based on its energetic metabolism, which leads mainly to the production of high amounts of lactic acid. Anaerobic glycolysis is the principal energy-generating process of *L. lactis*, it is thus considered exclusively as a fermenting microorganism. Nevertheless, in aerobic conditions and in presence of an exogenous source of heme, *L. lactis* may be able to carry out oxidative phosphorylation (Duwat *et al.*, 2001). This cofactor-dependent respiration capacity has also been discovered in other LAB species (Lechardeur *et al.*, 2011). Although named and used for their capacity to produced lactic

acid, numerous LAB can be induced through a respiratory metabolism, thereby improving the population size and its survival. It follows that *L. lactis* is currently industrially produced as biomass using a heme-dependent respiration, while in the manufacture of fermented milk and cheeses the homolactic fermentation has a key role in the food matrix's transformation or preservation as a consequence of the sizable production lactic acid. Due to the relatively recent timing of studies on the respiratory behaviour of *L. Lactis*, most of the work carried out in order to elucidate the intricate regulation of the energetic metabolism in this species has focused on lactic fermentation. A detailed description of the dynamics of metabolic pools were obtained through *in vivo* measurements, and kinetic analysis by using cell extracts and the techniques of nonlinear systems modelling (Voit *et al.*, 2006). The monitoring of the glycolytic intermediates made, at first glance, intuitive sense. During homolactic fermentation, glucose was taken-up by lactococcal cells and converted into glucose 6-phosphate and then fructose 1,6-biphosphate. The latter is converted into trioses, which ultimately form lactate (Figure 2).

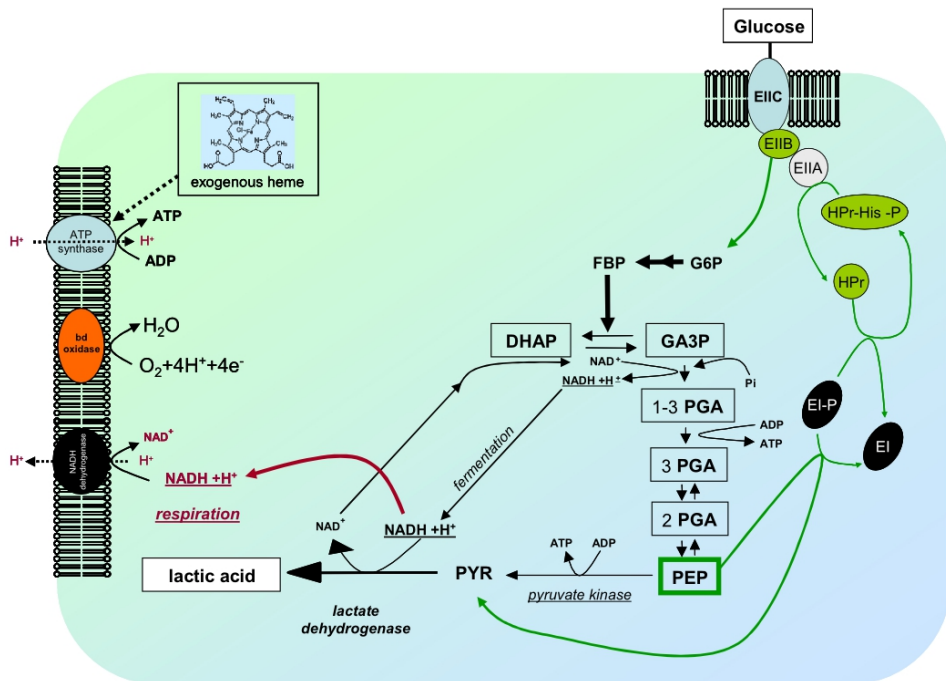


Fig. 2. Simplified representation of glycolysis, homolactic fermentation and heme-dependent respiration in *L. lactis*. The Black arrows show the metabolic fluxes. The red arrow shows the regeneration of NAD<sup>+</sup> occurring during the heme-dependent respiration. Glucose-6-phosphate (G6P), dihydroxyacetone phosphate (DHA-P), glyceraldehyde-3-phosphate (GA3P), 1,3-biphosphoglycerate (1-3PGA), 3-phosphoglycerate (3PGA), 2-phosphoglycerate (2PGA) phosphoenolpyruvate (PEP), pyruvate (PYR). The green arrows show the role of PEP as a phosphate donor in the glucose uptake, PTS-dependent phosphoenolpyruvate phosphotransferase system (PTS). EIIIC, EIIB, EIIA, HPr, HPr-His-P, EI, and EI-P are components of the PTS system.

While it is usually assumed that the accumulation of intermediates in a linear pathway is disadvantageous because their storage is chemically costly, in *L. lactis* it is a strongly persistent accumulation of trioses (3-phosphoglycerate and phosphoenolpyruvate) at relatively high concentrations (6–20 mM) after glucose consumption was observed (Voit *et al.*, 2006). The reason for the accumulation of trioses in the glycolytic pathway was identified when the overall primary metabolism was considered (Figure 2) together with the nutritional characteristics of the environments where many homofermentative bacteria, including *L. lactis*, live. These environments are characterised by the availability of glucose, which fluctuates widely between high concentrations and extended periods of starvation. As long as glucose is available, the glycolytic pathway is efficiently fed so as to obtain energy production and population growth. During glucose starvation, it becomes crucial to be well-prepared for future carbohydrate availability, when the cell must use them as fast as possible in order to restart the flux of the glycolytic pathway and grow. The maintenance of the high concentration of trioses is, therefore, necessary because glucose transport across the membrane depends upon phosphoenolpyruvate (PEP) as phosphate donor through a PTS system (Figure 2) (Voit *et al.*, 2006). As such, it can be speculated that *L. lactis* and other homofermentative LAB have evolved regulatory mechanisms to be able to control the level of PEP in order to bridge normal periods of starvation.

The maintenance of the 'necessary' concentration of PEP (PEP holding pattern) during starvation periods requires a fine tuning of downstream reactions in the pathway. If pyruvate kinase is closed too rapidly, unnecessary amounts of materials are stored in the form of trioses. Otherwise, if pyruvate kinase is deactivated too slowly, the glycolytic flux is accelerated towards the production of lactate. In other words, this regulatory mechanism has evolved to use the phosphotransferase system rather than ATP for glucose phosphorylation, thereby having most of the glycolytic process short-circuited through the PTS system. The main ecological advantage of such metabolic control is that cells use the first available glucose directly in order to produce pyruvate and then lactate, thereby acidifying the local environment when potential competitors attempt to take up glucose (Voit *et al.*, 2006).

Beside the PEP holding pattern, a further interesting metabolic control mechanism developed by *L. lactis* is represented by the 'feed-forward activation', which is quite rare in metabolic systems. The observation of a transient high concentration of fructose 1,6-biphosphate (FBP) during glucose consumption led to the hypothesis of a regulatory role for this glycolytic intermediate. It was suggested that FBP represents a strong activator of the pyruvate kinase (PK), thereby facilitating the very quick conversion of PEP into pyruvate and lactate while glucose is available. On the other hand, the reduction of glucose availability and, therefore a drop in FBP concentration, allows the decrease of PK activity until an effective stop when glucose is no longer available. The specific activation of PK by FBP has also affected the tuning of PEP concentration. This complex regulation of the energetic metabolism was strictly driven by environmental and ecological constraints. In a more general view, the 'PEP holding' strategy and the FBP 'feed-forward activation' represent an adaptive prediction of environmental changes (in this case related to the availability of carbohydrates). The increasing concentration of PEP during glucose starvation represents a metabolic anticipation of the next environmental stimulus (i.e. new

glucose availability). The anticipation of environmental change is considered an adaptive trait because pre-exposure to the stimulus - which typically appears early in the ecology - improves the organism's fitness when it encounters a second stimulus (Mitchell *et al.*, 2009). In the regulatory mechanisms described above, carbohydrates-availability and carbohydrates-starvation represent two consecutive and predictable environmental stimuli for fermentative domesticated LAB. In *L. lactis* the FBP 'feed-forward activation' represents a clear example of the relevance of allosteric regulatory mechanisms (Figure 1) on the modulation of the energetic metabolism.

A study done to explain the ability of *L. lactis* to grow, retain an active metabolism and survive at low pH highlights the complexity and the interplay of the overlapping regulatory mechanisms that operate in the regulation of the energetic metabolism. Culturing the microorganisms at low environmental pH sees the biomass yield diminished and the energy dedicated to maintenance increased as a response to the organic acid inhibition and cytoplasmic acidification (Even *et al.*, 2003). The request for energy for maintenance in acid conditions resulted in an increase in glucose consumption and the glycolytic rate with a significant reduction of biomass yield relative to ATP production. The adjustment of the metabolic flux in response to a low environmental pH was determined by an increase in the enzymes' capacity and by a specific modulation of the enzyme activities of the glycolytic pathway. A transcription profile and regulation analysis were effective in evaluating the contribution of each layer of regulatory mechanisms in the observed phenomena, highlighting the primary contribution of translational regulation to the increased concentration of glycolytic enzymes in acidic conditions, and confirming that the translation apparatus of *L. lactis* was optimised under acid stress conditions (Even *et al.*, 2003). In this case, the decrease of intracellular pH due to the acidity of the extracellular environment determines an important decrease in enzyme activity that was compensated for by an increase in the enzyme capacity through the efficiency of the translation machinery. In this context, it should be underlined that the enzyme concentration results from the rate of protein synthesis, corrected by dilution coefficient, which is affected by protein turnover (normally negligible except under conditions of stress) and the rate of cell division (at each cell division, the enzymes cellular content will be halved). It follows that cells growing at different rates will have substantially different rates of protein synthesis, even though the specific activities may remain similar (Even *et al.*, 2001). More recently, the primary role of allosteric regulatory mechanisms in controlling the glycolytic flux of *L. lactis* has been questioned, underlining the predominant regulatory role of the enzymes' concentration. This statement was supported by a new methodology whereby experimental measurements of fluxes and enzyme concentrations can be integrated into flux functions capable of predicting the 'falsome' from the proteome (Rossel *et al.*, 2011). Nevertheless, by such an approach the understanding of the role of each layer of regulation can only be partially addressed. In this case, the approach of regulation analysis is more informative in delineating which regulatory layer is responsible for establishing fluxes through a given enzyme (Gerosa & Sauer, 2011).

Concerning the hierarchical (i.e. expression and post-translational modification) regulation of the energetic metabolism of LAB, the little information available are related to the catabolite control protein CcpA, the major regulator of the carbon metabolism in *L. lactis* and

other Gram-positive bacteria. CcpA belongs to the LacI/GalR family of bacterial regulator proteins, and the disruption of the *ccpA* gene reduces the carbon catabolite repression (CR) of several genes involved in carbohydrate metabolisms. CcpA-mediated regulation depends basically on three elements: i) a specific *cis*-acting DNA sequence, termed catabolite-responsive element (*cre*) which is present near the promoter region of genes affected by CR, ii) the HPr protein, a phosphotransferase protein of the PTS system, and iii) the concentration of glycolytic intermediates (such as FBP). A metabolite-activated kinase has been shown to phosphorylate HPr on residue serine 46. This phosphorylated form of HPr [HPr(Ser-P)] interacts with CcpA, and this interaction enhances the binding of CcpA to *cre* on the promoter region of genes, so affecting the level of their expression. Indirectly, the phosphorylation of HPr on serine residue, enhanced by high level of glycolytic intermediates (e.g. FBP), reduces the number of HPr molecules that can be phosphorylated on histidine residue so as to ensure the functionality of the PTS system in sugar uptake across the membrane (Figure 1). Besides the role of CcpA in the control of sugar metabolism (mainly the sugar uptake), it was demonstrated that the role of this protein in the transcriptional activation of the glycolytic *las* operon, encoding the enzymes phosphofructokinase, pyruvate kinase and L-lactate dehydrogenase (Luesink *et al.*, 1998). Specifically, the disruption of the *ccpA* gene lowered the activity of pyruvate kinase and L-lactate dehydrogenase, resulting in the production of metabolites that are characteristic of a mixed-acid fermentation. It was, therefore, speculated that homolactic fermentation in *L. lactis* is maintained by CcpA-mediated repression of mixed-acid fermentation (Luesink *et al.*, 1998).

The regulatory function of CcpA on the energetic metabolism was further confirmed when its primary role in the regulation of aerobic and respirational growth of *L. lactis* was described (Gaudu *et al.*, 2003). CcpA was found to repress NADH oxidase activity, thus maintaining a correct NADH/NAD<sup>+</sup> ratio that directed the metabolism in favour of respiration. Moreover, it was proposed that a CcpA-mediated repression of the heme transportation system thereby prevented the oxidative damage provoked by precocious heme uptake at the start exponential growth. CcpA thus appears to govern a regulatory network that coordinates oxygen, iron and the energetic metabolism.

### 3. The regulation of the glycolytic pathway in *Saccharomyces cerevisiae*

The *S. cerevisiae* metabolism has been exploited by humans for several millennia through a variety of food processes in order to produce alcoholic beverages and leavened bread. Alcoholic fermentation began due to the presence of indigenous yeast in grapes, must, wort and dough, and with total ignorance regarding the existence of microorganisms and their fermentative role. In practice, humans started to apply microbiology before the role of yeast in beer, wine and bread production was formally proven by Pasteur in 1860 (Pasteur, 1860). Starting with the work of Emil Christian Hansen at the Carlsberg Laboratory in Copenhagen, in the early 1880s, the control of the *S. cerevisiae* metabolism became of crucial importance to enhance the efficiency of fermentation processes as well as the quality of the various products. Alcoholic fermentation is not the unique energetic metabolism in *S. cerevisiae* since it can use the more energetically favourable respiration, which sees a significant increase of ATP being produced per mole of glucose (Figure 3).

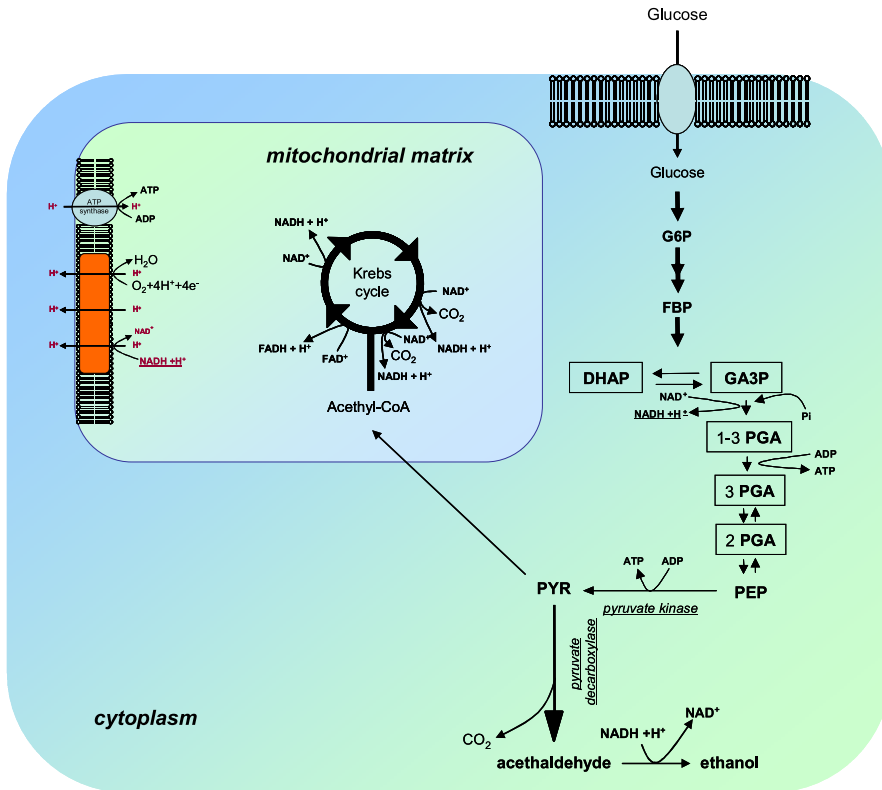


Fig. 3. Simplified representation of the glycolysis, alcoholic fermentation and respiration metabolism in *S. cerevisiae*. Black arrows show the metabolic fluxes. Glucose-6-phosphate (G6P), dihydroxyacetone phosphate (DHA-P), glyceraldehyde-3-phosphate (GA3P), 1,3-bisphosphoglycerate (1-3PGA), 3-phosphoglycerate (3PGA), 2-phosphoglycerate (2PGA) phosphoenolpyruvate (PEP), pyruvate (PYR).

A fundamental characteristic of *S. cerevisiae* is the ability to ferment sugars, even in the presence of oxygen in aerobic conditions. This phenomenon is called the Crabtree effect, in honour of Herbert Grace Crabtree who first described the reversible switch between the glycolytic and oxidative metabolism in some cancer cells (Crabtree 1929). In more general terms, the duality of the *S. cerevisiae* metabolism allows this microorganism to use two different strategies for exploiting resources: the 'selfish' strategy and the 'cooperative' strategy. According to the 'selfish' strategy the individuals quickly consume resources and increase their own reproduction rate, whilst according to the 'cooperative' strategy the individuals exploit resources slowly but efficiently. A high rate of ATP production per unit of time is associated with a high reproduction rate and is considered to be a 'selfish' strategy (e.g., fermentation), whereas a high yield of ATP production (the number of units of ATP per unit of resource consumed) is associated with a low reproduction rate but with high biomass production, and is therefore considered to be a 'cooperative' strategy (e.g., respiration) (Pfeiffer, 2001). Given that, resource supply is one of the most important

ecological factors that drive the evolution of organisms, the presence in *S. cerevisiae* of two different metabolic strategies for exploiting resources (fermentation and respiration) represents an ecological advantage that has allowed this species to survive under different environmental conditions. The duality of the *S. cerevisiae* metabolism increases the complexity of the regulatory mechanisms interacting with each other to control the energetic metabolism under different environmental stimuli.

Despite *S. cerevisiae* has been extensively studied with regard to several of its characteristics, little information is available concerning the complexity of the regulatory mechanisms acting on the glycolytic pathway, i.e. the common pathway for fermentative and respiratory metabolism (Figure 3). Glycolysis is a highly conserved pathway from bacteria to yeast and humans, and presumably it has been under intense evolutionary pressure for its robust efficiency. It therefore represents an interesting model for investigating the correlation between the different levels of gene expression. As stated by the central dogma of molecular biology (DNA encodes mRNA and mRNA encodes proteins), a strong correlation was anticipated amongst mRNA concentrations, protein concentrations and metabolic fluxes. However, all attempts to verify these correlations – starting from the data on mRNA and protein levels, enzyme activities and *in vivo* fluxes – were far from perfect. A recent study developed a method to dissect the hierarchical regulation of *S. cerevisiae* glycolysis into contributions by transcription, translation, protein degradation and post-translational modification (Daran-Lapujade *et al.*, 2007). The authors propose the calculation of two coefficients, the hierarchical regulation coefficient  $\rho_h$  and the metabolic regulation coefficient  $\rho_m$ .  $\rho_h$  quantifies to what extent the local flux through the enzyme is regulated by a change in enzyme capacity which is affected by a cascade of gene expression, from transcription to post-translational modification.  $\rho_m$  quantifies the relative contribution of changes in the interaction of the enzyme with the rest of the metabolism to the regulation of the enzyme's local flux. While  $\rho_h$  can be measurable,  $\rho_m$  is calculated assuming that  $\rho_h + \rho_m = 1$ . It follows that a reaction that is purely regulated by a cascade of gene expression would have a  $\rho_h$  of 1, whereas a reaction that is solely metabolically regulated would have  $\rho_h$  of 0 and  $\rho_m$  of 1. A study by Daran-Lapujade compared different cultivation conditions in order to compare a fully respiratory metabolism with a fully anaerobic fermentative metabolism. Moreover, the anaerobic fermentative metabolism was studied by increasing the carbon fluxes in glycolysis by adding to the culture the non-metabolisable weak acid benzoic acid. The comparison of the three different cultivation conditions, carried out using a glucose-limited chemostat at the same dilution rate, highlights an increase of carbon fluxes (5- to 11-fold) in anaerobic rather than in aerobic cultures, with a further increase in the presence of benzoic acid. The dissection analysis revealed that in most cases the fluxes resulted from both hierarchical and metabolic regulatory mechanisms ( $\rho_h$  between 0.2 and 0.5). Surprisingly, the increase of glycolytic fluxes stimulated by benzoic acid revealed a dominant contribution of metabolic regulation because most of the reactions showed small  $\rho_h$  values and  $\rho_m$  values which were close to 1 (with the exception of the reactions governed by phosphofructokinase, fructose-bisphosphate aldolase, triose-phosphate isomerase and pyruvate kinase) (Daran-Lapujade, 2007). A further dissection approach was useful for analysing the contribution of transcription, mRNA degradation, translation, protein degradation or post-translational modification, to the hierarchical regulation of enzymes' capacities. The main conclusion was that fluxes through glycolytic enzymes were only marginally regulated by mRNA levels,

whereas most of the observed gene-expression regulation was exerted at the level of protein synthesis and/or degradation and the post-translational level. It was, therefore, speculated that in *S. cerevisiae*, the whole glycolytic regulation is an interplay of purely hierarchical regulation ( $\rho_h$  close to 1), purely metabolic regulation ( $\rho_m$  close to 1), cooperative regulation ( $\rho_m$  and  $\rho_m$  between 0 and 1) and antagonistic regulation (both  $\rho_h$  and  $\rho_m$  negative). The nature and the role of post-translational modification, which appeared to be relevant in the control of glycolytic fluxes, has not yet been investigated systematically for all glycolytic enzymes, even though phosphorylation seems to be the predominant mechanism of protein modification.

The ability of *S. cerevisiae* to switch from respiratory to fermentative metabolism is an important characteristic in the evolutionary and ecological context and for many of its industrial applications. In the natural – evolutionary – context, this ability may have helped this organism to quickly recover sugars and create a hostile environment for competing microorganisms. Concerning the industrial application of *S. cerevisiae*, yeast biomass starved of glucose during storage must rapidly adapt to a high sugar concentration when it is added to bread dough or wort. As has been reported, the shift from respiratory to fermentative metabolism resulted in a rapidly increase of the yeast glycolytic flux in order to compensate the differences in the ATP yield of the two metabolisms. The dynamics of glycolytic regulation during the adaptation of *S. cerevisiae* to fermentative metabolism have been investigated with the aim of understanding the time-dependent, multilevel regulation of glycolytic enzymes during the metabolic switch just described (van de Brink *et al.*, 2008). It was reported that within 45 min of the switch from respiratory to fermentative metabolism, the glycolytic flux increases eightfold without any changes in the glycolytic enzymes' capacities, thereby highlighting an increase of the enzymes activities via metabolic regulation (i.e. the regulation of activities by interaction with low-molecular-weight substrates, products and effectors). By prolonging the incubation during the fermentative metabolism under anaerobic, glucose-excessive conditions, a hierarchical regulation of enzymes was also observed. Specifically, the capacity of the kinases of the upper part of the glycolysis remained unaffected, whereas the enzymes' capacities of the lower part of the glycolysis increased, establishing a new homeostasis of glycolytic metabolites. The delay of the transcriptional regulation compared to the metabolic regulation of glycolytic enzymes observed after the metabolic switch was ascribed to the dramatic change in the rate of ATP production. While the glucose consumption rate increased more than 12-fold during the 2 hours after the switch, the rate of ATP decreased during the first 15 minutes as a result of the reduced ATP yield under fermentative conditions. It was, therefore, speculated that cells energy levels influence the induction of the enzymatic capacity in glycolysis. Due to the fact that an increased level of glycolytic enzymes was only observed 45 minutes after the metabolic switch, and given that the majority of the relevant transcripts were induced after 10 minutes, the step was severely affected by the cellular energetic status which was identified in the translation machinery.

#### 4. Alkalisng reactions and cell bioenergetics

Food associated bacteria, and in particular LAB, have been selected and used by humans in several food processes because of their ability to acidify milk or vegetables in order to obtain a more stable and safer food products. Acidification occurs in homofermentative LAB





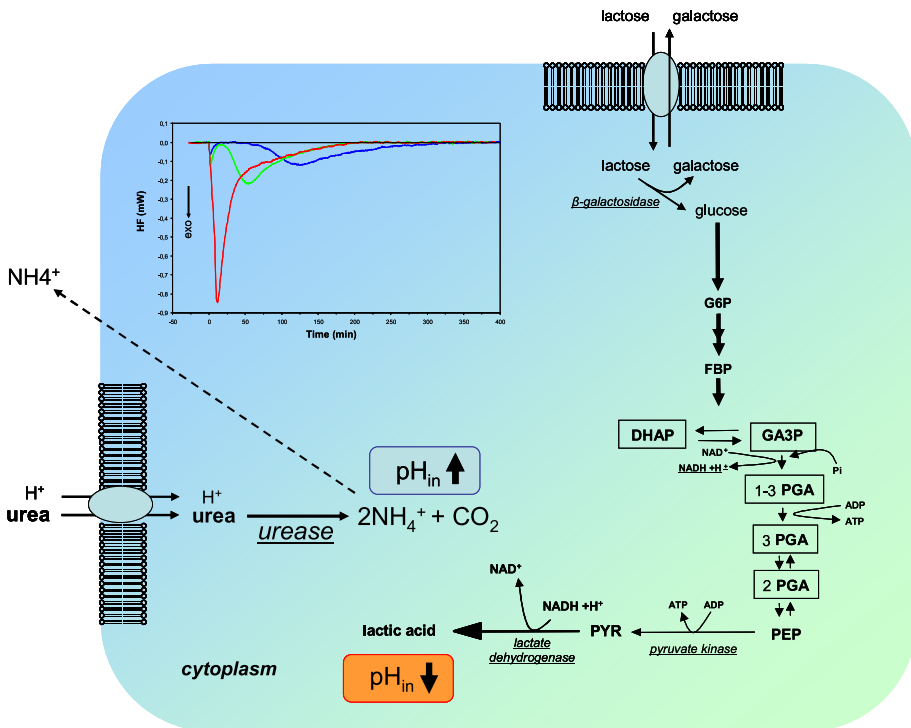


Fig. 5. Simplified representation of glycolysis, homolactic fermentation and urease activity in *S. thermophilus*. The inset represents the raw isothermal titration calorimetry data (heat flux versus time) of *S. thermophilus* lactose metabolism either alone (blue line) or in the presence of ammonia (green line) or urea (red line) (for the detailed experimental procedure see Arioli *et al.*, 2010).

Quite recently, the urease activity – an enzymatic reaction known as a stress response to counteract environmental acidic pH in several bacteria – has been described as a metabolic regulatory mechanism of the energetic metabolism in the dairy bacterium *Streptococcus thermophilus* (Arioli *et al.*, 2010). Urease is a multi-subunit urea amidohydrolase (EC 3.5.1.5) that catalyses the hydrolysis of urea to yield ammonia and carbamate, which spontaneously decomposes to yield a second molecule of ammonia and carbonic acid (Figure 4). The released carbonic acid and the two molecules of ammonia are in equilibrium with their deprotonated and protonated forms respectively, and the net effect of these reactions is an increase in intracellular ( $\text{pH}_{in}$ ) and extracellular ( $\text{pH}_{out}$ ) pH (Figure 5). Urea hydrolysis increases the catabolic efficiency of *S. thermophilus* by modulating the intracellular pH and thereby increasing the activity of  $\beta$ -galactosidase, glycolytic enzymes, and lactate dehydrogenase. Moreover, urease increases the overall change in enthalpy generated by the microbial metabolism as a consequence of an increased glycolytic flux (Figure 5).

In light of these considerations, urease activity – which is stimulated when environmental pH is weakly acidic (pH 5.8-6) (Mora *et al.*, 2005) – should be considered as a regulatory system that has evolved to optimise the activity of the glycolytic enzymes. These enzymes

are exposed to an increasingly acidic intracellular environment and must maintain cell energy homeostasis when the  $\text{pH}_{\text{out}}$  and  $\text{pH}_{\text{in}}$  decrease as a result of lactic acid production. Urease biogenesis is only important when the cells are actively growing, since it increases the fermentative capacity of *S. thermophilus* and leads to rapid growth and an increased acidification rate in milk (i.e. urease favour a cytoplasmic background suitable for a 'make-accumulate-consume' strategy). If we consider that energetic limitation is an important factor for organisms in their natural environment, we then expect that the properties of ATP-production pathways have been under strong selection during evolution (Pfeiffer *et al.*, 2001). Similarly, the regulatory mechanisms which act in optimising the efficiency of the ATP-production pathway should be under the same evolutionary selection. In this context, it is notable that eleven genes are necessary in order for the maintenance of an active urease, which accounts for 0.9% of the estimated core genome of *S. thermophilus*. This enzyme has been found in all the previously characterised *S. thermophilus* strains, and urease-negative mutants are not common in nature. The *S. thermophilus* genome has mainly evolved following divergent evolution from the phylogenetically related pathogenic streptococci bacteria. Loss-of-function mutations, counterbalanced by the acquisition of relevant traits (e.g. lactose utilisation) have resulted in a *S. thermophilus* genome that is well-adapted for dairy colonisation (Bolotin *et al.*, 2004). Because urease is not common in pathogenic streptococci (Mora *et al.*, 2005), its acquisition and maintenance within the *S. thermophilus* genome is likely to be dependent upon its contribution to the environmental fitness of this microorganism when linked to the environmental availability of urea. Urea is the major nitrogenous waste product of most terrestrial animals. Urea is produced in the liver, carried in the bloodstream to the kidneys and excreted in urine. Urea is also present in milk and in the secretions of the major and minor exocrine glands at concentrations approximately equivalent to serum, so a large proportion of circulating urea is translocated onto epithelial surfaces by secretory systems or else in tissue exudates. In this context, it is not surprisingly that urease is present in a high number of human pathogenic bacteria and represents an important factor in infection and disease (Burne and Chen, 2000; Mora *et al.*, 2005).

Since the activity of the bioenergetic machinery is modulated by the intracellular pH, the mechanism of metabolism regulation in other urease-positive bacteria, including human pathogens, should be further analysed. All of the metabolic reactions that result in the alkalinisation of the cytosol of acidogenic organisms (such as those involved in the arginine deiminase (ADI) pathway, the citrate metabolism or else those involved in malolactic conversion) should be analysed in light of these novel findings. Indeed, and not surprisingly, all previous pathways act by subtracting protons from the cytoplasm and are strongly induced by an acidic environmental pH (Magni *et al.*, 1999; Cotter & Hill, 2003; Broadbent *et al.*, 2010). The conserved role of alkalinising reactions across acidogenic bacteria is also supported by the data obtained for *L. lactis* IL1403-945 and *S. pneumoniae* SP292-945 in the presence of glucose and cellobiose as a carbon source (Arioli *et al.*, 2010). In both cases, the rate of ATP produced during the sugar catabolism was increased, alkalinising with the ammonia the cytoplasm. Besides the selfish utility of urease for cells harbouring this enzymatic activity, the cooperative behaviour of urease in an ecological context in which different microbial species share the same environment was also underlined. Urea hydrolysis results in a rise of both  $\text{pH}_{\text{in}}$  and  $\text{pH}_{\text{out}}$  due to the rapid diffusion of ammonia outside the cell. It follows that in the presence of urea and a urease-positive microorganism, (or a urease-negative microorganism) sharing the same micro-environment, there will be benefits from the local transient increase of pH (Arioli *et al.*, 2010).

## 5. Conclusions and perspectives

The regulation and control of metabolic fluxes in microbes is based on our knowledge of regulatory networks topology, on input-output regulatory logics and metabolic feedback, and on the quantitative effect of control exerted by regulation events. No less important is our understanding of how metabolic regulatory circuits have evolved and what the significance of the impact of environmental constraints on the regulatory configuration will be. It has recently been described that microbes can 'learn' from exposure to a series of new environmental changes and rearrange some regulatory networks so as to predict the new environmental stimuli (Mitchell *et al.*, 2009). The ecological forces and the molecular mechanisms that govern this ability are not clear but it is evident that the regulatory networks that link environmental stimuli to microbial responses are complex and can evolve rapidly (Cooper, 2009). The origin of the adaptability of regulatory networks could be ascribed to microbial cell individuality and the underlying sources of heterogeneity. This heterogeneity is related to stochastic fluctuations in transcription or translation, despite a genetically homogeneous background and constant environmental conditions. Heterogeneity at single-cell level is typically masked in conventional studies of microbial populations, which are based on the average behaviour of thousands or millions of cells, but it has the potential to create variant subpopulations better equipped to persist during environmental perturbation (Avery, 2006). In other words, a population might enhance its fitness by allowing individual cells to make a stochastically transition amongst multiple phenotypes, thus ensuring that some cells are always prepared for erratic, unpredictable environmental fluctuations. It can be therefore be concluded that the regulatory mechanisms that act in the optimisation of the bioenergetics of food-associated bacteria should be analyzed by always taking into consideration the 'predictable' succession of environmental stimuli that have driven their domesticated speciation and evolution.

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## **Part 3**

# **New Techniques and Findings in Bioenergetics Research**





# Phosphorescence Oxygen Analyzer as a Measuring Tool for Cellular Bioenergetics

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## 1. Introduction

The “*phosphorescence oxygen analyzer*” and its use to monitor O<sub>2</sub> consumption by cells and tissues are discussed in this chapter (Lo et al., 1996; Souid et al., 2003). This analytical tool assesses bioenergetics in cells undergoing apoptosis (e.g., the mitochondrial cell death pathway), in cells exposed to toxins (e.g., loss of viability) and in cells with a genetically altered energy metabolism (e.g., mitochondrial disorders) (Tacka et al., 2004a-b; Tao et al., 2007; Tao et al., 2008a). This method is applicable to suspended (e.g., Jurkat and HL-60 cells) and adherent (TU183 human oral cancer cells) cells and to fresh tissues from humans (e.g., lymphocytes, spermatozoa and tumors) and animals (e.g., liver, spleen, heart, pancreas and kidney) (Badawy et al., 2009a-b; Whyte et al., 2010; Al Shamsi et al., 2010; Al-Salam et al., 2011; Al Samri et al., 2011). The analyzer allows investigating anticancer compounds (single agents or combinations) for dosing, order of administration and exposure (Jones et al., 2009; Tao et al., 2008b; Souid et al., 2006; Goodisman et al., 2006; Tao et al., 2006a-b; Tack et al. 2004b). It can also be used to monitor reactions consuming or producing O<sub>2</sub> (Tao et al., 2008b; Tao et al., 2009).

## 2. Relevant biological processes

The term “*cellular bioenergetics*” describes the biochemical processes involved in energy metabolism (energy conversion or transformation), while the term “*cellular respiration*” describes delivery of O<sub>2</sub> to the mitochondria, the breakdown of reduced metabolic fuels with passage of electrons to O<sub>2</sub>, and the resulting synthesis of ATP. Impaired respiration thus implies any abnormality involving cellular bioenergetics, including glycolysis. The term “*apoptosis*” describes cellular mechanisms responsible for initiating and executing cell death. The initiation step requires a leakage of cytochrome c from the mitochondrial intermembrane to the cytosol. In the cytosol, cytochrome c binds to the apoptotic protease activating factor-1 (Apaf-1), triggering the caspase cascade (a series of cysteine, aspartate-specific proteases). Caspase activation executes mitochondrial dysfunction (Nicholson et al., 1997). This mitochondrial perturbation involves opening the permeability transition pores (accelerating oxidations in the mitochondrial respiratory chain) and collapsing the

electrochemical potential  $\Delta\psi$  (Ricci et al., 2004). Thus, induction of apoptosis is directly linked to mitochondrial dysfunction (Green and Kroemer, 2004).

### 3. Expressions of dissolved oxygen

Dissolved  $O_2$  is expressed in mm Hg, mL  $O_2$  per L, mg  $O_2$  per L, or  $\mu\text{mol}$  per L ( $\mu\text{M}$ ). For conversion, a partial pressure of  $O_2$  ( $PO_2$ ) of 1.0 mm Hg = 0.03 mL  $O_2$  per L; 1.0 mL  $O_2$  per L = 1.4276 mg  $O_2$  per L; and 1.0 mg  $O_2$  per L = 1000/32  $\mu\text{M}$ . In *freshwater* at 760 mm Hg and 20°C, dissolved  $[O_2]$  is 9.1 mg/L, or 284  $\mu\text{M}$ . Using a Clark electrode,  $PO_2$  of the reaction mixture phosphate-buffer saline (PBS), 10 mM glucose and 0.5% fat-free bovine serum albumin is  $170.5 \pm 6.6$  mm Hg ( $n = 4$ ), or  $228 \pm 9$   $\mu\text{M}$ . The 56 mm Hg difference between  $[O_2]$  in *freshwater* and the reaction solution reflects the effect of salinity on dissolved  $O_2$  (Weiss, 1970).

### 4. Principles and tools of the oxygen measurement

$O_2$  concentration is determined from the phosphorescence decay rate ( $1/\tau$ ) of the *palladium (II) complex of meso-tetra-(4-sulfonatophenyl)-tetrabenzoporphyrin* (Pd phosphor). This measurement is based on quenching the phosphorescence of Pd phosphor by  $O_2$  (Lo et al., 1996). The probe has an absorption maximum at 625 nm and an emission maximum at 800 nm. Samples are exposed to light flashes (10 per sec) from a pulsed light-emitting diode array with peak output at 625 nm (OTL630A-5-10-66-E, Opto Technology, Inc), Wheeling, IL. Emitted phosphorescent light is detected by a Hamamatsu photomultiplier tube (PMT #928) after first passing it through a wide-band interference filter centered at 800 nm. Amplified phosphorescence is digitized at 1-2 MHz using an analog/digital converter (PCI-DAS 4020/12 I/O Board) with 1 to 20 MHz outputs (Computer Boards, Inc.). Pulses are captured using a developed software program at 0.1 to 4.0 MHz, depending on speed of the computer (Souid, 2003).

The values of  $1/\tau$  are linear with dissolved  $O_2$  concentration:  $1/\tau = 1/\tau_o + k_q[O_2]$ , where  $1/\tau$  = the phosphorescence decay rate in the presence of  $O_2$ ,  $1/\tau_o$  = the phosphorescence decay rate in the absence of  $O_2$ , and  $k_q$  = the second-order  $O_2$  quenching rate constant in  $\text{sec}^{-1} \mu\text{M}^{-1}$  (Lo et al., 1996).

Cellular respiration is measured at 37°C in 1-mL sealed vials. Mixing is carried out with the aid of parylene-coated stirring bars. The respiratory substrates are the endogenous metabolic fuels supplemented with glucose. In cell suspensions sealed from air,  $[O_2]$  decreased linearly with time, indicating the kinetics of cellular mitochondrial  $O_2$  consumption is zero-order. The rate of respiration ( $k$ , in  $\mu\text{M } O_2 \text{ min}^{-1}$ ) is thus the negative of the slope  $d [O_2]/dt$ . Cyanide markedly inhibited respiration, confirming  $O_2$  is consumed mainly by the mitochondrial respiratory chain.

### 5. Developed software program and instrument description

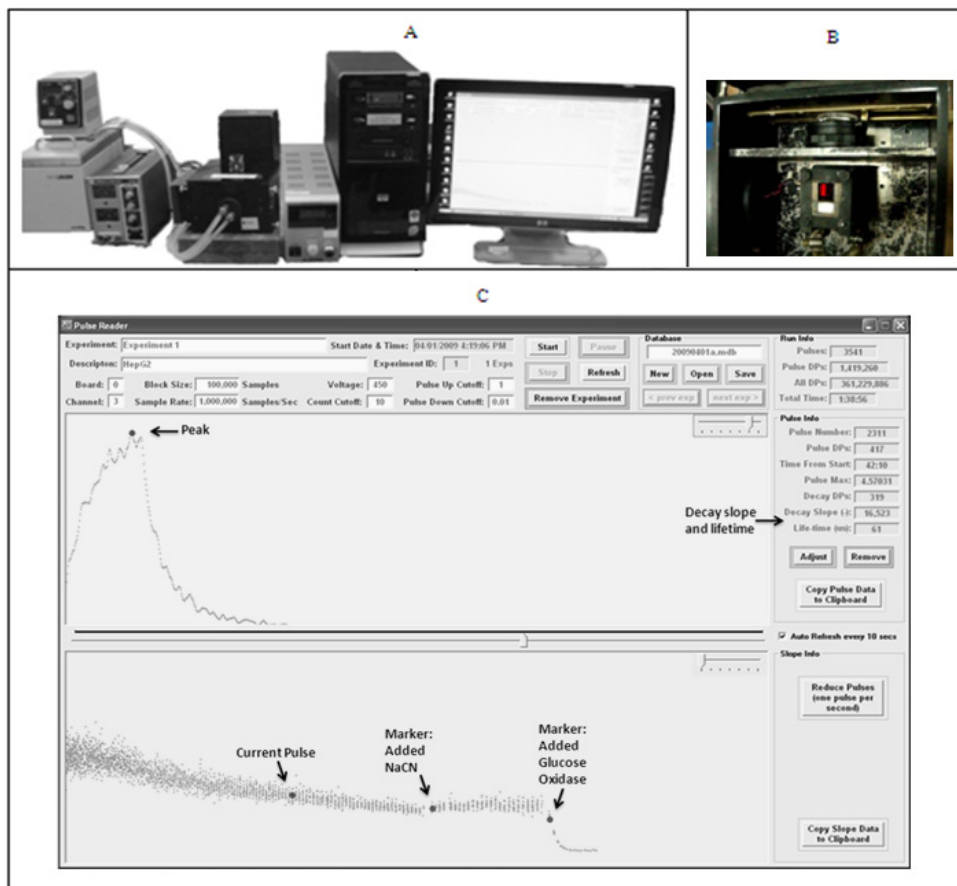
The software program was developed using Microsoft Visual Basic 6 (VB6) programming language, Microsoft Access Database 2007 (Access) database management system, and Universal Library components developed by the electronic board company, Measurement Computing, for use with Microsoft Visual Basic 6 programming language

(<http://www.mccdaq.com/daq-software/universal-library.aspx>). It allows direct reading from the PCI-DAS 4020/12 I/O Board (<http://www.mccdaq.com/pci-data-acquisition/PCI-DAS4020-12.aspx>). The software utilizes a relational database that stores experiments, pulses and pulse metadata, including slopes. Pulse identification is performed by detecting 10 phosphorescence intensities above 1.0 volt (by default). Peak identification is performed by the program which detects the highest 10% data points of a pulse and chooses the point in the group that is closest to the pulse's decay curve. Depending on the sample rate, a minimum number of data points per pulse is set and used as a cutoff to remove invalid pulses with too few data points (Shaban, 2010).

Main advantages of the developed program over commercially available packages (e.g., DASyLab™ or TracerDAQ™) are provision of full control and customization of the data acquisition, storage and analysis. The choices of VB6 and Access as programming and storage environments are due to their availability, simplicity, widespread use and VB6 components that read directly from the PCI card made available by Measurement Computing. Table 1 displays identified tasks of the program. Fig. 1 shows a picture of the data acquisition system and the developed software program. Fig. 2 shows a reaction vial.

Experiment identification (title, date, time and sample rate)
Reading directly from the PCI card at the fastest possible rate
Distinguishing pulse data from non-pulse data
Allowing a fuzzy detection of the pulse peak
Calculating the exponential decay rate ( $1/\tau$ ) and lifetime ( $\tau$ ) of each pulse
Storing each pulse data points, along with the peak, decay and lifetime values
Viewing a representative pulse every 10 sec
Viewing decay rates ( $1/\tau$ ) in a second graph
Ability to pause and place a marker with a note
Ability to remove erroneous (incomplete) pulses and adjust peak values if necessary
Ability to copy pulse or slope data to clipboard for further analysis
Ability to access a previous experiment, review a pulse with its metadata, markers and associated notes

Table 1. Identified tasks of the customized software program for data acquisition, storage and analysis



The components (panel A, left to right) are circulating water bath, power supply for the mixer, sample chamber (panel B) attached to PMT, high voltage power supply for PMT, computer with PCI-DAS board, and monitor with developed software running. The PMT is connected to PCI-DAS board on the back of the computer. The developed software program interface is shown in panel C.

Fig. 1. The data acquisition system and developed software program.



Fig. 2. A sealed reaction vial containing Pd phosphor solution, stirring bar and a mouse liver specimen.

## 6. Instrument calibration

The instrument was calibrated with  $\beta$ -glucose and glucose oxidase system.



The reaction contained PBS, 3  $\mu\text{M}$  Pd phosphor, 0.5% fat-free albumin, 50  $\mu\text{g}/\text{mL}$  glucose oxidase and various concentrations of  $\beta$ -glucose. To achieve a high signal-to-noise ratio throughout the entire range of  $[\text{O}_2]$ , the photomultiplier tube was operated at 450 volts. Representative pulses (with exponential fits) for reactions containing PBS with 0, 125 or 500  $\mu\text{M}$   $\beta$ -glucose, 50  $\mu\text{g}/\text{mL}$  glucose oxidase, 3  $\mu\text{M}$  Pd phosphor and 0.5% fat-free bovine serum albumin are shown in Fig. 3.

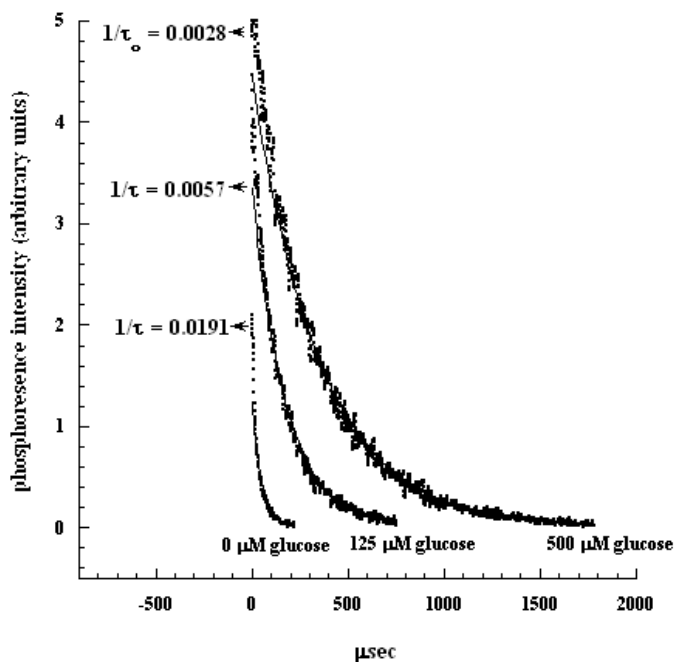
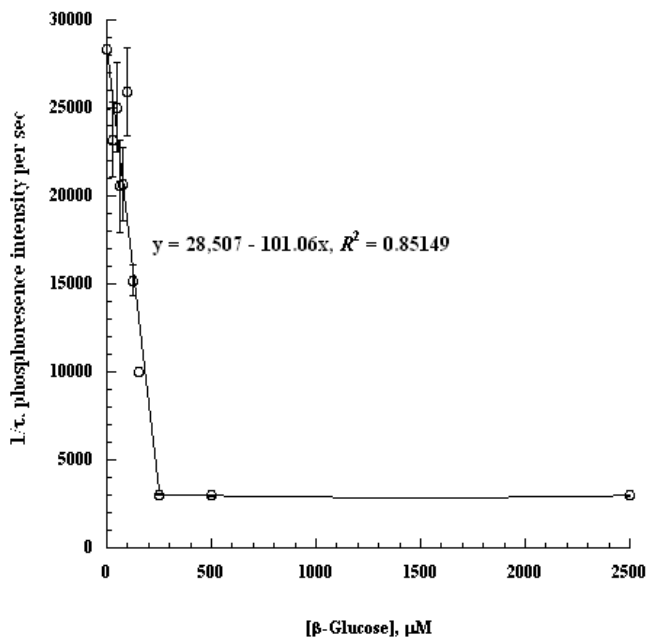


Fig. 3. Representative phosphorescence pulses for reaction mixtures containing 0, 125 or 500  $\mu\text{M}$  glucose. The lines are exponential fits ( $R^2 > 0.924$ ,  $> 0.985$  and  $> 0.992$ , respectively).

The values of  $1/\tau$  (mean  $\pm$  SD,  $n = 1200$  over 2 min) as function of  $[\beta\text{-glucose}]$  are shown in Fig. 4. The line is linear fit and the value of  $k_q$  ( $101.1 \text{ sec}^{-1} \mu\text{M}^{-1}$ ) is the negatives of the slope. The value of  $1/\tau$  for air-saturated solution (without glucose) was  $28,330 \text{ sec}^{-1}$  (coefficient of variation,  $C_v = 12\%$ ), for  $[\beta\text{-glucose}] = 125 \mu\text{M}$   $5,650 \text{ sec}^{-1}$ , and for  $\text{O}_2$ -depleted solution (with  $500 \mu\text{M}$   $\beta$ -glucose,  $1/\tau_0$ )  $2,875 \text{ sec}^{-1}$  ( $C_v = 1\%$ ). The high values of  $C_v$  for the air-saturated solutions were due to the lower phosphorescence intensities with high  $[\text{O}_2]$  (little light reaching the photomultiplier tube). The corresponding lifetimes ( $\tau$ ) were  $52 \mu\text{sec}$ ,  $177 \mu\text{sec}$  and  $352 \mu\text{sec}$ , respectively. Oxygen concentration was calculated using,  $1/\tau = 1/\tau_0 + k_q[\text{O}_2]$ .



The reaction mixtures contained PBS, 3  $\mu\text{M}$  Pd phosphor, 0.5% fat-free bovine serum albumin, 50  $\mu\text{g}/\text{mL}$  glucose oxidase and shown concentrations of  $\beta$ -glucose. The values of  $1/\tau$  (mean  $\pm$  SD,  $n = 1200$  flashes over 2 min) as a function of  $[\beta\text{-glucose}]$  are shown. The lines are linear fits.

Fig. 4. Calibration with  $\beta$ -glucose plus glucose oxidase

## 7. Aflatoxin B1 impairs human lymphocyte respiration

Aflatoxins (most notably, aflatoxin B1) are highly carcinogenic compounds, commonly found in food contaminated by *aspergillus flavus*, *parasiticus* and *penicillium* species (Williams, et al., 2004; Eaton & Gallagher, 1994). These potent mycotoxins create major health problems, especially where food storage is subjected to heat and humidity. A high rate of dietary exposure is reported in Sahara Africa, China and Taiwan. For example, in eastern China (where liver cancer exceeds 1 per 10,000 population per year), an average human exposure to aflatoxins is estimated to be 2.2  $\mu\text{g}/\text{kg}/\text{day}$ . For comparison, the exposure in the United States is about 3 orders of magnitude less (Wang et al., 1996).

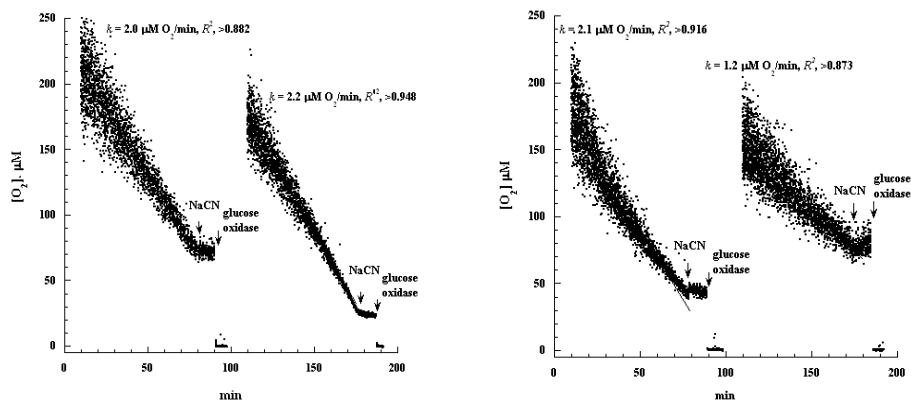
Biotransformation of aflatoxin B1 is critical for its activation. The parent compound undergoes oxidation by monooxygenases, especially the hepatic cytochrome P450 3A4. The active metabolite, AFB exo-8,9-epoxide, undergoes base-catalyzed rearrangement to a dialdehyde, which rapidly reacts with guanyl N7 in DNA and lysine in proteins (Johnson et al., 1996).

Exposure to aflatoxin B1 has been associated with hepatocellular carcinoma (Montesano et al., 1997), mutagenesis (e.g., in the tumor suppressor gene p53) and immune suppression (Corrier, 1991). Most of the information on immunotoxicity of aflatoxin B1 is derived from animal studies (Stec et al., 2009; Reddy et al., 1987; Reddy et al., 1989; Jiang et al., 2008; reviewed in Williams, et al., 2004]. In healthy humans, exposure to aflatoxin B1 is associated

with lower perforin (a cytolytic protein produced by natural killer lymphocytes) expression on CD8+ T-lymphocytes (Jiang et al., 2008). A dose-related decrease in DNA synthesis in lymphocyte cultures (with and without mitogens) is found in mice exposed *in vivo* to aflatoxin B1 (Reddy et al., 1987). A decrease in DNA synthesis is also observed in normal splenic mouse lymphocytes cultured *in vitro* with  $>10 \mu\text{M}$  aflatoxin B1; a decrease in RNA synthesis is observed at dosing  $>25 \mu\text{M}$  and a decrease in protein synthesis at dosing  $>100 \mu\text{M}$  (Reddy et al., 1989).

The phosphorescence oxygen analyzer is used to monitor the effects of aflatoxin B1 on human lymphocyte mitochondrial oxygen consumption. These experiments investigate whether aflatoxin B1 impairs respiration of the lymphoid tissue, an organ that is typically targeted by this potent mycotoxin. Aflatoxin B1 (1.0 mg = 3.2 micromol) was freshly dissolved in 1.0 mL dry methanol and immediately added to cell suspensions with vigorous mixing. Alternatively, aflatoxin B1 powder was directly added to the cell suspension with vigorous mixing. The concentrations were determined by the absorbance at 350 nm (10  $\mu\text{L}$  aflatoxin B1 stock solution or cell-free supernatant in 1.0 mL dry methanol), using an extinction coefficient of  $21,500 \text{ M}^{-1} \text{ cm}^{-1}$  (Nesheim et al., 1999); the aflatoxin B1 excitation wavelength is 366 nm and the emission wavelength 455 nm. The reactions were carried out in glass vials and protected from light.

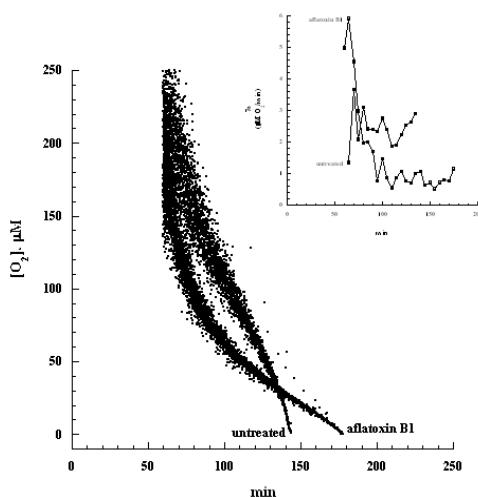
PBMC ( $0.6 \times 10^7$  cells/mL) were suspended in 6.0 mL PBS, 10 mM glucose, 3  $\mu\text{M}$  Pd phosphor and 0.5% fat-free bovine serum albumin. The mixture was divided into 2 equal aliquots. Methanol (25  $\mu\text{L}$  per mL, Fig. 5, left panel) or aflatoxin B1 (25  $\mu\text{M}$ , Fig. 5, right panel) was then added and the incubation continued at 37°C (open to air with gentle stirring). At  $t = 10$  and 110 min, 1.0 mL of each mixture was simultaneously placed in the instruments for  $\text{O}_2$  measurement. The rate of respiration ( $k$ , in  $\mu\text{M O}_2 \text{ min}^{-1}$ ) for  $t = 10$  to 78 min for the methanol-treated cells was 2.0 and for the aflatoxin B1-treated cells 2.1. The values of  $k$  for  $t = 110$  to 174 were 2.2 and 1.2, respectively (corresponding to 45% inhibition of lymphocyte respiration).



PBMC were incubated at 37°C with 25  $\mu\text{L}$  per mL methanol (left panel) or 25  $\mu\text{M}$  aflatoxin B1 (right panel). Minute zero corresponds to the addition of aflatoxin B1. At  $t = 10$  and  $t = 110$  min, 1.0 mL of each mixture was simultaneously placed in the instruments for  $\text{O}_2$  measurement. Rates of respiration ( $k$ ) were calculated from the best-fit linear curves. Additions of 5.0 mM NaCN and 50  $\mu\text{g}/\text{mL}$  glucose oxidase are shown.

Fig. 5. Effect of aflatoxin B1 on human PBMC respiration.

The time-course for aflatoxin B1-induced inhibition of lymphocyte respiration was investigated (Fig. 6). PBMC ( $1.3 \times 10^7$  cells/mL) were suspended in 3.0 mL PBS, 10 mM glucose and divided into 2 equal aliquots. Aflatoxin B1 powder was directly added to one aliquot with vigorous mixing (final concentration,  $\sim 75 \mu\text{M}$ ). The 2 aliquots were then incubated at  $37^\circ\text{C}$  for 60 min (open to air with continuous stirring). At  $t = 60$  min, 5 mg albumin and  $2.0 \mu\text{M}$  Pd phosphor were added to each suspension. The samples were then simultaneously placed in the chambers for  $\text{O}_2$  measurement. For the untreated cells,  $\text{O}_2$  consumption was linear with time ( $k = 2.4 \mu\text{M O}_2/\text{min}$ ,  $R^2 > 0.916$ ). For the treated cells,  $\text{O}_2$  consumption was exponential with time,  $R^2 > 0.934$ . Changes at 5-min intervals for the treated cells showed a sharp decline in the values of  $k$  for  $t = 60$  to 90 min, followed by a steady low rate for  $t = 95$  to 175 min. In contrast, the values of  $k$  remained relatively stable for  $t = 60$  to 140 min. The mean  $\pm$  SD (coefficient of variation) for the values of  $k$  for the untreated cells was  $2.43 \pm 0.55$  ( $C_v = 23\%$ ) and for the treated cells  $1.56 \pm 1.80$  ( $C_v = 87\%$ );  $p$ -value  $< 0.02$  (Fig. 6, insert).



The lines are linear fit for the untreated cells ( $R^2 > 0.916$ ) and exponential fit for the treated cells ( $R^2 > 0.936$ ). Insert, changes in the values of  $k$  at 5-min intervals.

Fig. 6. Time-course of the effect of aflatoxin B1 on human lymphocyte respiration.

The exponential profile of  $\text{O}_2$  consumption in the presence of aflatoxin B1 is similar to dactinomycin (Tao et al., 2006b; Tao et al., 2008a). This pattern of bioenergetic derangements could stem from progressive mitochondrial and metabolic disturbances, ranging from uncoupling oxidative phosphorylation (which accelerates  $\text{O}_2$  consumption and rapidly depletes the metabolic fuels) to mitochondrial respiratory chain function collapse. Experimentally, these two phases are clearly distinguishable in our system (Fig. 6, insert).

Caspase activation in lymphocytes treated with aflatoxin B1 was then examined. Many of the caspases (e.g., caspase-3, -2 and -7) target the asp-glu-Val-asp (DEVD) motif and cleave at sites next to the last aspartate residue (Nicholson et al., 1997). Synthetic cell-permeable substrates, such as N-acetyl-DEVD-7-amino-4-trifluoromethyl coumarin (Ac-DEVD-AFC) and N-acetyl-DEVD-7-amino-4-methyl coumarin (Ac-DEVD-AMC) have been used to investigate caspase activities. For example, cleavage of Ac-DEVD-AFC by specific caspases



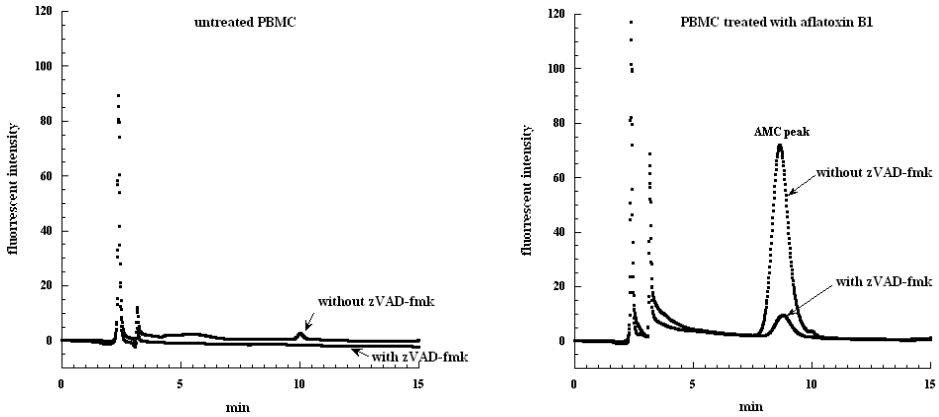
releases the fluorogenic AFC; the latter can be separated on HPLC and detected by fluorescence with a great sensitivity (Tao et al., 2007).

Caspase-3 activity in lymphocytes exposed to aflatoxin B1 is shown in Fig. 7. The purpose of these experiments is to confirm caspases are activated within the time period required for inhibition of respiration. The mixtures (final volume, 0.5 mL) contained  $1.5 \times 10^6$  cells in PBS, 10 mM glucose and 68  $\mu\text{M}$  Ac-DEVD-AMC (N-acetyl-asp-glu-val-asp-7-amino-4-methyl coumarin, a caspase-3 substrate) with and without 20  $\mu\text{M}$  zVAD-fmk (benzyloxycarbonyl-val-ala-DL-asp-fluoromethylketone, a pan-caspase inhibitor) (Slee et al., 1996). The suspensions were incubated at 37°C for 2 hr without other additions (Fig. 7, left panel) or with the addition of  $\sim 100$   $\mu\text{M}$  aflatoxin B1 (Fig. 7, right panel). At the end of the incubation period, the cells were disrupted and their supernatants were separated on HPLC and monitored by fluorescence. The results show AMC moieties (the cleavage product of Ac-DEVD-AMC) appear in the cells about 2 hr after the addition of aflatoxin B1. This 2-hr period is the same as that observed for aflatoxin B1-induced inhibition of respiration (see Fig. 5). Thus, the results suggest aflatoxin B1 impairs human lymphocyte mitochondrial function by activating caspases.

The above findings also demonstrate the lymphocyte preparation contain monooxygenases that activate aflatoxin B1. These results are consistent with previous reports (Stec et al., 2009; Rossano et al., 1999; Savel et al., 1970; Wang et al., 1999). In one study, the addition of aflatoxins B1 at concentrations up to 32  $\mu\text{M}$  had a minimum effect on phytohemagglutinin-p-stimulated human lymphocyte proliferation (Meky et al., 2001). However, an earlier study on human lymphocytes by Savel et al. (1970) showed a reduced phytohemagglutinin-p-stimulated lymphocyte proliferation with 16  $\mu\text{M}$  aflatoxin B1. More recently, aflatoxin B1 was shown to inhibit *in vitro* concanavalin A-induced proliferation of pig blood lymphocytes; in 72-hr cultures, the concentration of aflatoxin B1 producing 50% inhibition ( $\text{IC}_{50}$ ) was 60 nM (Stec et al., 2009). In other studies, aflatoxin G1 induced *in vitro* apoptosis in human lymphocytes (Wang et al., 1999; Sun et al., 2002). In summary, the data presented show human lymphocytes exposed *in vitro* to aflatoxin B1 exhibit impairments of cellular respiration, which could result from caspase activation. The results substantiate the potent immunosuppressive activity of aflatoxins in human.

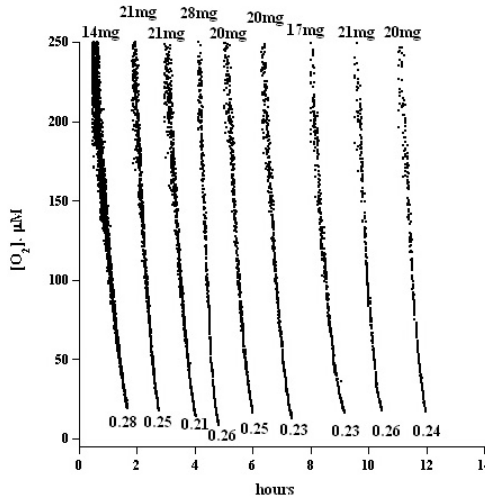
## 8. Measurement of O<sub>2</sub> consumption in murine tissues

A novel *in vitro* system is developed to measure O<sub>2</sub> consumption by various murine tissues over several hours (Al-Salam et al., 2011; Al Samri et al., 2011; Al Shamsi et al., 2010). Small tissue specimens excised from male Balb/c mice were immediately immersed in ice-cold Krebs-Henseleit buffer (115 mM NaCl, 25 mM NaHCO<sub>3</sub>, 1.23 mM NaH<sub>2</sub>PO<sub>4</sub>, 1.2 mM Na<sub>2</sub>SO<sub>4</sub>, 5.9 mM KCl, 1.25 mM CaCl<sub>2</sub>, 1.18 mM MgCl<sub>2</sub> and 6 mM glucose, pH  $\sim 7.4$ ), saturated with 95% O<sub>2</sub>:5% CO<sub>2</sub>. The samples were incubated at 37°C in the same buffer and continuously gassed with O<sub>2</sub>:CO<sub>2</sub> (95:5). Normal tissue histology at hr 5 was confirmed by light and electron microscopy. NaCN inhibited O<sub>2</sub> consumption, confirming the oxidation occurred in the mitochondrial respiratory chain. A representative experiment of pneumatocyte respiration is shown in Fig. 8. The rate of lung tissue respiration incubated *in vitro* for  $3.9 < t < 12.4$  hr was  $0.24 \pm 0.03$   $\mu\text{M}$  O<sub>2</sub> min<sup>-1</sup> mg<sup>-1</sup> (mean  $\pm$  SD,  $n = 28$ ). The corresponding rate for the liver was  $0.27 \pm 0.13$  ( $n = 11$ ,  $t < 4.7$  hr), spleen  $0.28 \pm 0.07$  ( $t < 5$  hr,  $n = 10$ ), kidney  $0.34 \pm 0.12$  ( $t < 5$  hr,  $n = 7$ ) and pancreas  $0.35 \pm 0.09$  ( $t < 4$  hr,  $n = 10$ ), Table 2. This approach provided accurate assessment of tissue bioenergetics *in vitro* over several hours.



The reactions contained  $1.5 \times 10^6$  cells in PBS plus 10 mM glucose and 68  $\mu\text{M}$  Ac-DEVD-AMC with and without 20  $\mu\text{M}$  zVAD-fmk. The suspensions were incubated at 37°C for 2 hr without other additions (left panel) or with the addition of  $\sim 100 \mu\text{M}$  aflatoxin (right panel). At the end of the incubation period, the cells were disrupted and their supernatants were separated on HPLC and monitored by fluorescence. The retention time for Ac-DEVD-AMC was  $\sim 2.4$  min and for the released AMC  $\sim 8.7$  min.

Fig. 7. Caspase activation by aflatoxin B1 in human peripheral blood mononuclear cells parenthesis for PBMC:PBMC



Specimens were excised from the lung of an anesthetized mouse and immediately immersed in ice-cold Krebs-Henseleit buffer saturated with 95%  $\text{O}_2$ :5%  $\text{CO}_2$ . The samples were incubated at 37°C in the same buffer with continuous gassing with  $\text{O}_2$ :5% $\text{CO}_2$ . At indicated time periods, specimens were removed from the incubation mixture, weighed and placed in Krebs-Henseleit buffer containing 0.5% albumin and 3  $\mu\text{M}$  Pd phosphor for  $\text{O}_2$  measurement. The rate of respiration was set as the negative of the slope of  $[\text{O}_2]$  vs. time. The weight is shown at the top and the respiration rate (in  $\mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$ ) at the bottom of each run (Al Samri et al., 2011).

Fig. 8. Representative experiment of  $\text{O}_2$  consumption by lung tissue.

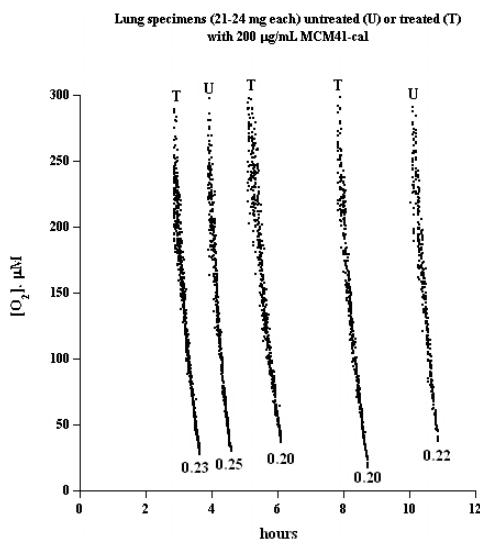
Tissues	Respiration ( $\mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$ )
Lung	$0.24 \pm 0.03$
Liver	$0.27 \pm 0.13$
Spleen	$0.28 \pm 0.07$
Kidney	$0.34 \pm 0.12$
Pancreas	$0.35 \pm 0.09$

Values are mean  $\pm$  SD. For unit conversion, 1.0 mL  $\text{O}_2$  = 1.4276 mg or 0.0446125 mmol.

Table 2.  $\text{O}_2$  consumption by murine tissues.

## 9. Biocompatibility of calcined mesoporous silica particles with murine tissue bioenergetics

The *in vitro* system discussed in Section 8 is used to investigate the effects of two forms of calcined mesoporous silica particles (MCM41-cal and SBA15-cal) on cellular respiration of mouse tissues (Al Shamsi et al., 2010; Al-Salam et al., 2011; Tao et al., 2008c).  $\text{O}_2$  consumption by lung, liver, kidney, spleen and pancreatic tissues was unaffected by exposure to 200  $\mu\text{g}/\text{mL}$  MCM41-cal or SBA15-cal for several hours. A representative experiment of pneumatocyte respiration is shown in Fig. 9.



The rate of respiration ( $k$ ) was set as negative of the slope of  $[\text{O}_2]$  vs. time; the values of  $k$  (in  $\mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$ ) are shown at the bottom of the runs. Zero minute corresponds to the addition of the particles. U, untreated; and T, treated.

Fig. 9. Pneumatocyte respiration with and without 200  $\mu\text{g}/\text{mL}$  MCM41-cal.

Normal tissue architecture and histology were confirmed by light microscopy. Intracellular accumulation of the particles in the studied tissues was evident by electron microscopy. The results show reasonable *in vitro* biocompatibility of the mesoporous silicas with murine

tissue bioenergetics. Therefore, the measurements of respiration can be used to explore biocompatibility and viability of tissues and cells as a result of various treatments.

### 10. Liver tissue bioenergetics in concanavalin A hepatitis in mice

Concanavalin A (Con A) is a plant lectin from the seeds of *Canavalia ensiformis* (jack bean). This toxin serves as a polyclonal T-cell mitogen. It produces fulminant hepatitis in mice, a disease that mimics human infection with hepatitis B virus (Tiegs et al., 1992 & 1997). The hepatic injury is typically noted within 3 hr of intravenous injection of > 1.5 mg/kg of Con A and progresses with time (Tiegs et al., 1992). Activation and recruitment of Natural Killer (NK) T-cells and other cells of the innate immune system are early events, which lead to increased secretion of various inflammatory cytokines (e.g., TNF- $\alpha$ , IL-2, IL-10, IL-12 and IFN- $\gamma$ ) (Takeda et al., 2000; Margalit et al., 2005; Chen et al., 2010; Sass et al., 2002). This immune response targets multiple organs including the liver. Its outcome is irreversible hepatotoxicity, which includes inflammatory infiltrates and necrosis (Leist et al., 1996).

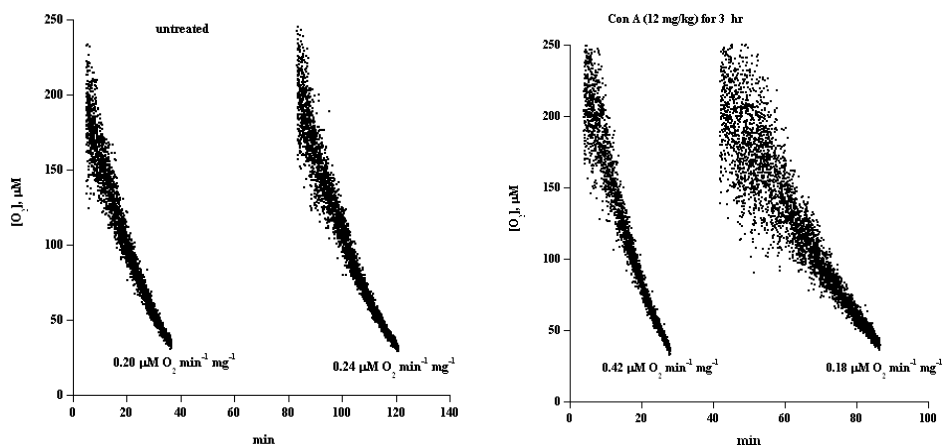
The above described *in vitro* system is employed to assess liver tissue respiration in Con A treated C57BL/6 mice. The purpose of the work was to estimate hepatocyte bioenergetics in this well-studied hepatitis model. The mice were injected intravenously with 12 mg/kg Con A or PBS. Specimens (20 to 30 mg each) were cut from the liver of anesthetized (urethane, 100  $\mu$ L per 10 g body weight, using 25% solution, w/v, in 0.9% NaCl) mice using a sharp scissor (Moria Vannas Wolg Spring, cat. # ST15024-10) (Al Samri et al., 2011). The specimens were immediately immersed in ice-cold Krebs-Henseleit buffer (115 mM NaCl, 25 mM NaHCO<sub>3</sub>, 1.23 mM NaH<sub>2</sub>PO<sub>4</sub>, 1.2 mM Na<sub>2</sub>SO<sub>4</sub>, 5.9 mM KCl, 1.25 mM CaCl<sub>2</sub>, 1.18 mM MgCl<sub>2</sub> and 6 mM glucose, pH ~7.2), gassed with 95% O<sub>2</sub>:5% CO<sub>2</sub>. Pieces were then weighed and placed in 1-ml Pd phosphor solution (Krebs-Henseleit buffer containing 0.5% albumin and 3  $\mu$ M Pd phosphor) for O<sub>2</sub> measurement. The results are summarized in Table 3.

Strain	Treatment	$k_c$ ( $\mu$ M O <sub>2</sub> min <sup>-1</sup> mg <sup>-1</sup> )	
		mean $\pm$ SD (n)	range
C57BL/6	PBS	0.26 + 0.04 (5)	0.22 - 0.32
	12 mg/kg Con A	0.18 + 0.03 (5)*	0.13 - 0.20

\* *P*-value = 0.005

Table 3. Liver tissue respiration in Con A treated C57BL/6 mice. Mice were injected with Con A or PBS. Liver specimens were collected 12 hr post injection.

A representative experiment following 3-hr treatment is shown in Fig. 10. Liver tissue respiration was measured 3 hr post injection of PBS (Fig. 10, left panel) or 12 mg/kg Con A (Fig. 10, right panel). In untreated mouse, the rates of respiration at  $t = 0$  min and  $t = 80$  min (post tissue collection) were similar. In Con A-treated mouse, the rate of respiration at  $t = 0$  min was high and at  $t = 40$  min it was low. Thus, at 3-hr, Con A treatment doubled the rate of liver tissue O<sub>2</sub> consumption. However, respiration deteriorated *in vitro* in 40 min.



Minutes zero correspond to collecting the liver tissue specimens at 3 hr post injections. Two runs were done for each condition. Rates of respiration ( $k_r$ , in  $\mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$ ) are shown at the bottom of the runs.

Fig. 10. Representative experiment for liver tissue respiration in C57BL/6 mice 3 hr post injection of PBS (left panel) or 12 mg/kg Con A (right panel)

Thus, Con A treatment produced a concurrent impairment of hepatocyte respiration. The lower rate of respiration at 12 hr post treatment (Table 3) concurred with large areas of necrosis and the enhanced rate of respiration at  $\sim 3$  hr post treatment (Fig. 10) concurred with inflammatory infiltrates limited to the perivascular space without any notable necrosis. The latter finding suggests a role for inflammatory mediators, such as  $\text{TNF-}\alpha$  and IL-2 (both known to peak 3 hr post Con A treatment) in modulating hepatocyte energy metabolism (Louis et al., 1997; Gottlieb et al., 2000). The mechanism for the presumed inflammation-induced increase in hepatocyte oxygen consumption could be uncoupling oxidative phosphorylation *vs.* up-regulating the energy metabolism. Nevertheless, for both assumptions, there is a large demand for energy supply to prevent fulminant liver necrosis. In an *in vitro* experiment, liver tissue respiration was measured with and without IL-2 (added directly to the  $\text{O}_2$  measuring vial). The rate of respiration without IL-2 was  $0.21 \mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$  and with IL-2  $0.087 \mu\text{M O}_2 \text{ min}^{-1} \text{ mg}^{-1}$  ( $\sim 60\%$  inhibition). Thus, similar to  $\text{TNF-}\alpha$ , IL-2 also inhibits cellular respiration *in vitro* (Gottlieb et al., 2000).

## 11. Spermatozoa respiration

The above *in vitro* system was also used to measure human spermatozoa respiration.  $\text{O}_2$  concentrations in solutions containing glucose and human spermatozoa declined linearly with time. Sodium cyanide also inhibited sperm oxygen consumption, confirming the oxidations occurred in the respiratory chain. The rate of respiration (mean  $\pm$  SD,  $n = 10$ ) was  $1.0 \pm 0.3 \mu\text{M O}_2 \text{ min}^{-1}$  per  $10^8$  sperm. Immediate decline in the rate of sperm respiration was noted when toxic agents [e.g., 4-hydroperoxycyclophosphamide (4OOH-CP),  $\Delta^9$ -tetrahydrocannabinol ( $\Delta^9$ -THC) or  $\Delta^8$ -tetrahydrocannabinol ( $\Delta^8$ -THC)] were added to washed sperm or neat semen. The inhibition was concentration-dependent and irreversible (Badawy et al., 2009a-b).

The toxic effect of the cannabinoids was confirmed on isolated mitochondria from beef heart. The effect of  $\Delta^8$ -THC on respiration of beef heart mitochondria is shown in Fig. 11. The value of  $k$  (in  $\mu\text{M O}_2 \text{ min}^{-1}$ ) decreased by 64% in the presence of 240  $\mu\text{M}$   $\Delta^8$ -THC.

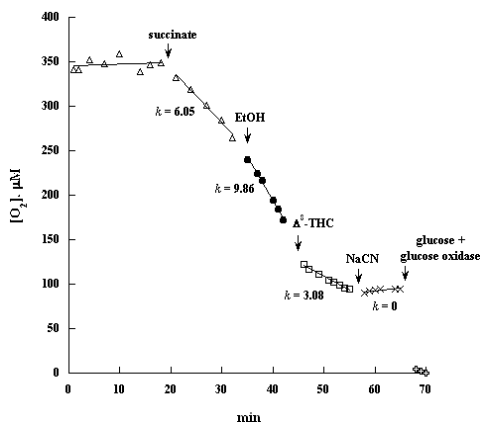


Fig. 11.  $\Delta^8$ -THC added to isolated mitochondria from beef heart.

## 12. Phosphorescence $\text{O}_2$ analyzer as a screening tool for disorders of impaired cellular bioenergetics

Disorders of cellular bioenergetics are challenging clinically and biochemically (Chretien and Rustin, 2003; Chretien et al., 1994; Rotig et al., 1990; Rustin et al., 1994). Their manifestations frequently overlap with numerous clinical entities. Furthermore, mutations that limit these processes in humans are incompletely identified (<http://www.gen.emory.edu/mitomap.html>) (Kogelnik et al., 1997). Therefore, clinicians usually rely on a laborious analysis of skin and muscle biopsies for diagnosis (Chretien and Rustin, 2003; Chretien et al., 1994; Rustin et al., 1994). As suggested by Rustin et al., laboratory evaluation of mitochondrial disorders require testing samples from multiple tissues. The authors also recommended the use of circulating lymphocytes in the initial screening (Rustin et al., 1994). These interrelations justify developing non-invasive simple screening methods that are applicable to various types of samples. Recently, Marriage et al. showed ATP synthesis in permeabilized lymphocytes is an effective screening tool for impaired oxidative phosphorylation (Marriage et al., 2003; Marriage et al., 2004). Decreased ATP synthesis in the lymphocytes was present in the 5 studied mitochondrial disorders (Marriage et al., 2003).

Described herein is the use of the phosphorescence  $\text{O}_2$  analyzer to measure lymphocyte respiration in volunteers and a patient. The measurement primarily aimed to show feasibility of using the phosphorescence  $\text{O}_2$  analyzer to screen for clinical disorders with impaired cellular bioenergetics. Peripheral blood mononuclear cells (PBMC) were collected from healthy volunteers and patient. The rate of respiration (mean  $\pm$  SD, in  $\mu\text{M O}_2$  per min per  $10^7$  cells) for adult volunteers is  $2.1 \pm 0.8$  ( $n = 18$ ), for children  $2.0 \pm 0.9$  ( $n = 20$ ), and for newborns (umbilical cord samples)  $0.8 \pm 0.4$  ( $n = 18$ ,  $p < 0.0001$ ). Representative experiments of the volunteers are shown in Fig. 12.

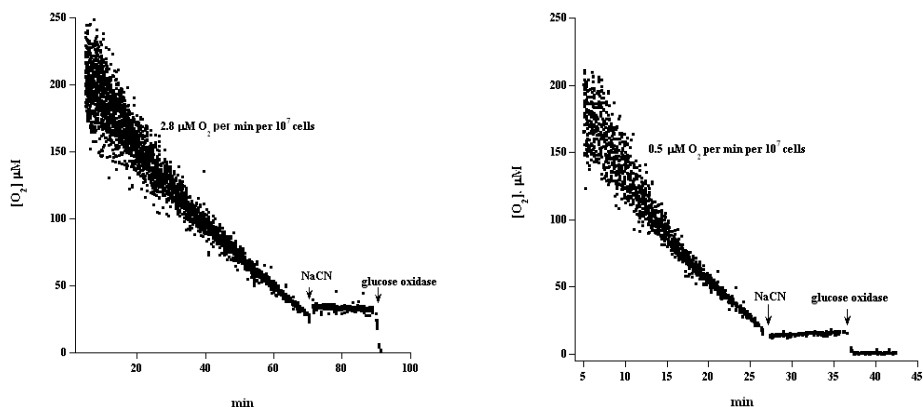


Fig. 12. Left panel: Lymphocytes ( $1.0 \times 10^7$  cells/mL) were collected from a 9-year-old girl; the rate of respiration was  $2.8 \mu M O_2$  per min per  $10^7$  cells ( $R^2 > 0.942$ ). Right panel: Lymphocytes ( $15 \times 10^7$  cells/mL) were collected from umbilical cord; the rate of respiration was  $8.0 \mu M O_2$  per min ( $R^2 > 0.934$ ), or  $0.5 \mu M O_2$  per min per  $10^7$  cells. The additions of 5.0 mM NaCN and 50  $\mu g/mL$  glucose oxidase are shown.

For an 8-year-old patient with reduced muscle NADH dehydrogenase and pyruvate dehydrogenase activities, the rate was  $0.7 \pm 0.2$  ( $n = 3$ )  $\mu M O_2$  per min per  $10^7$  cells.

As previously noted in muscle specimens, the rate of lymphocyte mitochondrial oxygen consumption is very similar in adults and children ( $p = 0.801$ ) (Chretien et al., 1994). However, cord blood cells have lower rates of respiration ( $p < 0.001$ ). This finding could be attributed to the high number of nucleated red blood cells in the umbilical cord blood.

Fresh lymphocytes were previously used as a source of tissue for measuring respiratory chain enzymes by polarography (Clark-type  $O_2$  electrode) and spectroscopy (Chretien and Rustin, 2003; Chretien et al., 1994; Rustin et al., 1994). Rotig et al. reported a rate (mean + SD,  $n=15$ ) of  $3.5 \pm 0.5$  nmol  $O_2$  per min per  $10^7$  cells (Rotig et al., 1990). Hedekov and Esmann reported a rate of  $2.0 \pm 0.07$  nmol  $O_2$  per min per  $10^7$  for cell concentrations  $>4 \times 10^7$  per mL and higher rates for less concentrated cells (Hedekov and Esmann, 1966). Pachman reported rate of  $1.0 \pm 0.2$  nmol  $O_2$  per min per  $10^7$  equine lymphocytes (Pachman, 1967).

Clinical presentations of entities with impaired cellular bioenergetics vary markedly. Their manifestations may include progressive neuromuscular defects (e.g., psychomotor retardation and hypotonia), heart muscle involvement and encephalopathy. One typical example is Leigh syndrome, which results from an isolated mitochondrial complex I deficiency (Benit et al., 2004). This clinical heterogeneity stems from various mechanisms, including tissue-specific of nuclear-encoded isoforms of the respiratory chain and existence of normal and mutated mtDNA in the same organ (mtDNA heteroplasmy) (Rustin et al., 1994). Therefore, as suggested by Rustin et al., the biochemical analysis should not be limited to skeletal muscle and skin tissues (Rustin et al., 1994). In one study, 42 patients with respiratory chain defects were investigated. The results showed that 50% of the patients had deficiencies in skeletal muscles and lymphocytes, 45% in skeletal muscles only, and 5% in lymphocytes only (Chretien et al., 1994). Patients with Pearson's syndrome on the other hand consistently express defects in the lymphocyte (Rotig et al., 1990).

### 13. Conclusions

A novel *in vitro* system that allows monitoring of cellular respiration over several hours is described. The method has numerous biological applications, including studying mitochondrial dysfunction during apoptosis or toxic exposure. It also allows screening for metabolic disorders in patients. The procedure is sensitive and reproducible. It is applicable to cells in suspension, adherent cells and various organs, including the heart muscle, liver, spleen, pancreas and kidney.

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# Targeting the Mitochondria by Novel Adamantane-Containing 1,4-Dihydropyridine Compounds

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## 1. Introduction

Mitochondria are important regulators of cellular functions and energy metabolism, therefore mitochondrial dysfunction leads to a compromised energy-generating system, deteriorated cellular homeostasis and neurodegenerative disorders, such as Parkinson's disease and Alzheimer's disease (Shapira, 1999; 2009). Hence, the protection of mitochondria, even their repair mechanisms at the level of complex I, may be a key strategy in limiting mitochondrial damage and ensuring cellular integrity (Dawson & Dawson, 2003). Thus, in addition to traditionally used antiparkinsonian drugs, which are focused on the activation of the dopaminergic system, different mitochondria-protecting agents are being used in clinics for the treatment of Parkinson's disease. For instance, agents with antioxidant properties, such as melatonin (Esposito & Cuzzocrea, 2010), coenzyme Q10 and creatine (Kones, 2010), lipoic acid (De Araújo et al., 2011), and the extract of *Hyoscyamus niger* seeds (Sengupta et al., 2011), are currently used to treat Parkinson's disease.

Recently, antihypertensive drugs of the calcium antagonistic series, which belong to 1,4-dihydropyridine (DHP) class and are capable of penetrating the blood-brain barrier (e.g., nifedipine, nimodipine), were shown to significantly reduce the risk of developing Parkinson's disease (Becker et al., 2008; Ritz et al., 2010). This was explained by blocking L-type calcium channels in the dopaminergic neurons of the substantia nigra, where elevated calcium ion concentrations initiate cell death (Sulzeret & Schmitz, 2007). However, the mechanism of the antiparkinsonian action of DHPs is not yet understood.

Our investigation of DHP compounds showed that many of them are capable of protecting mitochondrial processes (Fernandes et al., 2003, 2005, 2008, 2009). For instance, the most

active compound cerebrocrast {4-[2-(difluoromethoxy)phenyl-2,6-dimethyl-1,4-dihydropyridine-3,5-dicarboxylic acid di(2-propoxyethyl)diester}, which has shown neuroprotective effects in different neurodeficiency models (Klusa, 1995), decreased mitochondrial toxin 1-methyl-4-phenylpyridinium (MPP<sup>+</sup>)-induced cell death in rat cerebellar granule cells (Klimaviciusa et al., 2007). In isolated mitochondria of rat liver, cerebrocrast inhibited the inner mitochondrial anion channel, Ca<sup>2+</sup>-induced opening of the mitochondrial membrane permeability transition pore and permeabilization of the mitochondrial inner membrane (Vicente et al., 2006). In addition, it normalized oxidative phosphorylation and increased adenosine triphosphate (ATP)-induced contraction in swollen mitochondria of isolated rat skeletal muscle (Velena et al., 1997). Cerebrocrast and its congeners also protected against histopathological changes caused by azidothymidine, known to be a mitochondrial toxin (Pupure et al., 2008).

The present study investigates two novel DHP compounds, cerebrocrast analogues containing structure elements that may enhance the delivery of molecules through the blood-brain barrier and improve their access to mitochondria. The compounds are composed of either one adamantane moiety in position 3 (AV-6-93) or two adamantane moieties in positions 3 and 5 (diflurone) of the DHP ring. We suggest that these DHP structures may possess mitochondria-protecting and antiparkinsonian activity due to both the adamantane moiety, which can be considered to be an important functional unit, and the DHP structure, which may serve as the carrier molecule. Adamantane molecules were previously used in the design of neuroprotective drugs. For example, amantadine (1-aminoadamantane) is used in antiparkinsonian drugs with mechanisms focused on NMDA-receptor gated ion channels (Kornhuber et al., 1991). Adamantane derivatives, particularly memantine, are reported as neuroprotective agents against mitochondrial toxicity *in vivo* (Rojas et al., 2008) and *in vitro* (McAllister et al., 2008). Memantine may act directly on dopamine D2High receptors (Seeman et al., 2008), whereas amantadine may stimulate the synthesis and release of dopamine in the rat striatum (Spilker & Dhasmana, 1973), which is beneficial in the treatment of Parkinson's disease. Aminoadamantane derivatives 4-(1-adamantylamino)-2,2,6,6-tetramethylpiperidine-1-oxyl and 4-(1-adamantylammonio)-1-hydroxy-2,2,6,6-tetramethylpiperidinium dihydrochloride were also synthesised as antiparkinsonian drugs (Skolimowski et al., 2003). However, compounds with adamantane moieties attached to the DHP structure have not yet been synthesised.

In this study, we tested novel compounds *in vitro* to assess their influence on mitochondrial processes in primary cultures of rat cortical neurons, using mitochondrial toxin MPP<sup>+</sup>, and on isolated rat liver mitochondria.

## 2. Materials and methods

### 2.1 Animals

Male Wistar rats (250-350 g), housed at 22 ± 2 °C under artificial light for a 12-h light/dark cycle and with access to water and food *ad libitum*, were used for these experiments. All of the experimental procedures were performed in accordance with the guidelines of Directive 86/609/EEC "European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes" (1986) and were approved by the National Ethics Committee.

### 2.2 Chemicals

AV-6-93 [2,6-dimethyl-3-(1-adamantylloxycarbonyl)-4-(2-difluoromethoxyphenyl)-5-[(2-propoxy)ethoxycarbonyl]-1,4-dihydropyridine] (Fig. 1A) and diflurone [2,6-dimethyl-3,5-

bis(1-adamantyloxycarbonyl)-4-(2-difluoromethoxyphenyl)-1,4-dihydropyridine] (Fig. 1B) were synthesised at the Latvian Institute of Organic Synthesis, 21 Aizkraukles Street, Riga, LV-1006. AV-6-93 and diflurone were dissolved in 100% DMSO and further diluted to concentrations of 0.1% (v/v) and less.

Chemicals for the mitochondrial studies were obtained from Sigma Chemical Company (St Louis, MO, USA); chemicals for cytotoxicity studies mentioned in 2.3. and 2.4.

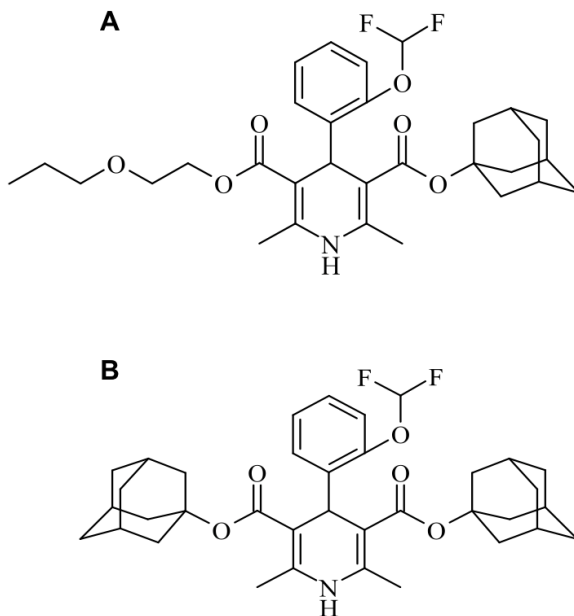


Fig. 1. The structures of AV-6-93 (A) and diflurone (B).

### 2.3 Primary culture of rat cortical neurons

Primary cultures were prepared from 1-day-old Wistar rat pups, according to the method of Alho et al., 1988, with minor modifications. Briefly, cortices were dissected in ice-cold Krebs-Ringer solution (135 mM NaCl, 5 mM KCl, 1 mM MgSO<sub>4</sub>, 0.4 mM KH<sub>2</sub>PO<sub>4</sub>, 15 mM glucose, 20 mM HEPES, pH 7.4, containing 0.3% bovine serum albumin) and trypsinised in 0.8% trypsin-EDTA (Invitrogen, U.K.) for 10 min at 37 °C, followed by trituration in 0.008% DNase I solution containing 0.05% soybean trypsin inhibitor (both obtained from Surgitech AS, Estonia). Cells were resuspended in Eagle's basal medium with Earle's salts (BME, Invitrogen, U.K.), containing 10% heat-inactivated foetal bovine serum (FBS, Invitrogen, U.K.), 25 mM KCl, 2 mM GlutaMAX™-I (Invitrogen, U.K.) and 100 µg/mL gentamycin. Cells were plated onto poly-L-lysine- (Sigma Chemical Co., MO, USA) coated 48-well plates at a density of 1.8 × 10<sup>5</sup> cells/cm<sup>2</sup>. The medium was changed to Neurobasal™-A medium containing 2 mM GlutaMAX™-I with B-27 supplement and 100 µg/mL gentamycin 2.5 hr later. Cultures were incubated for 6 days in a 5% CO<sub>2</sub>/95% air atmosphere at 37 °C, and one-fifth of the culture medium was changed on DIV 3 (day 3 *in vitro*).

#### 2.4 Measurement of cell death in cytotoxicity assay

Primary rat cortical neurons were cultured for 5 days as described above. On DIV 5, cultures were incubated with 1-methyl, 4-phenylpyridinium (MPP<sup>+</sup>, Sigma Chemical Co., MO, USA) for the following 24 hr at a concentration of 300  $\mu$ M. Cells were pre-incubated with the tested compounds AV-6-93 and diflurone for 90 min followed by the addition of MPP<sup>+</sup> and further incubation with MPP<sup>+</sup> plus the tested compounds or a solvent (control) for the next 24 hours. Cell death was measured with a Trypan blue assay (Tymianski et al., 1993). Cells were incubated with 0.4% Trypan blue solution in phosphate buffered saline (PBS, 145 mM NaCl, 3 mM KCl, 0.42 mM Na<sub>2</sub>HPO<sub>4</sub>, 2.4 mM KH<sub>2</sub>PO<sub>4</sub>, pH = 7.4) at 37 °C for 7 min and then washed twice with PBS and fixed with 4% paraformaldehyde in PBS. Only dead neurons were stained with Trypan blue (Tymianski et al., 1993). The fixed cultures were rinsed with PBS for microscopic observation, and approximately 150 cells per 5 fields in each well were counted to determine the number of dead cells and the total number of cells. Neuronal death was calculated as the percentage of dead cells from the total (viable plus dead) number of cells, and the obtained data were averaged for each well.

#### 2.5 Isolation of rat liver mitochondria

Rat liver mitochondria were isolated from male Wistar rats by differential centrifugation according to conventional methods (Gazotti et al., 1979). After washing, the pellet was gently resuspended in the washing medium at a protein concentration of about 50 mg/ml. Protein content was determined by the biuret method (Gornall et al., 1949), using bovine serum albumin as a standard.

#### 2.6 Measurement of respiratory activities

Oxygen consumption was monitored polarographically with a Clark-type electrode at 30 °C in a closed glass chamber equipped with magnetic stirring. Mitochondria (1 mg/ml) were incubated in a respiratory medium containing 130 mM sucrose, 5 mM HEPES (pH 7.2), 50 mM KCl, 2.5 mM K<sub>2</sub>HPO<sub>4</sub>, and 2.5 mM MgCl<sub>2</sub> (in the presence and absence of AV-6-93 or diflurone) for 3 min before energisation with 10 mM glutamate/5 mM malate. When 10 mM succinate was used as the respiratory substrate, the reaction medium was supplemented with 2  $\mu$ M rotenone. To induce state 3 respiration, adenosine diphosphate (ADP, 150  $\mu$ M) was added. FCCP (p-trifluoromethoxyphenylhydrazone)-stimulated respiration was initiated by the addition of 1  $\mu$ M FCCP. The respiratory control ratio (RCR), which is calculated by the ratio between state 3 (consumption of oxygen in the presence of substrate and ADP) and state 4 (consumption of oxygen after ADP phosphorylation), is an indicator of mitochondrial membrane integrity. The ADP/O ratio, which is expressed by the ratio between the amounts of ADP added and the oxygen consumed during state 3 respiration, is an index of oxidative phosphorylation efficiency. Respiration rates were calculated assuming that the saturation of oxygen concentration was 250  $\mu$ M at 30 °C (Chance & Williams, 1956), and the values are expressed in percentage of control (% of control).

#### 2.7 Measurement of mitochondrial transmembrane potential

The mitochondrial transmembrane potential ( $\Delta\psi$ ) was measured indirectly based on the detection of lipophilic cation tetraphenylphosphonium (TPP<sup>+</sup>) using a TPP<sup>+</sup>-selective electrode, as previously described (Kamo et al., 1979). The  $\Delta\psi$  was estimated from the following equation <sup>(1)</sup>:



$$\Delta\psi = 59 \times \log (v/V) - 59 \times \log (10^{\Delta E/59} - 1) \quad (1)$$

where  $v$ ,  $V$ , and  $\Delta E$  stand for inner mitochondrial volume, incubation medium volume, and deflection of the electrode potential from the baseline, respectively. A mitochondrial matrix volume of 1.1  $\mu\text{l}/\text{mg}$  protein was assumed. No correction was made for the "passive" binding of  $\text{TPP}^+$  to the mitochondrial membranes because the purpose of the experiments was to show relative changes in potential rather than absolute values. As a consequence, we anticipate some overestimation for the  $\Delta\psi$  values. To monitor  $\Delta\psi$  associated with mitochondrial respiration, liver mitochondria (1 mg/ml) were incubated for 3 min in the respiratory medium described above, supplemented with 3  $\mu\text{M}$   $\text{TPP}^+$ , at 30 °C in the absence or presence of different concentrations of AV-6-93 or diflurone before energisation with 10 mM glutamate/5 mM malate or 10 mM succinate. When succinate was used as the respiratory substrate, the medium was supplemented with 2  $\mu\text{M}$  rotenone. AV-6-93 or diflurone did not affect  $\text{TPP}^+$  binding to mitochondrial membranes or the electrode response.

### 2.8 $\text{Ca}^{2+}$ -induced mitochondrial membrane transition pore (MPT)

$\text{Ca}^{2+}$ -induced MPT was evaluated by measuring changes in mitochondrial transmembrane potential ( $\Delta\psi$ ) using a  $\text{TPP}^+$  electrode, changes in oxygen consumption using a Clark-type electrode, and changes in  $\text{Ca}^{2+}$  fluxes using a  $\text{Ca}^{2+}$ -selective electrode. The reactions were conducted in a medium containing 200 mM sucrose, 10 mM Mops-Tris (pH 7.4), 1 mM  $\text{KH}_2\text{PO}_4$ , and 10  $\mu\text{M}$  EGTA, supplemented with 2  $\mu\text{M}$  rotenone, as previously described (Custódio et al., 1998a, 1998b). Mitochondria (1mg/ml) that were incubated at 30 °C for 3 min (in the absence and presence of AV-6-93 or diflurone) were energised with 10 mM succinate, and the single addition of  $\text{Ca}^{2+}$  (100 nmol/mg protein) was used to induce MPT. Control assays, in both the absence and presence of  $\text{Ca}^{2+}$  plus 0.75 nmol/mg protein cyclosporin A (CsA) and compound (when necessary) were also performed.

### 2.9 Lipid peroxidation

The extent of lipid peroxidation was evaluated by oxygen consumption using a Clark-type electrode at 30 °C in an open glass chamber equipped with magnetic stirring. Mitochondria (1 mg/ml) were pre-incubated for 3 min in a medium containing 175 mM KCl, 10 mM Tris-Cl (pH 7.4), supplemented with 3  $\mu\text{M}$  rotenone (in the presence or absence of tested compounds) to avoid mitochondrial respiration induced by endogenous respiratory substrates. The iron solution was prepared immediately before use and was protected from light. The changes in  $\text{O}_2$  tension were recorded in a potentiometric chart record and oxygen consumption was calculated assuming an oxygen concentration of 230 nmol/ml. Membrane lipid peroxidation was initiated by adding 1 mM ADP/0.1 mM  $\text{Fe}^{2+}$  as oxidizing agents. Controls, in the absence of ADP/ $\text{Fe}^{2+}$ , were performed under the same conditions.

Lipid peroxidation was also determined by measuring thiobarbituric acid reactive substances (TBARs), using the thiobarbituric acid assay (Ernst & Nordenbrand, 1967). Aliquots of mitochondrial suspensions (0.5 ml each), removed 10 min after the addition of ADP/ $\text{Fe}^{2+}$ , were added to 0.5 ml of ice cold 40% trichloroacetic acid. Then, 2 ml of 0.67% of aqueous thiobarbituric acid containing 0.01% of 2,6-di-*tert*-butyl-*p*-cresol was added. The mixtures were heated at 90 °C for 15 min, then cooled on ice for 10 min, and centrifuged at 850 g for 10 min. Controls, in the absence of ADP/ $\text{Fe}^{2+}$ , were performed under the same conditions. The supernatant fractions were collected and lipid peroxidation was estimated

spectrophotometrically at 530 nm. As blanks, we used control reactions performed in the absence of mitochondria and ADP/Fe<sup>2+</sup>. The amount of TBARs formed was calculated using a molar extinction coefficient of  $1.56 \times 10^5 \text{ mol}^{-1} \text{ cm}^{-1}$  and expressed as nmol TBARs/mg protein (Buege & Aust, 1978).

### 2.10 Statistical analysis

The cytotoxicity data were calculated as a mean  $\pm$  S.E. Statistical analysis was performed using Student's t-test or one-way analysis of variance (ANOVA), followed by a Bonferroni multiple comparisons test.

The mitochondrial experiments were performed using three independent experiments with different mitochondrial preparations. The values are expressed as means  $\pm$  S.E. Means were compared using one-way ANOVA for multiple comparisons, followed by Tukey's test. Statistical significance was set at  $p < 0.05$ .

## 3. Results

### 3.1 Protection against the cell death induced by MPP<sup>+</sup>

In primary rat cortical neurones, AV-6-93 at concentrations of 1 and 10  $\mu\text{M}$  decreased MPP<sup>+</sup>-induced cell death by 75% and 56%, respectively (Fig. 2A). Diflurone exerted the protective ability only at the highest tested concentration, 10  $\mu\text{M}$ , and decreased the MPP<sup>+</sup>-induced cell death by 35% (Fig. 2B). Neither AV-6-93 nor diflurone, added without MPP<sup>+</sup>, changed cell viability at the highest tested concentrations (Fig. 2).

### 3.2 Effects of AV-6-93 and diflurone on rat liver mitochondrial bioenergetics

AV-6-93 and diflurone (up to 100  $\mu\text{M}$ ) were studied for their effects on mitochondrial bioenergetics by evaluating several mitochondrial respiratory chain parameters (state 2, state 3, state 4, FCCP-stimulated respiration, RCR, ADP/O ratio,  $\Delta\psi$ , and phosphorylation rate) using glutamate/malate as the respiratory substrate.

The effects of AV-6-93 on glutamate/malate-supported respiratory rates (state 2, state 3, state 4 and FCCP-stimulated respiration), respiratory indices RCR and ADP/O of rat liver mitochondria were almost non-existent and insignificant at concentrations of up to 100  $\mu\text{M}$  (Table 1), indicating that the compounds did not significantly affect mitochondrial bioenergetics.

These results are demonstrated in Table 2, where AV-6-93 and diflurone, at concentrations of up to 100  $\mu\text{M}$ , did not significantly affect either the  $\Delta\psi$  induced by glutamate/malate-dependent respiration or the phosphorylation time.

As for glutamate/malate-supported respiration, the effects of AV-6-93 and diflurone on succinate-supported respiratory rates (state 2, state 3, state 4 and FCCP) and respiratory indices RCR and ADP/O of rat liver mitochondria were not significantly affected (results not shown), further supporting the finding that these compounds did not affect mitochondrial bioenergetics.

### 3.3 Effects of AV-6-93 and diflurone on Ca<sup>2+</sup>-induced MPT

The effect of AV-6-93 and diflurone on Ca<sup>2+</sup>-induced MPT was studied in order to evaluate their capacity to protect mitochondria against MPT opening by measuring the decrease in  $\Delta\psi$ , the increase in oxygen consumption, and the Ca<sup>2+</sup>-induced release of mitochondrial Ca<sup>2+</sup>, which are typical phenomena that follow the induction of MPT. The amount of Ca<sup>2+</sup> used to induce MPT was 100 nmol/mg protein.

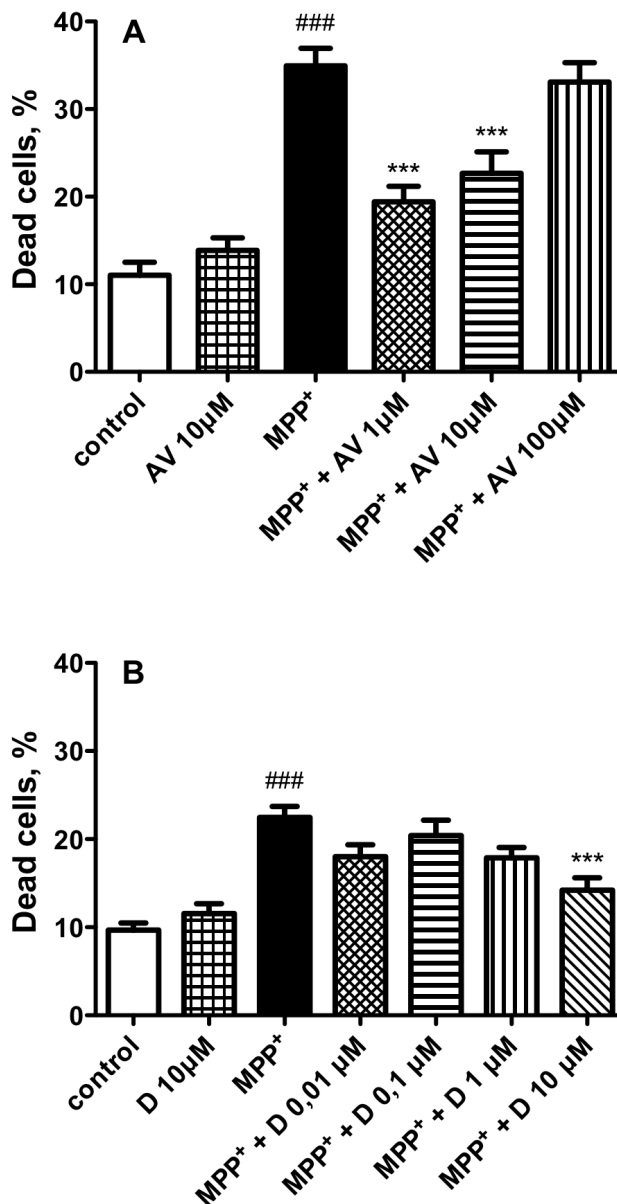


Fig. 2. Influence of AV-6-93 (AV) and diflurone (D) on MPP<sup>+</sup>-induced cell death in primary rat cortical neurons (A and B, respectively). Cell death measured by Trypan blue method. Data are presented as a mean  $\pm$  S.E. ###  $p < 0.001$  vs control, t-test, \*\*\*  $p < 0.001$  vs MPP<sup>+</sup>, one-way ANOVA followed by Bonferroni multiple comparison's test.

Compounds ( $\mu\text{M}$ )	Oxygen consumption (% of control)				RCR	ADP/O
	State 2	State 3	State 4	State FCCP		
<b>AV-6-93</b>						
0.0	100.0 $\pm$ 0.0	100 $\pm$ 0.0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	6.8 $\pm$ 1.3	3.01 $\pm$ 0.1
1.0	100.0 $\pm$ 0.0	113.4 $\pm$ 6.7	94.4 $\pm$ 5.6	100.2 $\pm$ 8.7	6.5 $\pm$ 1.5	2.9 $\pm$ 0.1
10.0	105.0 $\pm$ 18.9	104.0 $\pm$ 7.3	119.4 $\pm$ 10.0	101.9 $\pm$ 7.3	6.4 $\pm$ 1.0	2.8 $\pm$ 0.4
100.0	127.2 $\pm$ 31.9	109.9 $\pm$ 6.6	145.8 $\pm$ 44.5	91.2 $\pm$ 8.5	6.3 $\pm$ 2.7	2.8 $\pm$ 0.1
<b>Diflurone</b>						
0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	6.8 $\pm$ 1.3	3.01 $\pm$ 0.1
100	107.3 $\pm$ 4.8	95.9 $\pm$ 2.9	104.4 $\pm$ 5.27	94.4 $\pm$ 4.03	6.4 $\pm$ 1.2	2.9 $\pm$ 0.09

Table 1. Effects of AV-6-93 and diflurone on the respiratory parameters (state 2, state 3, state 4, FCCP-stimulated respiration) and respiratory indices (RCR and ADP/O ratio) of rat liver mitochondria using glutamate/malate as respiratory substrate.

The values, which are given in percentage of control (% of control), correspond to the mean  $\pm$  S.E. of the respiratory parameters, evaluated in three different mitochondrial preparations, at the different indicated situations. Control values are expressed in  $\text{nmol O}_2 \cdot \text{mg}^{-1} \text{protein min}^{-1}$ : state 2 =  $7.1 \pm 0.7$ ; state 3 =  $39.4 \pm 4.0$ ; state 4 =  $5.62 \pm 0.8$ ; FCCP-stimulated respiration =  $57.14 \pm 10.4$ .

Compounds ( $\mu\text{M}$ )	$\Delta\psi$ (mV)			Phosphorylation time (s)
	Glu/Mal energisation	ADP depolarisation	Repolarisation	
<b>AV-6-93</b>				
0	-220.5 $\pm$ 5.1	21.7 $\pm$ 2.2	-216.8 $\pm$ 2.6	33.0 $\pm$ 3.0
1	-219.0 $\pm$ 4.0	21.3 $\pm$ 1.9	-217.0 $\pm$ 4.3	32.7 $\pm$ 2.9
10	-220.6 $\pm$ 4.1	23.5 $\pm$ 2.1	-218.7 $\pm$ 4.2	32.5 $\pm$ 4.5
100	-216.0 $\pm$ 5.6	23.4 $\pm$ 1.1	-212.5 $\pm$ 4.7	39.0 $\pm$ 1.7
<b>Diflurone</b>				
0	-220.5 $\pm$ 5.1	21.7 $\pm$ 2.2	-216.8 $\pm$ 2.6	33.0 $\pm$ 3.0
100	-218.0 $\pm$ 1.7	21.0 $\pm$ 0.3	-216.0 $\pm$ 1.4	32.8 $\pm$ 2.3

Table 2. Effects of AV-6-93 and diflurone on glutamate/malate-dependent transmembrane potential ( $\Delta\psi$ ) and phosphorylation time of rat liver mitochondria.

The values correspond to the mean  $\pm$  S.E. of the  $\Delta\psi$  and the phosphorylation time, evaluated in three different mitochondrial preparations, at the different indicated situations.

The results of the effect of AV-6-93 on MTP protection are depicted in Fig. 3. Under control conditions, the addition of 10 mM succinate to mitochondrial suspensions produced a  $\Delta\psi$  of about -216 mV (negative inside mitochondria) (Fig. 3A), corresponding to respiratory state 4 (Fig. 3B). The addition of  $\text{Ca}^{2+}$  led to a rapid depolarisation (decrease of  $\Delta\psi$ ), followed by a partial repolarisation (recover of  $\Delta\psi$ ), the subsequent total depolarisation of mitochondria (Fig. 3A), and an increase in respiratory state 4 (Fig. 3B).

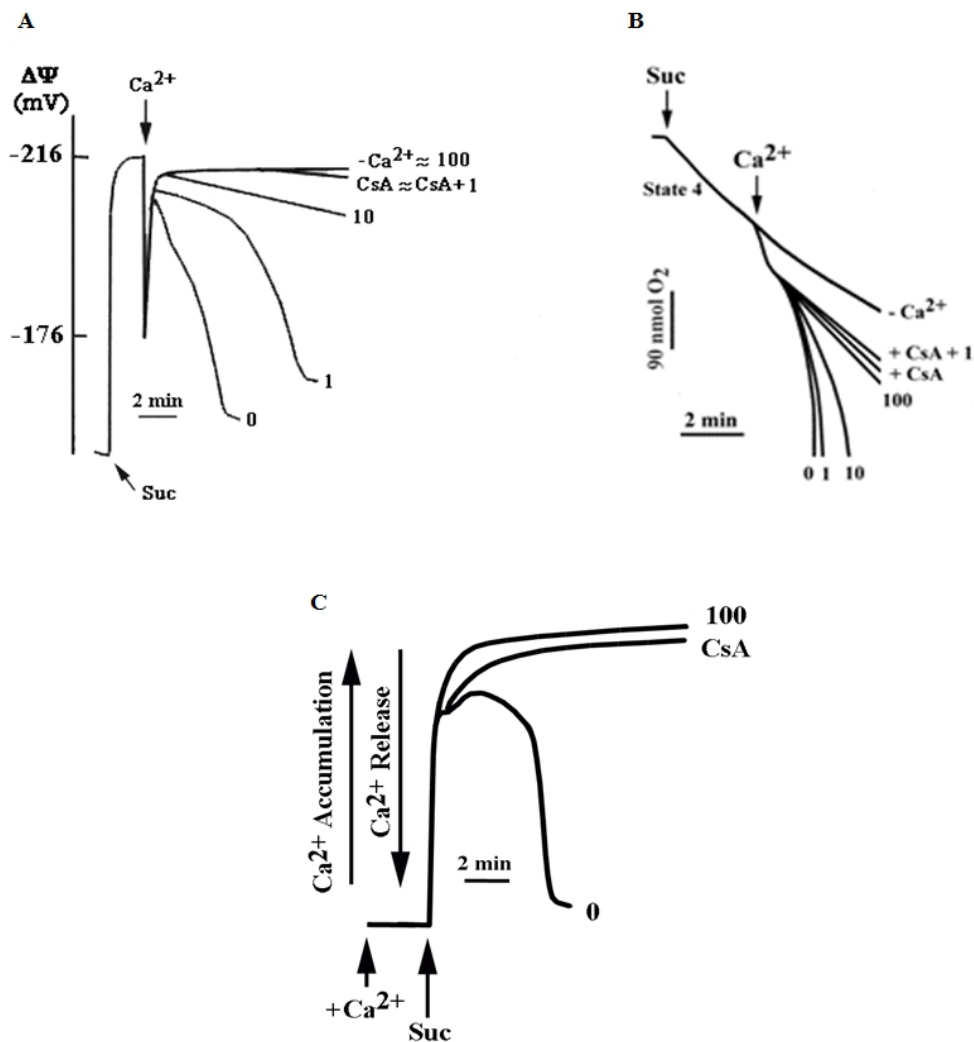


Fig. 3. Effect of AV-6-93 on rat liver MPT induced by  $\text{Ca}^{2+}$ .

Evaluation was performed by measuring succinate-supported transmembrane potential ( $\Delta\Psi$ ) (A), oxygen consumption (B), and mitochondrial  $\text{Ca}^{2+}$  fluxes (C). Additions of 100 nmol calcium/mg protein ( $\text{Ca}^{2+}$ ) and 10 mM succinate (Suc); additions of AV-6-93 at the concentrations of 1, 10, and 100  $\mu\text{M}$  (1, 10, 100) are indicated. Assays in the absence of  $\text{Ca}^{2+}$  ( $-\text{Ca}^{2+}$ ); assays in the presence of  $\text{Ca}^{2+}$  plus CsA (0.75 nmol/mg protein (CsA)); assays in the presence of  $\text{Ca}^{2+}$  plus CsA + 1  $\mu\text{M}$  AV-6-93 (CsA+ 1). The traces are representative of assays with three different mitochondrial preparations.

These effects were due to the entry of  $\text{Ca}^{2+}$  into the electronegative mitochondrial matrix (Fig. 3C), followed by the efflux of  $\text{H}^+$  for restoring the  $\Delta\Psi$ . Incubation of mitochondria with

AV-6-93 concentrations of up to 100  $\mu\text{M}$  for 3 min before energisation with succinate prevented total depolarisation of mitochondria (Fig. 3A), the increase in respiratory state 4 (Fig. 3B), and the release of mitochondrial  $\text{Ca}^{2+}$  (Fig. 3C), suggesting that this compound has a high ability to protect mitochondria against MPT induction. Incubation of mitochondria with 0.75 nmol/mg protein, CsA, a specific inhibitor of MPT (Broekemeier et al., 1989), for 2 min before energising with succinate, either in the absence or presence of 1  $\mu\text{M}$  AV-6-93, completely blocked mitochondrial depolarisation (Fig. 3A), the increase in respiratory state 4 (Fig. 3B), and the  $\text{Ca}^{2+}$ -induced release of mitochondrial  $\text{Ca}^{2+}$  (Fig. 3C). These data show that these effects had been induced by MPT. In contrast to AV-6-93, diflurone, in the same concentration range, did not prevent either the depolarisation of mitochondria or the release of mitochondrial  $\text{Ca}^{2+}$  (results not shown), indicating that this compound did not protect mitochondria against MPT.

### 3.4 Effects of AV-6-93 and diflurone on mitochondrial oxidative stress

The effects of AV-6-93 and diflurone on mitochondrial oxidative damage were assessed by detecting the mitochondrial membrane lipid peroxidation induced by the pro-oxidant pair ADP/ $\text{Fe}^{2+}$ . Lipid peroxidation was evaluated by measuring oxygen consumption (Fig. 4) and TBARs formation (Table 3). In the absence of AV-6-93 and after the addition of the pro-oxidant pair, it is possible to distinguish two-phase kinetics in oxygen consumption: an initial lag phase, characterized by slow oxygen consumption lasting about 2 min, is followed by a rapid oxygen consumption phase. The lag phase is probably related with the time required for the generation of a sufficient amount of the perferryl ion complex ( $\text{ADP-Fe}^{2+}\text{-O}_2 \Rightarrow \text{ADP-Fe}^{3+}\text{-O}_2$ ), which has been suggested to be responsible for the initiation of lipid peroxidation. The rapid oxygen consumption phase is probably due to the oxidation of the polyunsaturated fatty acid acyl chain of membrane phospholipids by reactive oxygen species (ROS) and, consequently, due to the propagation phase of lipid peroxidation (Sassa et al., 1990). AV-6-93 concentrations up to 100  $\mu\text{M}$  enlarged the lag phase of slow oxygen consumption before the oxygen uptake burst induced by the ADP/ $\text{Fe}^{2+}$  complex and increased the rate of the rapid oxygen consumption phase (Fig. 4), suggesting that the compounds affected both the initiation and the propagation of lipid peroxidation of mitochondrial membranes.

These results agree with the quantitative evaluation of TBARs formation performed to confirm the protective effects of AV-6-93. The data in Table 3 show that the kinetics of TBARs formation induced by ADP/ $\text{Fe}^{2+}$  are similar to that observed for oxygen consumption. The same range of AV-6-93 concentrations used in the oxygen consumption assays also affected TBARs formation. TBARs formation in the absence of ADP/ $\text{Fe}^{2+}$  was negligible ( $0.44 \pm 0.25$  nmol/mg of protein). In contrast to AV-6-93, diflurone, in the same concentration range, did not affect oxygen consumption induced by the ADP/ $\text{Fe}^{2+}$  complex or TBARs formation (results not shown), indicating that this compound has no capacity to protect mitochondria against the lipid peroxidation induced by the pro-oxidant pair ADP/ $\text{Fe}^{2+}$ .

Lipid peroxidation was evaluated by oxygen consumption and initiated by adding 1 mM ADP/0.1 mM  $\text{Fe}^{2+}$  to mitochondrial suspensions (Fig. 4). The traces represent typical direct oxygen consumption recordings of three experiments obtained from different mitochondrial preparations; controls in the absence of ADP/ $\text{Fe}^{2+}$  ( $-\text{ADP}/\text{Fe}^{2+}$ ); assays in the presence of AV-6-93 at the concentrations 1, 10, 20, 50, 100  $\mu\text{M}$  (1, 10, 20, 50, 100).

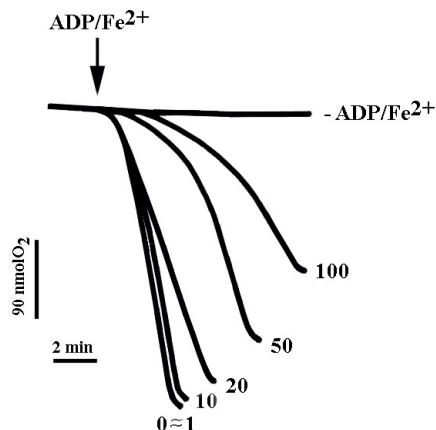


Fig. 4. Effect of AV-6-93 on membrane lipid peroxidation of rat liver mitochondria induced by the pro-oxidant pair ADP/Fe<sup>2+</sup> evaluated by oxygen consumption.

AV-6-93 ( $\mu\text{M}$ )	TBARs (nmol/mg protein/10 min)
0	10.2 $\pm$ 1.0
1	9.6 $\pm$ 1.0
10	8.5 $\pm$ 0.5
20	7.6 $\pm$ 1.0
50	5.2 $\pm$ 2.1
100	3.1 $\pm$ 1.9*

Table 3. Effect of AV-6-93 on membrane lipid peroxidation of rat liver mitochondria induced by the pro-oxidant pair ADP/Fe<sup>2+</sup> evaluated by TBARs assay. The data correspond to the mean  $\pm$  S.E. of three independent experiments.

\**p* < 0.05 vs control (in the absence of AV-6-93).

#### 4. Discussion

Studies examining the importance of mitochondrial pathophysiology in neurodegeneration provide a target for additional treatments with agents that improve mitochondrial function, protect MPT, and/or exert antioxidant activity (Petrozzi et al., 2007). These studies lead to novel approaches in the treatment of neurodegenerative diseases, such as Parkinson’s disease, with disease-modifying drugs.

The aim of the present study was to examine the abilities of two novel adamantane-containing DHP analogues, AV-6-93 and diflurone, to protect against cell death induced by mitochondrial toxin MPP<sup>+</sup> and beneficially influence mitochondrial processes in an attempt to identify putative antiparkinsonian drugs.

First, we examined how both compounds acted in primary cortical cultures in response to MPP<sup>+</sup>. AV-6-93, at concentrations of 1 and 10  $\mu\text{M}$ , significantly protected against MPP<sup>+</sup>-induced cell death by 75% and 56%, respectively, whereas diflurone protected against cell death by 35% at a concentration of 10  $\mu\text{M}$ . Neither AV-6-93 nor diflurone, added without MPP<sup>+</sup>, changed cell viability.

A larger difference between the compounds' activities was observed in isolated rat liver mitochondria by the assessment of their ability to affect both the  $\text{Ca}^{2+}$ -induced mitochondrial permeability transition (MPT) and lipid peroxidation. To assess the  $\text{Ca}^{2+}$ -induced MPT, the evaluation of the drop of  $\Delta\psi$ , the increase in mitochondrial respiration associated with  $\text{Ca}^{2+}$  accumulation in the mitochondrial matrix, and the mitochondrial  $\text{Ca}^{2+}$  fluxes were carried out. Changes in these parameters help us to conclude whether the compound protects mitochondria against MPT induction and, consequently, to discern whether the compound alters mitochondrial  $\text{Ca}^{2+}$  homeostasis. AV-6-93, at a concentration of 10  $\mu\text{M}$ , significantly protected mitochondria against MTP induction and provided complete protection at 100  $\mu\text{M}$ , as revealed by its ability to prevent the depolarisation of mitochondria, the increase in mitochondrial respiration and mitochondrial  $\text{Ca}^{2+}$  release. These effects were comparable with that of CsA (0.75 nmol/mg protein), a specific inhibitor of the mitochondrial permeability transition pore. Diflurone was ineffective in these tests. The effectiveness of AV-6-93 can be considered to be very promising because it indicates the ability of this compound to halt mitochondrial swelling and cell death, both consequences of the induction of the permeability transition pore.

A critical factor for induction of MPT is the oxidation of thiol groups of the MPT complex, creating diethyl cross-links (Costantini et al., 1996; 1998, Halestrap et al., 1997; McStay et al., 2002). Therefore, the most plausible hypothesis to explain the partial MPT protection induced by AV-6-93 is that changes in the redox-state of thiol groups of the MPT complex is provided via avoiding of diethyl cross-links. This hypothesis is supported by the observation that AV-6-93 protected mitochondria against oxidative stress. Oxidative stress was assessed by evaluating the extent of lipid peroxidation by measuring oxygen consumption and TBARs formation. Alterations of these parameters may reveal whether the compound protects mitochondria against oxidative stress, i.e., whether the compound acts as an antioxidant. AV-6-93, at concentrations up to 100  $\mu\text{M}$ , protected (by about a half) mitochondria against membrane lipid peroxidation, as inferred by its ability to inhibit both oxygen consumption and TBARs formation induced by the pro-oxidant pair  $\text{ADP}/\text{Fe}^{2+}$ . These data suggest that this compound may act as antioxidant because it can avoid both the initiation and the propagation of the oxidation of polyunsaturated fatty acid acyl chains of membrane phospholipids induced by the perferryl ion complex  $\text{ADP}-\text{Fe}^{3+}-\text{O}_2$ , a mechanism suggested to be responsible for lipid peroxidation (Sassa et al., 1990). In contrast to AV-6-93, diflurone, under the same conditions, had no capacity to protect mitochondria against oxidative damage induced by the pro-oxidant pair  $\text{ADP}/\text{Fe}^{2+}$ .

The only common feature of both compounds was a lack of influence on mitochondrial bioenergetics, which was assessed by analysing several mitochondrial functioning parameters of the respiratory chain (respiration states 2, 3, 4, FCCP-stimulated respiration, the RCR, and the  $\text{ADP}/\text{O}$  ratio) and the oxidative phosphorylation system ( $\Delta\psi$  and phosphorylation time), using both glutamate/malate and succinate as respiratory substrates. According to the mitochondrial parameters affected, it is possible to assess how the compound interferes with mitochondrial bioenergetics: by perturbing the permeability (integrity) of the inner mitochondrial membrane (stimulation of respiration states 2 and 4), by impairing the respiratory chain (inhibition of FCCP-stimulated respiration), and/or by acting at the level of the phosphorylation system (affecting respiration state 3). Both AV-6-93 and diflurone, at concentrations of up to 100  $\mu\text{M}$ , failed to significantly affect liver mitochondrial bioenergetics, as shown by the lack of effects on both glutamate/malate- and succinate-supported respiration in state 2, state 3, state 4, FCCP-stimulated respiration, RCR and  $\text{ADP}/\text{O}$  ratios,  $\Delta\psi$  and phosphorylation time.



To address why both adamantane-containing compounds showed very distinct effects on mitochondrial damage induced by both  $\text{Ca}^{2+}$  and  $\text{ADP/Fe}^{2+}$ , one may suggest that the molecular “volume” of AV-6-93 (one adamantane ring-containing DHP) is more optimal than that of diflurone (two adamantane ring-containing DHP) for mitochondrial protection. The two adamantane rings in the diflurone molecule probably generate a steric hindrance that prevents or delays the chemical reaction, which can easily occur in the case of AV-6-93, a one adamantane ring-containing DHP.

Based on the results obtained in primary cortical cultures, the two-adamantane DHP structure is not as crucial as it is in isolated rat liver mitochondria because diflurone has not lost its activity to prevent cell death caused by  $\text{MPP}^+$  (a toxin focused on mitochondrial complex I). However, the activity of diflurone was lower than that of AV-6-93. One could suggest that, in addition to the protection of complex I, other cellular signalling mechanisms may be initiated by DHP compounds to increase cell survival.

## 5. Conclusion

The novel one-adamantane 1,4-dihydropyridine compound AV-6-93 is capable of regulating cell survival processes with regards to mitochondrial processes, such as inhibition of the induction of the permeability transition pore and prevention of oxidative stress. The effectiveness of AV-6-93 can be considered to be very promising in the treatment of neurodegenerative diseases associated with compromised mitochondrial processes, e.g., Parkinson’s disease.

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