

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/340405763>

# Current concepts and outcomes in cemented femoral stem design and cementation techniques: the argument for a new classification system

Article in *EFORT Open Reviews* · April 2020

DOI: 10.1302/2058-5241.5.190034

CITATIONS

15

READS

746

6 authors, including:



**Rosie Mc Colgan**

Trinity College Dublin

6 PUBLICATIONS 21 CITATIONS

[SEE PROFILE](#)



**Patrick Kenny**

59 PUBLICATIONS 455 CITATIONS

[SEE PROFILE](#)



**Colin G Murphy**

Galway University Hospitals

107 PUBLICATIONS 1,533 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Extended Trochanteric Osteotomy (ETO) fixation for femoral stem revision in periprosthetic fractures: Dall-Miles plate versus cables [View project](#)



Damage to the superior gluteal nerve after two different approaches to the hip [View project](#)



# Current concepts and outcomes in cemented femoral stem design and cementation techniques: the argument for a new classification system

Adrian J. Cassar-Gheiti<sup>1</sup>  
Rosie McColgan<sup>2</sup>  
Martin Kelly<sup>3</sup>  
Theresa M. Cassar-Gheiti<sup>1</sup>  
Paddy Kenny<sup>1,3</sup>  
Colin G. Murphy<sup>2</sup>

- Cemented implant fixation design principles have evolved since the 1950s, and various femoral stem designs are currently in use to provide a stable construct between the implant–cement and cement–bone interfaces.
- Cemented stems have classically been classified into two broad categories: taper slip or force closed, and composite beams or shaped closed designs. While these simplifications are acceptable general categories, there are other important surgical details that need to be taken into consideration such as different broaching techniques, cementing techniques and mantle thickness.
- With the evolution of cemented implants, the introduction of newer implants which have hybrid properties, and the use of different broaching techniques, the classification of a very heterogeneous group of implants into simple binary categories becomes increasingly difficult. A more comprehensive classification system would aid in comparison of results and better understanding of the implants' biomechanics.
- We review these differing stem designs, their respective cementing techniques and geometries. We then propose a simple four-part classification system and summarize the long-term outcomes and international registry data for each respective type of cemented prosthesis.

**Keywords:** arthroplasty; cement; hip replacement

Cite this article: *EFORT Open Rev* 2020;5:241-252.  
DOI: 10.1302/2058-5241.5.190034

## Introduction

In the 1950s, self-curing polymethylmethacrylate (PMMA), also known as bone cement, was introduced in orthopaedic practice for femoral stem fixation by Edward Haboush

(New York), Frederick Roeck Thompson (New York), Kenneth McKee (Norwich), John Watson-Farrar (Norwich) and Maurice E. Müller (Bern).<sup>1-4</sup> Cement was initially used to stabilize or fix hemiarthroplasty stems until Sir John Charnley, in the early 1960s, popularized its use in total hip arthroplasty.<sup>5,6</sup> Since the 1950s the designs and techniques used for cemented implants have evolved dramatically, based on biomechanical engineering principles and PMMA properties.<sup>7-11</sup> Nowadays there are a variety of cemented femoral implants that are used for either hemi or total arthroplasty with excellent clinical and radiographic outcomes,<sup>12-18</sup> but the nomenclature remains confusing. We review these differing stem designs, their respective cementing techniques and geometries, we propose a simple four-part classification system, and summarize the long-term outcomes and national joint registry data for each respective type of cemented prosthesis.

## Basic science of cemented femoral stem fixation

### *Bone cement*

### *Cement properties*

Polymethylmethacrylate (PMMA) has been used clinically since the 1940s in various subspecialties of surgery; mainly dentistry, ophthalmology, and plastic surgery. It was introduced in hip surgery in the 1950s and is described as a synthetic self-curing material that is used to fill up space or to create an interlock.<sup>1,19-22</sup> PMMA, as the name implies, is a polymer of methyl methacrylate and polymerizes through an exothermic reaction. PMMA has viscoelastic properties and can undergo creep and stress relaxation.<sup>21,23-25</sup> Creep or cold flow is the tendency of a solid material to move slowly or deform permanently and

results from long-term exposure to mechanical stress below the yield strength of the material.<sup>21,23,24</sup> All PMMA cement undergoes creep, this can produce movement of cement in any direction and increases with temperature and stress level.<sup>26</sup> Stress relaxation is the decrease in stress in response to constant strain generated in a structure.<sup>27</sup> PMMA tolerates compressive loads (90 MPa) better than shear forces (50 MPa) and is weakest in tension (25 MPa).<sup>21,25</sup> PMMA bone cement is most commonly loaded with antibiotics that are heat stable, the benefits of which are well documented in the literature.<sup>28</sup> Adding antibiotics to PMMA changes its mechanical properties by reducing tensile stress more than compressive stress, and studies suggest that this should not exceed 5% addition by weight.<sup>29</sup> The mechanism of cement failure was initially thought to be due stem–cement interface debonding,<sup>30</sup> but recent studies show that cement failure occurs due to crazing.<sup>31</sup> Crazing is time, temperature, and stress-dependent damage behaviour in polymers.<sup>32,33</sup> A craze is a small crack-like defect and has load-bearing capacity due to stretched fibrils connecting the opposite faces of the craze. The process of crazing is thought to be responsible for fracture propagation in cement over time.<sup>32</sup>

#### *Cement viscosity*

Bone cement is available in different levels of viscosity, this ranges for low to high. High-viscosity cement is widely used and has good clinical performance.<sup>34,35</sup> The theoretical advantages of low-viscosity cement are easier handling during cementation due to reduced stickiness, longer polymerization time, improved penetration into cancellous bone and lower curing temperature. A randomized controlled trial using radiostereometric analysis (RSA) reported no statistical difference in mean migration or in clinical outcome after 10-year follow up.<sup>36</sup>

#### *Registry data*

Data published from both the Nordic Arthroplasty Register Association (NARA) and the British National Joint Registry (NJR) report no statistical significance in revision rates between the different viscosity levels, but they did report higher revision rates between different brands of cement.<sup>37,38</sup> Higher revision rates were reported when CMW1 (Depuy-Synthes, Warsaw, Indiana, USA) and CMW3 (Depuy-Synthes, Warsaw, Indiana, USA) compared to Palacos (Heraeus, Hanau, Germany) and Simplex (Howmedica, Mahwah, New Jersey, USA) cement were used with similar implants at 10 years.<sup>37,38</sup> Fixation of femoral implants in cement depends on cementing technique and stem design. Modern cementing techniques are associated with significantly lower hip arthroplasty revision rates as reported in national joint registries.<sup>14,39,40</sup>

#### *Femoral preparation*

Meticulous femoral bone preparation is essential for long-term survivorship of cemented stems. The femur is prepared with the aim to provide a clean and stable cement interlock between the two interfaces, i.e. bone–cement and cement–implant. There are two main techniques of femoral broaching which depend mostly on the implant design. The most common technique is the standard or over-broaching technique where the implant is smaller than the same size broach used. This allows for a cement mantle of 2 mm or more depending on the implant design. Several studies based on clinical, radiological, and histological analyses, have suggested that a thin cement mantle is subjected to increased strain and may fragment.<sup>41,42</sup> Although clinically a thick cement mantle has very good outcome,<sup>12,43</sup> a recent study reported that increased cement thickness results in increased stem subsidence and migration in association with a tapered polished stem.<sup>44</sup> There is still a lot of debate over what constitutes an optimal cement thickness<sup>8,45,46</sup> and whether defects in the cement are detrimental.<sup>47,48</sup> Another femoral preparation technique is the line-to-line or ‘French paradox’ technique, where the implant inserted is the same size as the last broach used, producing a very thin cement mantle.<sup>46,49,50</sup> This technique is commonly associated with complete removal of the medullary cancellous bone and occasionally reaming of the canal.<sup>49</sup> Both line-to-line broaching and the standard technique have very good outcomes reported in the literature.<sup>48,51,52</sup> The cementing technique used is dependent on the implant design and implants which are designed for the standard technique tend to do worse if a line-to-line cementing technique is used.<sup>50,53,54</sup> Skinner et al reported survival rate of 97.2% for standard technique and a 98.8% survival rate for the line-to-line cementing technique 10 years after total hip arthroplasty.<sup>41</sup> They concluded that the common suggestion for the necessity of a thick complete cement mantle may be incorrect.<sup>31</sup>

#### *Modern cementing techniques*

Modern cementing techniques aim to improve the cement–bone interlock by thorough cleansing of the bone bed using pulsatile lavage, use of distal cement restrictor, retrograde application using a cement gun and pressurization of the cement.<sup>55–57</sup> Pressurization and pulsatile lavage of cancellous bone have been identified to be significant factors with regard to improved cement penetration and improved cement shear strength.<sup>57,58</sup> The introduction of a distal cement intramedullary restrictor allowed for cement containment and better pressurization. This resulted in improved cement penetration and better clinical outcome.<sup>59,60</sup> Retrograde cement application using a cement gun and sustained cement pressurization further improved the cement–bone

interdigitation.<sup>61–63</sup> There are several clinical studies that compare outcomes of cemented stem fixation before and after the introduction of modern cementing techniques that confirm their improved benefit.<sup>12,64–66</sup>

### Surface roughness

Studies suggest that all cemented prostheses migrate in the cement mantle.<sup>67</sup> The ideal surface roughness of the implant is still debatable. The original Charnley was a polished stem with an average roughness of 0.1  $\mu\text{m}$ ; this was later changed to an average surface roughness of 0.75  $\mu\text{m}$  or higher in an attempt to improve the interlock between the cement and the implant.<sup>68–71</sup> Although high surface roughness improves the cement–implant interlock, it also increases wear debris if the implant becomes loose. This results in extensive osteolysis in areas of mantle defects.<sup>72</sup> Finite element models demonstrate that local cement stresses have a complex relationship with surface roughness and that these are not directly proportional. At roughness values of  $R_a = 15 \mu\text{m}$  local cement stresses are high, and beyond that local stresses were reduced due to reduced micromotions with improved interlock between the two interfaces.<sup>73</sup> From published studies we know that certain femoral stem types do better with a polished surface than a rough surface.<sup>74</sup> An example of this was the temporary change of the Exeter stem from a polished to a matt surface as part of a change to 316L steel to increase strength and reduce costs. The Exeter with matt surface has increased surface roughness to about 1  $\mu\text{m}$ , while the polished stem was less than 0.1  $\mu\text{m}$ .<sup>75,76</sup> This resulted in an increase in aseptic loosening with reported rates of up to 20%.<sup>69,76</sup> Similar results were found when a matt Harvard ( $R_a 2.2 \mu\text{m}$ ) stem was compared to a smoother surface Charnley stem ( $R_a 0.8 \mu\text{m}$ ), with the smooth surface stem having better survival rates.<sup>77</sup> There are rough surface stems such as the Lubinus SPII, that have an excellent outcome reported in the literature and arthroplasty registries, which demonstrates that aseptic loosening may be a multifactorial event rather than just being related to surface roughness.<sup>18,78,79</sup>

### Stem material

Material selection for total hip arthroplasty (THA) is very important; the material must resist cyclic loading in a demanding environment and be well tolerated by the body. The material chosen needs to be corrosion resistant, have adequate material strength, be inexpensive to manufacture and be available in large quantities. Alloys of cobalt-chromium, iron and titanium are the most common metals used in hip implants. With its Young modulus approximating to that of bone and PMMA, titanium is an attractive material to be used in femoral stems. Although cemented titanium stems are known to fail earlier than their cobalt-chromium equivalent,<sup>80,81</sup> some authors report excellent

results with different and longer stem designs.<sup>82–86</sup> Failure in titanium cemented stems is thought to be related to the poor wear properties of titanium and its susceptibility to crevice corrosion. There are a few reports on titanium stems exhibiting crevice corrosion but none in relation to stainless steel and cobalt-chromium.<sup>87,88</sup> Nowadays most cemented implants are made of proprietary cobalt-chromium or stainless-steel alloys; these are usually inert, resistant to corrosion and have excellent outcomes in the literature.<sup>12,14</sup>

## Designs utilized in cemented arthroplasty

Cemented implant fixation design principles have evolved since the 1950s and various femoral stem geometries are currently in use to achieve this. The aim of each design is to provide a stable unit between the implant–cement and cement–bone interface. Cemented stems have classically been classified into two broad categories, *taper slip* or *force closed*, and *composite beams* or *shaped closed* designs. While these simplifications are acceptable general categories, they miss important design features, have different broaching techniques and make comparisons misleading. With the evolution of cemented implants, the introduction of newer implants which have hybrid properties, and the use of different broaching techniques, the classification of these implants into these simple categories becomes increasingly difficult. A more comprehensive classification system would aid in comparison of results and better understanding of the implants biomechanics. We propose the following classification system.

Cemented stems can be classified according to their geometry, broaching technique, and biomechanics. We define four general types based on shape, broaching technique used and biomechanics, with all four categories having a revision version (Table 1 and Fig. 1). The revision stem can be subclassified into long and short versions of the primary stem. In this classification Type 1 and Type 2 stems use traditional broaching techniques which allow for a cement mantle of 2 mm or more. Type 3 implants use a line-to-line broaching technique often referred as the ‘French paradox’ with a cement mantle of 1 mm or less. Type 4 are anatomical stems and have mixed features when compared to the other types and have a consistent cement mantle of 2 mm along the length of the stem. While future prosthesis may not fit into one of these categories, this classification system represents the great majority of the cemented stems currently in use and with long-term follow up.

### Type 1

Type 1 stems, known as *taper slip* or *force closed* are tapered in two or three dimensions, double and triple tapered respectively. They are usually flat and thin in the antero-posterior plane and wide in the medio-lateral

**Table 1.** Classification system of cemented femoral stem design. Revision stem for each type can be subclassified into the short or long version, R<sub>s</sub> and R<sub>l</sub>, respectively (e.g. Type 1R<sub>s</sub>)

Classification system of cemented stem design							
Type	Subtype	Geometry	General category	Description	Fixation	Cement mantle	Example
1	1a	Double taper	Collarless Polished Tapers – Force closed	Flat and thin antero-posteriorly, wide medio-lateral. Tapers distally in both planes. Polished.	Force closed	2 mm to 4 mm	Exeter, CPCS, CPT, MS-30
	1b	Triple taper		Flat and thin antero-posteriorly and narrows medially, wide medio-lateral. Tapers distally in three planes (AP, ML & medially in the axial plane). Polished.	Force closed		C-Stem
2	2a	Rounded, Flanged	Flanged and roughened – Shape closed	Round and thick with minimal tapering distally, can be flanged and have a collar.	Shape closed	2 mm to 4 mm	Charnley, Excia, Spectron EF
	2b	Tapered, Flanged		Narrowed antero-posterior, wide medio-lateral straight stems, flanged an usually have a collar.	Shape closed		Cemented Synergy, Cemented Summit
3		Single wedge	Press-fit Wedge – Line to line	Rectangular cross section. Flat stem, thin in the antero-posterior plane, wide medio-lateral straight stem. Rough or polished surface.	Shape closed, 3-point fixation	1 mm or less	Mueller, CMK, Cemented Taperloc, Quadra C, Cemented Avenir, Cemented Corail, Cemented TwinSys
4		Anatomical	Curved Anatomical	Curved, rounder, wider mediolateral than antero-posterior, posterior bow in metaphysis, anterior bow in diaphysis, inbuilt neck anteversion.	Shape closed	2 mm	Lubinus SP I and II, Olympia

Note. AP, Antero-Posterior; ML, MedioLateral.

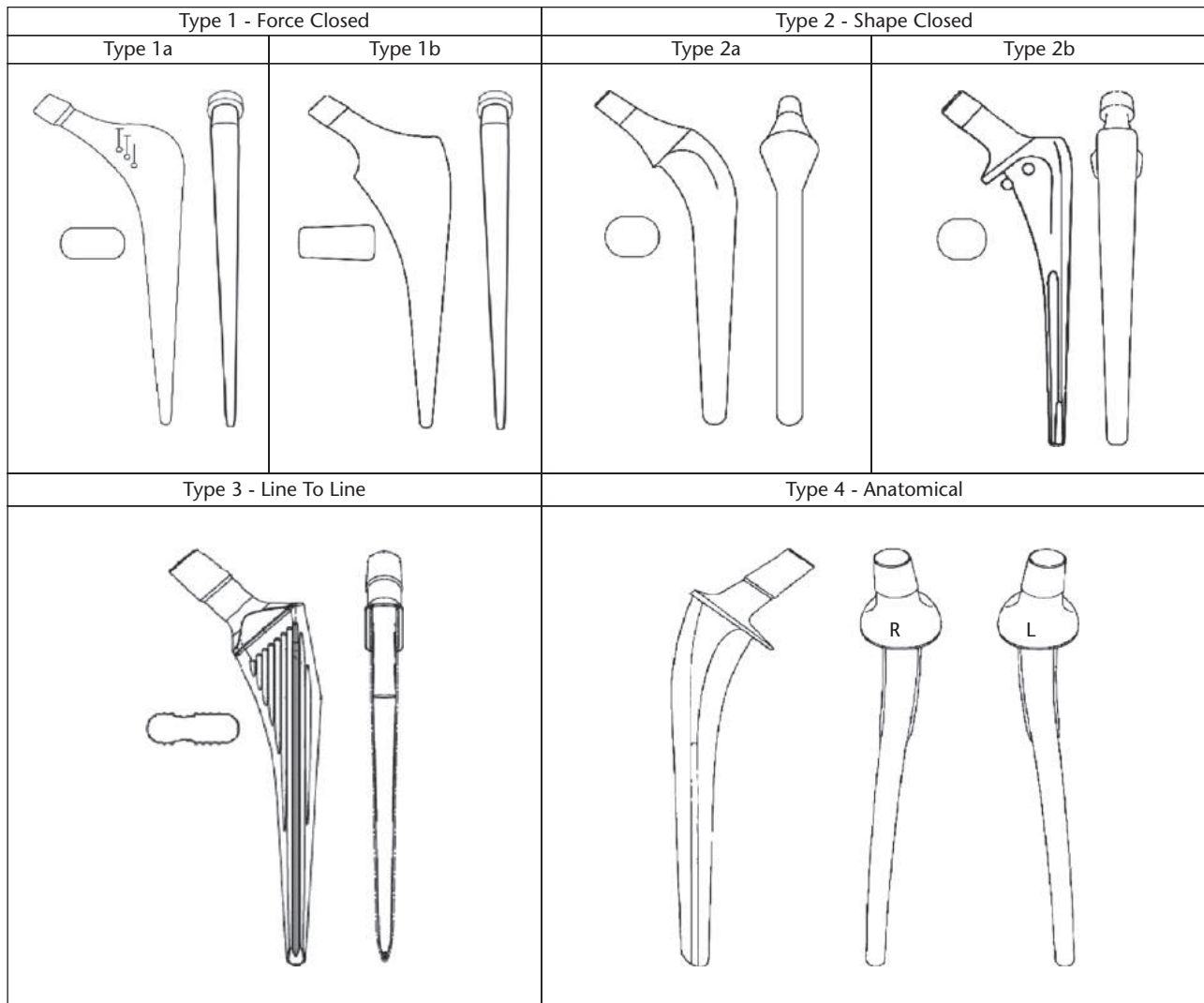
plane. The component tapers distally primarily in the medio-lateral plane and antero-posterior plane, while in some designs medially as well.<sup>16,43</sup> Surface roughness in these implants is usually low with a polished surface finish.<sup>43,75</sup> These implants tend to have rounded edges and rotational stability is achieved through a rectangular cross-section and in some implants through the third taper.<sup>15,16</sup> Type 1 implants are collarless and have a distal hollow centralizer that allows a central position of the stem and controlled subsidence in bone cement. This is known to be central to the mechanical behaviour of stem of this design.<sup>89</sup> Subsidence of Type 1 stems, as a rule, takes place within the first two years after surgery, then becomes slower or completely stops after this time.<sup>90</sup> While various authors have reported continued subsidence probably throughout the entire life of the stem,<sup>91,92</sup> continued subsidence after the second year or more than 5 mm must be considered as definitive loosening.<sup>93</sup> Type 1 stems utilize force closed fixation, which means that the cement and bone are loaded principally in compression and shear forces are reduced. Furthermore, for Type 1 stems the major load component is radial compression.<sup>7,94</sup>

Preparation of the femoral canal requires broaching and no distal reaming. The broaches are diamond edge and serve to remove bone rather than impacting it; this

leaves a bed of porous cancellous bone in the shape of the implant. The broaches are at least 2 mm bigger than the same size stem. Utilizing modern cementing techniques, this allows a cement mantle of 2 mm or more which interdigitates with cancellous bone. Attention to the native metaphyseal diaphyseal anatomy and the implant is important. In Dorr type A femurs, where the diaphysis narrows substantially, the slim distal taper of the implant may engage distally with little or no cement mantle increasing the risk of implant failure.<sup>95</sup>

### Type 2

Type 2 stems can be rounded and tapered, and in contrast to Type 1 they have a rough surface finish; these implants are known as the *shape closed* or *composite beam* type. Type 2 implants may have an array of design features including flanges, collars and flutes. Type 2 implants are wider than Type 1 implants in the antero-posterior dimension, with rounded edges and curved or shoulder back. These design features are used to improve rotational stability and prevent stem subsidence and debonding at the implant cement interface. In an attempt to maximize the interlock between the stem and the cement, several authors have investigated the relationship between surface roughness and shear strength achieved at the interface.<sup>96</sup>



**Fig. 1** Schematic diagram demonstrating the classification system of cemented femoral stem design. Revision stem for each type can be subclassified into the short or long version,  $R_s$  and  $R_l$  respectively (e.g. Type 1  $R_s$ ).

Contrary to Type 1 stems, subsidence in Type 2 implants is associated with stem loosening.

Preparation of the femoral canal requires reaming and broaching, with these implants the calcar needs to be cleared with a curette to achieve optimal cement mantle in this region. Broaches tend to be of the impaction type and are used to impact cancellous bone. Type 2 implants have solid centralizers that assist stem alignment but do not allow the stem to subside.

### Type 3

Type 3 cemented stems are designed to achieve a press-fit fixation in the anterior-posterior plane with a self-centring effect.<sup>97</sup> They are rectangular in cross-section and were originally designed with a rough surface coating. Like Type 2 stems they are used to achieve a composite structure

with bone and cement. Composite beam effect in Type 3 implants is achieved with a self-centring, press-fit design, a thin cement mantle and close stem–bone contact in the coronal plane.<sup>46</sup> Though some implants may share similarities in their appearance, they often possess a design difference that makes them function in a manner that is dissimilar to each other. An example of this is the Charnley (Depuy-Synthes, Warsaw, Indiana, USA) (Type 2) and the CMK stem (ZimmerBiomet, Warsaw, Indiana, USA) (Type 3). Compared to the Charnley stem, the CMK has a smoother surface finish ( $R_a$  0.04  $\mu\text{m}$ ), it is rectangular in cross section, has a higher caput-collum-diaphyseal (CCD) angle and is wider and thickened proximally. These differences give the CMK its press-fit, self-centring, canal-filling properties found in Type 3 implants.<sup>48,98,99</sup> Modern versions of Type 3 implants have low surface roughness, flutes to

improve cement interlock and may or may not have a small collar. The design of Type 3 implants achieves optimum adaptation by increasing rigidity, decreasing stress peaks and minimizing micromotion.<sup>51</sup>

Femoral canals are usually prepared using the line-to-line technique with either impaction or complete removal of cancellous bone. Since the implant is the same size as the last broach used, these implants need to be hammered down the canal as one would with an uncemented implant.<sup>46,48</sup> Type 3 implants are self-centring and do not make use of a distal or proximal centralizer. Cement mantle thickness varies along the length of the stem and in some regions the stem is in direct contact with cortical bone.<sup>100</sup>

#### Type 4

Type 4 stems are curved, anatomic stems that match the femoral geometry.<sup>10,18,78,101</sup> Type 4 stems can have a rough or polished surface coating. Anatomic stems are three-dimensionally tapered and can have flutes and collars which enhance rotational stability and limit subsidence.<sup>18</sup> Both polished and rough anatomic stems work as a composite beam.<sup>18</sup> Their three-dimensional geometry follows the natural femoral torque and provides a natural anteversion within the implant.<sup>101</sup>

Standard broaching technique is used for this type of stem, which allows a constant cement mantle of around 2 mm in thickness. The anatomical shape of Type 4 stems allows them to maintain a uniform cement mantle throughout the length of the stem.<sup>10</sup>

#### Revision stems

All four types of primary cemented stems are available in revision versions which can be either a shorter or longer version of the stem with similar mechanical properties to the primary stems described above.

## Results of use of cemented stems

Cemented stems are not perfect, and problems exist with both their use and the use of cement. These include loosening at either interface, stem fractures, stress shielding and proximal femoral fractures. The long-term results of successful designs of each type are presented.

#### Type 1

Type 1 stems are one of the original cemented stems used for total hip arthroplasty and have been the subject of many published reports. The polished collarless taper can be further subdivided into double tapers (Type 1a, Exeter, CPT) and triple tapers (Type 1b, C-Stem). Type 1 stems have been used for the past 48 years, with excellent results. Westermann et al recently published 10-year data of Exeter V40 stems with 100% survivorship for aseptic

loosening.<sup>102</sup> Swedish Hip Arthroplasty Registry (SHAR) data from 2017 report 93% survivorship for Exeter stems (Stryker, Kalamazoo, Michigan, USA) at 12 years and 94% for MS30 stems (ZimmerBiomet, Warsaw, Indiana, USA) at 10 years.<sup>79</sup> The Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR) reports an average revision rate at 15 years of 6.7% for the MS30 stem (ZimmerBiomet, Warsaw, Indiana, USA), 7.3% for the Exeter stem (Stryker, Kalamazoo, Michigan, USA), 6.55% for the CPT (ZimmerBiomet, Warsaw, Indiana, USA), 5.2% for the CPCS (Smith&Nephew, Watford, UK) and 13% for the C-Stem (Depuy-Synthes, Warsaw, Indiana, USA). The cumulative revision rates were dependent on the combination of stem and cup used. Certain combinations had higher revision rates than others, such as Exeter V40 – Exeter contemporary had a higher revision rate (4.5%) than the Exeter V40 – Mallory Head (2.8%) combination.<sup>103</sup> The National Joint Registry (NJR) of England, Wales and Northern Ireland reports an average revision rate at 14 years of 2.26% for the MS-30 (ZimmerBiomet, Warsaw, Indiana, USA), 3.93% for the C-Stem (Depuy-Synthes, Warsaw, Indiana, USA), 4.45% for the CPT (ZimmerBiomet, Warsaw, Indiana, USA) and 4.48% for the Exeter stem (Stryker, Kalamazoo, Michigan, USA).<sup>104</sup> Junnila et al reported from the NARA similar survival rates as other registries with 10-year survival rates of 96.6% (MS-30), 95.8% (C-Stem), 94.9% (CPT) and 93.5% (Exeter).<sup>14</sup> The most common cause of revision throughout all registries is aseptic loosening.

Type 1 stems are being used extensively throughout all age groups and disease process around the hip, with all reporting excellent results in both the young and the elderly. Schmitz et al reported on 104 cemented Exeter stems with a mean follow up of 13 years and survivorship of 97.1% for all causes of revision, and 100% survivorship for aseptic loosening at 10 years in patients under 40 years of age.<sup>66</sup> Burston et al reported 100% survivorship for aseptic loosening at 10 years follow up in patients under 50 years old in a consecutive series with a combination of 2 different Type 1 stems.<sup>105</sup> Lewthwaite et al reported a survival rate with an endpoint of reoperation for any reason of 94.4% at 10 years and 92.6% at a mean follow up of 12.5 years when using a Type 1 stem in patients aged 50 years or younger.<sup>106</sup> While Yates et al reported 100% survival rates for aseptic loosening as endpoint and 95.9% survival with revision of Type 1 stems for any reason at 10-year follow up in 191 consecutive THRs.<sup>43</sup>

Recently, with Type 1 stems, there is increasing concern about the increased rate of periprosthetic fracture when compared to other cemented stem types.<sup>107–112</sup> Grammatopoulos et al reported a case series of 21 consecutive periprosthetic fractures around Type 1 stems, 67% of cases were classified as Vancouver B2 and 29% were B1 types.<sup>111</sup> The B2-type fractures had common

radiological and intraoperative findings: a spiral fracture with extensive fragmentation of bone and cement, debonding of cement and cement fractures. The authors found that, intraoperatively, these fractures were more difficult to manage than suggested by the preoperative radiographs.<sup>111</sup> In 2015, Brodén et al published on 1357 patients who underwent THA with a Type 1 stem; 3.3% of these patients sustained a periprosthetic fracture occurring within one year of surgery.<sup>109</sup> They have also reported that they had a higher rate of periprosthetic fractures in patients older than 80 years.<sup>109</sup> Data from the NJR of England, Wales and Northern Ireland show that the revision risk ratios due to periprosthetic fractures for Type 1 stems (CPT, Exeter, C-Stem) is higher (0.46, 0.12 and 0.14 respectively) compared to the Type 2 stems (Charnley, 0.07).<sup>107</sup> Palan et al reported that the risk of revision of periprosthetic fractures depends on the design, with some Type 1a (CPT) stems having a higher incidence than the Type 1b (C-Stem).<sup>107</sup> This may be related to the radius of the shoulder of Type 1a stems with the CPT stem having a smaller radius than Type 1b stems (C-stem).<sup>107</sup> A study by Brodén et al showed a high incidence of early periprosthetic fracture with a Type 1a stem (CPT) and suggested that this design may act as a wedge, splitting the femur following a fall.<sup>109</sup> This corresponds to data published by other authors which demonstrates that Type 1 stems have a higher rate of periprosthetic fracture when compared to other cemented stem types.<sup>108,110,113–115</sup> Overall, long-term results of Type 1 stems are excellent. These stems have proven to be reliable in both young and old patients, and for multiple pathologies.

### Type 2

Type 2 stems are the second most common type of cemented stems in use. Studies have demonstrated excellent short, medium and long-term results after the use of Type 2 stems.<sup>13,14,40,45,79,103,113</sup> Type 2 stems are based on the design of the Charnley low friction arthroplasty and include Charnley elite (Depuy-Synthes, Warsaw, Indiana, USA), cemented Summit (Depuy-Synthes, Warsaw, Indiana, USA), cemented Synergy (Smith and Nephew, Watford, UK), Spectron EF (Smith and Nephew, Watford, UK), and cemented Excia (B.Braun, Melsungen, Germany). The Charnley low-friction torque arthroplasty has reached 42 years of clinical application. Most osteolysis in these implants was noted in Gruen zones 1 or 7. Another study by Callaghan et al reported 78% survivorship of the Charnley prosthesis at 35-year follow up.<sup>116</sup> Garellick et al reported 96% survival of the Spectron stem with excellent clinical and radiological outcomes at 11-year follow up.<sup>117,118</sup> Urschel et al reported excellent results for a Type 2 cemented stem with 99.5% survivorship at six-year follow up.<sup>119</sup> Callaghan et al reported a 6% rate of aseptic loosening in the Charnley implant at 25-year follow up

and 90% of patients retained their original implant.<sup>120</sup> Smith et al had similar results with 5% revision rate of the Type 2 stem for aseptic loosening.<sup>121</sup> The AOANJRR reports a revision rate of 12.5% for the Charnley (Depuy-Synthes, Warsaw, Indiana, USA), and 13.5% for the Spectron EF (S&N, Watford, UK) at 15 years.<sup>103</sup> The British NJR reports revision rates of 5.07% for the Charnley stem (Depuy-Synthes, Warsaw, Indiana, USA) and 4.07% for the Stanmore (ZimmerBiomet, Warsaw, Indiana, USA) at 14-year follow up.<sup>104</sup> Overall long-term results of Type 2 stems are excellent, although there are increasing concerns with some implants that are exhibiting higher revision rates compared to others at the 10 to 15-year follow up.<sup>14,122,123</sup>

### Type 3

Type 3 stems are extensively used in central Europe. Studies have demonstrated excellent short, mid and long-term results with their use.<sup>51,52,124–128</sup> Type 3 stems include the Mueller straight stem (ZimmerBiomet, Warsaw, Indiana, USA), CMK (ZimmerBiomet, Warsaw, Indiana, USA), cemented Taperloc (ZimmerBiomet, Warsaw, Indiana, USA), CCA (MathysOrtho, Bettlach, Switzerland) and, more recently, the cemented Avenir (ZimmerBiomet, Warsaw, Indiana, USA), cemented Twinsys (MathysOrtho, Bettlach, Switzerland), Quadra C (Medacta, Castel San Pietro, Switzerland) and cemented Corail (Depuy-Synthes, Warsaw, Indiana, USA). The 10-year survival rate of the Mueller straight stem ranges from 98.3% to 91.2%.<sup>127,128</sup> Räder et al reported 92.7% stem survival after 15 years for the Mueller straight stem, but the clinical results were influenced by high cup revision due to loosening.<sup>129</sup> Similar results were reported by Riede et al with a survival rate of 94% at 15 years.<sup>125</sup> Kerboull et al reported an overall survival rate at 20 years of 85.4% using the CMK stem in those younger than 50 years of age.<sup>130</sup> Similar results for the CMK were reported by Nich et al, with a survival rate of 88.5% at 15-year follow up using revision for any reason as an endpoint.<sup>131</sup> El Masri et al reported survivorship of 94% at 17-years follow up for the CMK stem using a line-to-line cementation technique.<sup>48</sup> Short-term results for the Twinsys cemented stem show excellent results at two-years follow up, with 100% survival for aseptic loosening.<sup>126</sup> When it comes to registry data, the Müller straight stem has a revision rate of 3.7% at 14 years in the British NJR, and 2.4% at seven years in the Dutch registry (LROI).<sup>104,132</sup> Quadra C has a 2.5% revision rate at five years in the AOANJRR and the Covision straight stem has 93.7% survival at seven years in the SHAR.<sup>79,103</sup> Overall results of Type 3 stems are excellent and are a good option for younger and older patients and those with Type C proximal femoral geometry.

### Type 4

Excellent outcomes have been achieved with the use of Type 4 stems.<sup>133–137</sup> Type 4 stems are widely used in the



Nordic countries. Type 4 stems include the Lubinus SP (Link, Hamburg, Germany) and the Olympia (Biomet, Warsaw, Indiana, USA). Taylor et al reported 99% survival for a polished Type 4 stem with a nine-year follow up.<sup>101</sup> Oxford Hip Scores were good to excellent in more than 90% of patients.<sup>17</sup> Savilahti et al reported 96% survival for a rough surface Type 4 stem with mean follow up of seven years.<sup>138</sup> Junnila et al have analysed the NARA for the most common cemented stems and reported 92% survival rate at 15 years for Type 4 stems.<sup>14</sup> Mukka et al carried out a prospective cohort study between a Type 1a and a Type 4 stem, and reported a 3.8% incidence of periprosthetic fractures for a Type 1a stem compared to 0.2% for a Type 4 stem in patients older than 80 years of age.<sup>110</sup> Registry data show that the Lubinus SP II has a cumulative revision rate of 2.53% at seven years in the LROI<sup>132</sup> and 94.2% survivorship at 11 years in the SHAR.<sup>79</sup> Overall, Type 4 stems have excellent results and are an excellent option for all patient types.<sup>78,79</sup>

### Revision stems

Most of the stem types have a revision version of the stem. The revision version is available in either a long or a short version with variable outcomes. Short Type 1 revision stems are widely used across the globe due to the cement-in-cement technique popularized by the Exeter Group.<sup>139,140</sup> Cnudde et al analysed 1179 first-time revisions in the SHAR and reported similar survival at six years when using either a Type 1 stem (94%) or a Type 4 stem (95%) for a cement-in-cement revision technique.<sup>141</sup>

## Conclusion

Cemented femoral stem fixation is generally associated with excellent long-term results independent of the stem type used. All stem types demonstrate broadly similar survival rates. Differences in material composition seem to affect the outcome, with cemented titanium stems having a higher failure rate. The geometric design seems to influence the incidence of periprosthetic fractures with Type 1 stems, demonstrating a higher rate, compared to other types.<sup>14,107–110,115</sup>

It is important for the practising surgeon to understand the various types of cemented implants since Type 3 and Type 4 stems are available both in a collarless polished surface or matt surface variety. Type 3 and Type 4 stems have different femoral preparation and biomechanical behaviour than the classic collarless polished tapers, Type 2 stems.

Failure rates have decreased with modern designs, although no type is completely free from the risk of aseptic loosening. The outcomes associated with the newer designs will need to be compared with the excellent long-term results of the classic stems. Although registry data

have been extremely useful in following survivorship of different cemented implants, it is still unclear what the indications are for using one stem type over the other. The basic classification system described in this article should simplify the understanding of each type of stem and can be expanded accordingly.

### Future studies

Future studies on cemented implants should address activity level, deformities and bone type. This would allow more information on when to use the different design types. It is important to report clinical findings, outcomes, complications and bone changes related to the different design type used and any new design introduced.

### AUTHOR INFORMATION

<sup>1</sup>Cappagh National Orthopaedic Hospital, Dublin, Ireland.

<sup>2</sup>Galway University Hospital, Galway, Ireland.

<sup>3</sup>Connolly Hospital, Orthopaedic Department, Dublin, Ireland.

Correspondence should be sent to: Adrian J. Cassar-Gheiti, Cappagh National Orthopaedic Hospital, Cappagh Road, Finglas, Dublin, D11 EV29, Ireland.  
Email: adriangheiti@rcsi.com

### ICMJE CONFLICT OF INTEREST STATEMENT

CGM reports being Faculty for Hip Fracture Management Instructional Course, March 2019 for Johnson & Johnson NV.

The other authors declare no conflict of interest relevant to this work.

### FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

### LICENCE

©2020 The author(s)

This article is distributed under the terms of the Creative Commons Attribution-Non Commercial 4.0 International (CC BY-NC 4.0) licence (<https://creativecommons.org/licenses/by-nc/4.0/>) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed.

### REFERENCES

1. Reynolds LA, Tansey EM, eds. *Early development of total hip arthroplasty: witness seminar for the history of medicine*. London: University College London, 2006. <http://www.histmodbiomed.org/sites/default/files/44852.pdf> (date last accessed 1 June 2019).
2. McKee GK, Watson-Farrar J. Replacement of arthritic hips by the McKee-Farrar prosthesis. *J Bone Joint Surg Br* 1966;48:245–259.
3. Thompson FR. Vitallium intramedullary hip prosthesis, preliminary report. *N Y State J Med* 1952;52:3011–3020.
4. Müller ME. Total hip prostheses. *Clin Orthop Relat Res* 1970;72:46–68.
5. Charnley J. Anchorage of the femoral head prosthesis to the shaft of the femur. *J Bone Joint Surg Br* 1960;42-B:28–30.

6. **Breusch S, Malachua H.** *The well-cemented total hip arthroplasty.* Berlin, Heidelberg: Springer, 2005.
7. **Shen G.** Femoral stem fixation: an engineering interpretation of the long-term outcome of Charnley and Exeter stems. *J Bone Joint Surg Br* 1998;80:754–756.
8. **Shah N, Porter M.** Evolution of cemented stems. *Orthopedics* 2005;28:s819–s825.
9. **Verdonschot N.** Philosophies of stem designs in cemented total hip replacement. *Orthopedics* 2005;28:s833–s840.
10. **Hank C, Schneider M, Achary CS, Smith L, Breusch SJ.** Anatomic stem design reduces risk of thin cement mantles in primary hip replacement. *Arch Orthop Trauma Surg* 2010;130:17–22.
11. **Baumann B, Hendrich C, Barthel T, et al.** 9- to 11-year results of cemented titanium mueller straight stem in total hip arthroplasty. *Orthopedics* 2007;30:551–557.
12. **Petheram TG, Whitehouse SL, Kazi HA, et al.** The Exeter universal cemented femoral stem at 20 to 25 years: a report of 382 hips. *Bone Joint J* 2016;98-B:1441–1449.
13. **Wroblewski BM, Fleming PA, Siney PD.** Charnley low-frictional torque arthroplasty of the hip: 20-to-30-year results. *J Bone Joint Surg Br* 1999;81:427–430.
14. **Junnilla M, Laaksonen I, Eskelinen A, et al.** Implant survival of the most common cemented total hip devices from the Nordic Arthroplasty Register Association database. *Acta Orthop* 2016;87:546–553.
15. **Purbach B, Kay PR, Siney PD, Fleming PA, Wroblewski BM.** The C-stem in clinical practice: fifteen-year follow-up of a triple tapered polished cemented stem. *J Arthroplasty* 2013;28:1367–1371.
16. **Flatøy B, Röhrli SM, Rydinge J, Dahl J, Diep LM, Nordsletten L.** Triple taper stem design shows promising fixation and bone remodelling characteristics: radiostereometric analysis in a randomised controlled trial. *Bone Joint J* 2015;97-B:755–761.
17. **Schweizer A, Riede U, Maurer TB, Ochsner PE.** Ten-year follow-up of primary straight-stem prosthesis (MEM) made of titanium or cobalt chromium alloy. *Arch Orthop Trauma Surg* 2003;123:353–356.
18. **Sesselmann S, Hong Y, Schlemmer F, et al.** Migration measurement of the cemented Lubinus SP II hip stem: a 10-year follow-up using radiostereometric analysis. *Biomed Tech (Berl)* 2017;62:271–278.
19. **Cimatti B, Santos MAD, Brassesco MS, et al.** Safety, osseointegration, and bone ingrowth analysis of PMMA-based porous cement on animal metaphyseal bone defect model. *J Biomed Mater Res B Appl Biomater* 2018;106:649–658.
20. **Cimatti B, Engel EE, Nogueira-Barbosa MH, Frighetto PD, Volpon JB.** Physical and mechanical characterization of a porous cement for metaphyseal bone repair. *Acta Ortop Bras* 2015;23:197–201.
21. **Lee C.** *The mechanical properties of PMMA bone cement: the well-cemented total hip arthroplasty: theory and practice.* Berlin, Heidelberg: Springer Berlin Heidelberg, 2005:60–66.
22. **Kühn K-D.** *What is bone cement? The well-cemented total hip arthroplasty: theory and practice.* Berlin, Heidelberg: Springer, 2005:52–59.
23. **Treharne RW, Brown N.** Factors influencing the creep behavior of poly(methyl methacrylate) cements. *J Biomed Mater Res* 1975;9:81–88.
24. **Yetkinler DN, Litsky AS.** Viscoelastic behaviour of acrylic bone cements. *Biomaterials* 1998;19:1551–1559.
25. **Spierings PTJ.** *Testing and performance of bone cements: the well-cemented total hip arthroplasty: theory and practice.* Berlin, Heidelberg: Springer, 2005:67–78.
26. **Breusch SJ, Malchau H.** *The well-cemented total hip arthroplasty theory and practice.* Berlin; New York: Springer, 2005. SpringerLink (online service). <http://ezproxy.lib.ed.ac.uk/login?url=http://dx.doi.org/10.1007/3-540-28924-0> (date last accessed 1 June 2019).
27. **Eden OR, Lee AJ, Hooper RM.** Stress relaxation modelling of polymethylmethacrylate bone cement. *Proc Inst Mech Eng H* 2002;216:195–199.
28. **Buchholz HW, Elson RA, Heinert K.** Antibiotic-loaded acrylic cement: current concepts. *Clin Orthop Relat Res* 1984;190:96–108.
29. **Nelson RC, Hoffman RO, Burton TA.** The effect of antibiotic additions on the mechanical properties of acrylic cement. *J Biomed Mater Res* 1978;12:473–490.
30. **Jasty M, Maloney WJ, Bragdon CR, O'Connor DO, Haire T, Harris WH.** The initiation of failure in cemented femoral components of hip arthroplasties. *J Bone Joint Surg Br* 1991;73:551–558.
31. **Lennon AB, Prendergast PJ.** Residual stress due to curing can initiate damage in porous bone cement: experimental and theoretical evidence. *J Biomech* 2002;35:311–321.
32. **Evans SL.** Fatigue crack propagation under variable amplitude loading in PMMA and bone cement. *J Mater Sci Mater Med* 2007;18:1711–1717.
33. **Hingston JA, Dunne NJ, Looney L, McGuinness GB.** Effect of curing characteristics on residual stress generation in polymethyl methacrylate bone cements. *Proc Inst Mech Eng H* 2008;222:933–945.
34. **Havelin LI, Espehaug B, Vollset SE, Engesaeter LB.** The effect of the type of cement on early revision of Charnley total hip prostheses: a review of eight thousand five hundred and seventy-nine primary arthroplasties from the Norwegian Arthroplasty Register. *J Bone Joint Surg Am* 1995;77:1543–1550.
35. **Hallan G, Aamodt A, Furnes O, Skredderstuen A, Haugan K, Havelin LI.** Palamed G compared with Palacos R with gentamicin in Charnley total hip replacement: a randomised, radiostereometric study of 60 HIPS. *J Bone Joint Surg Br* 2006;88:1143–1148.
36. **Meinardi JE, Valstar ER, Van Der Voort P, Kaptein BL, Fiocco M, Nelissen RG.** Palacos compared to Palamed bone cement in total hip replacement: a randomized controlled trial. *Acta Orthop* 2016;87:473–478.
37. **Espehaug B, Furnes O, Havelin LI, Engesaeter LB, Vollset SE.** The type of cement and failure of total hip replacements. *J Bone Joint Surg Br* 2002;84:832–838.
38. **Trela-Larsen L, Sayers A, Blom AW, Webb JCI, Whitehouse MR.** The association between cement type and the subsequent risk of revision surgery in primary total hip replacement. *Acta Orthop* 2018;89:40–46.
39. **Hoskins W, van Bavel D, Lorimer M, de Steiger RN.** Polished cemented femoral stems have a lower rate of revision than matt finished cemented stems in total hip arthroplasty: an analysis of 96,315 cemented femoral stems. *J Arthroplasty* 2018;33:1472–1476.
40. **Klapach AS, Callaghan JJ, Goetz DD, Olejniczak JP, Johnston RC.** Charnley total hip arthroplasty with use of improved cementing techniques: a minimum twenty-year follow-up study. *J Bone Joint Surg Am* 2001;83:1840–1848.
41. **Skinner JA, Todo S, Taylor M, Wang JS, Pinskerova V, Scott G.** Should the cement mantle around the femoral component be thick or thin? *J Bone Joint Surg Br* 2003;85:45–51.
42. **Caruana J, Janssen D, Verdonschot N, Blunn GW.** The importance of a thick cement mantle depends on stem geometry and stem-cement interfacial bonding. *Proc Inst Mech Eng H* 2009;223:315–327.
43. **Yates PJ, Burston BJ, Whitley E, Bannister GC.** Collarless polished tapered stem: clinical and radiological results at a minimum of ten years' follow-up. *J Bone Joint Surg Br* 2008;90:16–22.

- 44. Takahashi E, Kaneuji A, Tsuda R, et al.** The influence of cement thickness on stem subsidence and cement creep in a collarless polished tapered stem: when are thick cement mantles detrimental? *Bone Joint Res* 2017;6:351–357.
- 45. Walker PS, Mai SF, Cobb AG, Bentley G, Hua J.** Prediction of clinical outcome of THR from migration measurements on standard radiographs: a study of cemented Charnley and Stanmore femoral stems. *J Bone Joint Surg Br* 1995;77:705–714.
- 46. Langlais F, Kerboul M, Sedel L, Ling RS.** The 'French paradox'. *J Bone Joint Surg Br* 2003;85:17–20.
- 47. Kawate K, Maloney WJ, Bragdon CR, Biggs SA, Jasty M, Harris WH.** Importance of a thin cement mantle: autopsy studies of eight hips. *Clin Orthop Relat Res* 1998;355:70–76.
- 48. ElMasri F, Kerboul L, Kerboul M, Coupied JP, Hamadouche M.** Is the so-called 'French paradox' a reality? Long-term survival and migration of the Charnley-Kerboul stem cemented line-to-line. *J Bone Joint Surg Br* 2010;92:342–348.
- 49. Kerboul M.** Thickness of the cement mantle. *Hip Int* 2002;12:101–102.
- 50. Kutzner KP, Freitag T, Bieger R, et al.** Biomechanics of a cemented short stem: standard vs. line-to-line cementation techniques. A biomechanical in-vitro study involving six osteoporotic pairs of human cadaver femurs. *Clin Biomech (Bristol, Avon)* 2018;52:86–94.
- 51. Erivan R, Villatte G, Khelif YR, et al.** The Müller self-locking cemented total hip prosthesis with polyethylene liner: after twenty years, what did they become? *Int Orthop* 2017;41:47–54.
- 52. Clauss M, Luem M, Ochsner PE, Ilchmann T.** Fixation and loosening of the cemented Muller straight stem: a long-term clinical and radiological review. *J Bone Joint Surg Br* 2009;91:1158–1163.
- 53. Morellato K, Grupp TM, Bader U, Sungu M, Fink B, Cristofolini L.** Standard and line-to-line cementation of a polished short hip stem: long-term in vitro implant stability. *J Orthop Res* 2018;36:2736–2744.
- 54. Cristofolini L, Erani P, Savigni P, Grupp T, Thies O, Viceconti M.** Increased long-term failure risk associated with excessively thin cement mantle in cemented hip arthroplasty: a comparative in vitro study. *Clin Biomech (Bristol, Avon)* 2007;22:410–421.
- 55. Ballard WT, Callaghan JJ, Sullivan PM, Johnston RC.** The results of improved cementing techniques for total hip arthroplasty in patients less than fifty years old: a ten-year follow-up study. *J Bone Joint Surg Am* 1994;76:959–964.
- 56. Barrack RL, Mulroy RD Jr, Harris WH.** Improved cementing techniques and femoral component loosening in young patients with hip arthroplasty: a 12-year radiographic review. *J Bone Joint Surg Br* 1992;74:385–389.
- 57. Breusch SJ, Norman TL, Schneider U, Reitzel T, Blaha JD, Lukoschek M.** Lavage technique in total hip arthroplasty: jet lavage produces better cement penetration than syringe lavage in the proximal femur. *J Arthroplasty* 2000;15:921–927.
- 58. Halawa M, Lee AJ, Ling RS, Vangala SS.** The shear strength of trabecular bone from the femur, and some factors affecting the shear strength of the cement-bone interface. *Arch Orthop Trauma Surg* 1978;92:19–30.
- 59. Oh I, Carlson CE, Tomford WW, Harris WH.** Improved fixation of the femoral component after total hip replacement using a methacrylate intramedullary plug. *J Bone Joint Surg Am* 1978;60:608–613.
- 60. Harris WH, McGann WA.** Loosening of the femoral component after use of the medullary-plug cementing technique: follow-up note with a minimum five-year follow-up. *J Bone Joint Surg Am* 1986;68:1064–1066.
- 61. Weber BG.** Pressurized cement fixation in total hip arthroplasty. *Clin Orthop Relat Res* 1988;232:87–95.
- 62. Dozier JK, Harrigan T, Kurtz WH, Hawkins C, Hill R.** Does increased cement pressure produce superior femoral component fixation? *J Arthroplasty* 2000;15:488–495.
- 63. Budnar VM, Bannister GC.** Enhancing proximal femoral pressure during cemented stem insertion. *Hip Int* 2012;22:302–306.
- 64. Britton AR, Murray DW, Bulstrode CJ, McPherson K, Denham RA.** Long-term comparison of Charnley and Stanmore design total hip replacements. *J Bone Joint Surg Br* 1996;78:802–808.
- 65. Roberts DW, Poss R, Kelley K.** Radiographic comparison of cementing techniques in total hip arthroplasty. *J Arthroplasty* 1986;1:241–247.
- 66. Schmitz MW, Bronsema E, de Kam DC, Gardeniers JW, Veth RP, Schreurs BW.** Results of the cemented Exeter femoral component in patients under the age of 40: an update at ten to 20 years' follow-up. *Bone Joint J* 2017;99-B:192–198.
- 67. Kärrholm J.** Radiostereometric analysis of early implant migration: a valuable tool to ensure proper introduction of new implants. *Acta Orthop* 2012;83:551–552.
- 68. Crowninshield RD, Jennings JD, Laurent ML, Maloney WJ.** Cemented femoral component surface finish mechanics. *Clin Orthop Relat Res* 1998;355:90–102.
- 69. Howie DW, Middleton RG, Costi K.** Loosening of matt and polished cemented femoral stems. *J Bone Joint Surg Br* 1998;80:573–576.
- 70. Ong A, Wong KL, Lai M, Garino JP, Steinberg ME.** Early failure of precoated femoral components in primary total hip arthroplasty. *J Bone Joint Surg Am* 2002;84:786–792.
- 71. Ebramzadeh E, Sangiorgio SN, Longjohn DB, Buhari CF, Dorr LD.** Initial stability of cemented femoral stems as a function of surface finish, collar, and stem size. *J Bone Joint Surg Am* 2004;86:106–115.
- 72. Murray DW, Rushton N.** Mediators of bone resorption around implants. *Clin Orthop Relat Res* 1992;281:295–304.
- 73. Verdonschot N, Tanck E, Huiskes R.** Effects of prosthesis surface roughness on the failure process of cemented hip implants after stem-cement debonding. *J Biomed Mater Res* 1998;42:554–559.
- 74. Collis DK, Mohler CG.** Comparison of clinical outcomes in total hip arthroplasty using rough and polished cemented stems with essentially the same geometry. *J Bone Joint Surg Am* 2002;84:586–592.
- 75. Fowler JL, Gie GA, Lee AJ, Ling RS.** Experience with the Exeter total hip replacement since 1970. *Orthop Clin North Am* 1988;19:477–489.
- 76. Rockborn P, Olsson SS.** Loosening and bone resorption in Exeter hip arthroplasties: review at a minimum of five years. *J Bone Joint Surg Br* 1993;75:865–868.
- 77. Datir SP, Wynn-Jones CH.** Staged bilateral total hip arthroplasty using rough and smooth surface femoral stems with similar design: 10-year survivorship of 48 cases. *Acta Orthop* 2005;76:809–814.
- 78. Prins W, Meijer R, Kollen BJ, Verheyen CC, Ettema HB.** Excellent results with the cemented Lubinus SP II 130-mm femoral stem at 10 years of follow-up: 932 hips followed for 5–15 years. *Acta Orthop* 2014;85:276–279.
- 79. Swedish Hip Arthroplasty Register (SHAR).** 2017. <https://registercentrum.blob.core.windows.net/shpr/r/Annual-Report-2016-BieWEH-mHM.pdf> (date last accessed 10 November 2019).
- 80. Schweizer A, Lüem M, Riede U, Lindenlaub P, Ochsner PE.** Five-year results of two cemented hip stem models each made of two different alloys. *Arch Orthop Trauma Surg* 2005;125:80–86.
- 81. Jergesen HE, Karlen JW.** Clinical outcome in total hip arthroplasty using a cemented titanium femoral prosthesis. *J Arthroplasty* 2002;17:592–599.

- 82. Bizot P, Hannouche D, Nizard R, Witvoet J, Sedel L.** Hybrid alumina total hip arthroplasty using a press-fit metal-backed socket in patients younger than 55 years: a six- to 11-year evaluation. *J Bone Joint Surg Br* 2004;86:190–194.
- 83. Hernigou P, Dupuys N, Delambre J, et al.** Long, titanium, cemented stems decreased late periprosthetic fractures and revisions in patients with severe bone loss and previous revision. *Int Orthop* 2015;39:639–644.
- 84. Hamadouche M, Boutin P, Daussange J, Bolander ME, Sedel L.** Alumina-on-alumina total hip arthroplasty: a minimum 18.5-year follow-up study. *J Bone Joint Surg Am* 2002;84:69–77.
- 85. Hinrichs F, Kuhl M, Boudriot U, Griss P.** A comparative clinical outcome evaluation of smooth (10–13-year results) versus rough surface finish (5–8-year results) in an otherwise identically designed cemented titanium alloy stem. *Arch Orthop Trauma Surg* 2003;123:268–272.
- 86. Bloch B, Brown S, Angadi D, Crawford E.** Long-term follow-up of a cemented titanium stem. *Acta Orthop Belg* 2015;81:225–232.
- 87. Thomas SR, Shukla D, Latham PD.** Corrosion of cemented titanium femoral stems. *J Bone Joint Surg Br* 2004;86:974–978.
- 88. Willert HG, Brobäck LG, Buchhorn GH, et al.** Crevice corrosion of cemented titanium alloy stems in total hip replacements. *Clin Orthop Relat Res* 1996;333:51–75.
- 89. Williams HD, Browne G, Gie GA, Ling RS, Timperley AJ, Wendover NA.** The Exeter universal cemented femoral component at 8 to 12 years: a study of the first 325 hips. *J Bone Joint Surg Br* 2002;84:324–334.
- 90. Kiss J, Murray DW, Turner-Smith AR, Bithell J, Bulstrode CJ.** Migration of cemented femoral components after THR: roentgen stereophotogrammetric analysis. *J Bone Joint Surg Br* 1996;78:796–801.
- 91. Nieuwenhuijse MJ, Valstar ER, Kaptein BL, Nelissen RG.** The Exeter femoral stem continues to migrate during its first decade after implantation: 10–12 years of follow-up with radiostereometric analysis (RSA). *Acta Orthop* 2012;83:129–134.
- 92. von Schewelov T, Carlsson A, Sanzén L, Besjakov J.** Continuous distal migration and internal rotation of the C-stem prosthesis without any adverse clinical effects: an RSA study of 33 primary total hip arthroplasties followed for up to ten years. *Bone Joint J* 2014;96-B:604–608.
- 93. Harris WH, McCarthy JC Jr, O'Neill DA.** Femoral component loosening using contemporary techniques of femoral cement fixation. *J Bone Joint Surg Am* 1982;64:1063–1067.
- 94. Howell JR, Hubble MJW, Ling RSM.** Implant choice: stem design – the surgeon's perspective. In: Breusch SJ, Malchau H, eds. *The well cemented hip arthroplasty*. Berlin, Heidelberg: Springer, 2005:180–189.
- 95. Davies BM, Branford White HA, Temple A.** A series of four fractured Exeter™ stems in hip arthroplasty. *Ann R Coll Surg Engl* 2013;95:e130–e132.
- 96. Chen CQ, Scott W, Barker TM.** Effect of metal surface topography on mechanical bonding at simulated total hip stem-cement interfaces. *J Biomed Mater Res* 1999;48:440–446.
- 97. Clauss M, Ilchmann T, Zimmermann P, Ochsner PE.** The histology around the cemented Müller straight stem: a post-mortem analysis of eight well-fixed stems with a mean follow-up of 12.1 years. *J Bone Joint Surg Br* 2010;92:1515–1521.
- 98. Numata Y, Kaneuji A, Kerboull L, et al.** Biomechanical behaviour of a French femoral component with thin cement mantle: the 'French paradox' may not be a paradox after all. *Bone Joint Res* 2018;7:485–493.
- 99. Scott GFM, Kerboull M.** Femoral components: the French paradox. In: Breusch SJ, Malchau H, eds. *The well cemented total hip arthroplasty*. Heidelberg: Springer, 2005:249–253.
- 100. Scheerlinck T, Casteleyn PP.** The design features of cemented femoral hip implants. *J Bone Joint Surg Br* 2006;88:1409–1418.
- 101. Taylor LJ, Singh G, Schneider M.** Femoral components: outcome with a tapered, Polished, Anatomic stem. In: Breusch SJ, Malchau H, eds. *The well cemented hip arthroplasty*. Heidelberg: Springer, 2005:242–248.
- 102. Westerman RW, Whitehouse SL, Hubble MJW, Timperley AJ, Howell JR, Wilson MJ.** The Exeter V40 cemented femoral component at a minimum 10-year follow-up: the first 540 cases. *Bone Joint J* 2018;100-B:1002–1009.
- 103. Australian Orthopaedic Association National Joint Replacement Registry(AOANJRR).** 2019. <https://aoanjrr.sahmri.com/documents/10180/397736/Hip%20C%20Knee%20%26%20Shoulder%20Arthroplasty> (date last accessed 10 November 2019).
- 104. National Joint Registry (NJR).** 2019. <http://www.njrcentre.org.uk/njrcentre/Reports-Publications-and-Minutes> (date last accessed 10 November 2019).
- 105. Burston BJ, Yates PJ, Hook S, Moulder E, Whitley E, Bannister GC.** Cemented polished tapered stems in patients less than 50 years of age: a minimum 10-year follow-up. *J Arthroplasty* 2010;25:692–699.
- 106. Lewthwaite SC, Squires B, Gie GA, Timperley AJ, Ling RS.** The Exeter universal hip in patients 50 years or younger at 10–17 years' followup. *Clin Orthop Relat Res* 2008;466:324–331.
- 107. Palan J, Smith MC, Gregg P, et al.** The influence of cemented femoral stem choice on the incidence of revision for periprosthetic fracture after primary total hip arthroplasty: an analysis of national joint registry data. *Bone Joint J* 2016;98-B:1347–1354.
- 108. Scott T, Salvatore A, Woo P, Lee YY, Salvati EA, Gonzalez Della Valle A.** Polished, collarless, tapered, cemented stems for primary hip arthroplasty may exhibit high rate of periprosthetic fracture at short-term follow-up. *J Arthroplasty* 2018;33:1120–1125.
- 109. Brodén C, Mukka S, Muren O, et al.** High risk of early periprosthetic fractures after primary hip arthroplasty in elderly patients using a cemented, tapered, polished stem. *Acta Orthop* 2015;86:169–174.
- 110. Mukka S, Mellner C, Knutsson B, Sayed-Noor A, Sköldenberg O.** Substantially higher prevalence of postoperative peri-prosthetic fractures in octogenarians with hip fractures operated with a cemented, polished tapered stem rather than an anatomic stem. *Acta Orthop* 2016;87:257–261.
- 111. Grammatopoulos G, Pandit H, Kambouroglou G, et al.** A unique peri-prosthetic fracture pattern in well fixed femoral stems with polished, tapered, collarless design of total hip replacement. *Injury* 2011;42:1271–1276.
- 112. Lindahl H, Garellick G, Regné H, Herberts P, Malchau H.** Three hundred and twenty-one periprosthetic femoral fractures. *J Bone Joint Surg Am* 2006;88:1215–1222.
- 113. Sherfey JJ, McCalden RW.** Mid-term results of Exeter vs Endurance cemented stems. *J Arthroplasty* 2006;21:1118–1123.
- 114. Cook RE, Jenkins PJ, Walmsley PJ, Patton JT, Robinson CM.** Risk factors for periprosthetic fractures of the hip: a survivorship analysis. *Clin Orthop Relat Res* 2008;466:1652–1656.
- 115. Thien TM, Chatziagorou G, Garellick G, et al.** Periprosthetic femoral fracture within two years after total hip replacement: analysis of 437,629 operations in the Nordic arthroplasty register association database. *J Bone Joint Surg Am* 2014;96:e167.
- 116. Callaghan JJ, Bracha P, Liu SS, Piyaworakun S, Goetz DD, Johnston RC.** Survivorship of a Charnley total hip arthroplasty: a concise follow-up, at a minimum of thirty-five years, of previous reports. *J Bone Joint Surg Am* 2009;91:2617–2621.

- 117. Garellick G, Malchau H, Regnér H, Herberts P.** The Charnley versus the Spectron hip prosthesis: radiographic evaluation of a randomized, prospective study of 2 different hip implants. *J Arthroplasty* 1999;14:414–425.
- 118. Garellick G, Malchau H, Herberts P.** The Charnley versus the Spectron hip prosthesis: clinical evaluation of a randomized, prospective study of 2 different hip implants. *J Arthroplasty* 1999;14:407–413.
- 119. Urschel C, Döring M, Strecker W.** [Cement-free and cemented Excia hip shaft prosthesis: comparison of intermediate term results]. *Orthopade* 2014;43:815–824.
- 120. Callaghan JJ, Albright JC, Goetz DD, Olejniczak JP, Johnston RC.** Charnley total hip arthroplasty with cement: minimum twenty-five-year follow-up. *J Bone Joint Surg Am* 2000;82:487–497.
- 121. Smith SW, Estok DM II, Harris WH.** Total hip arthroplasty with use of second-generation cementing techniques: an eighteen-year-average follow-up study. *J Bone Joint Surg Am* 1998;80:1632–1640.
- 122. Johanson PE, Antonsson M, Shareghi B, Kärrholm J.** Early subsidence predicts failure of a cemented femoral stem with minor design changes. *Clin Orthop Relat Res* 2016;474:2221–2229.
- 123. Burston BJ, Wood JH, Lewis JR, et al.** High failure rates of the Spectron EF stem at a minimum of 10 year's follow-up. *J Arthroplasty* 2014;29:1956–1960.
- 124. Nikolaou VS, Korres D, Lалlos S, et al.** Cemented Müller straight stem total hip replacement: 18 year survival, clinical and radiological outcomes. *World J Orthop* 2013;4:303–308.
- 125. Riede U, Lüem M, Ilchmann T, Eucker M, Ochsner PE.** The ME Müller straight stem prosthesis: 15 year follow-up. Survivorship and clinical results. *Arch Orthop Trauma Surg* 2007;127:587–592.
- 126. Siepen W, Zwicky L, Stoffel KK, Ilchmann T, Clauss M.** Prospective two-year subsidence analysis of 100 cemented polished straight stems: a short-term clinical and radiological observation. *BMC Musculoskelet Disord* 2016;17:395.
- 127. Oosterbos CJM, Tonino AJ.** Prognosis of the Müller straight stem. *Hip Int* 1997;1997:101–109.
- 128. Bremant JJ.** [10 years follow-up of the ME Muller self-locking cemented total hip prosthesis]. *Rev Chir Orthop Reparat Mot* 1995;81:380–388.
- 129. Råber DA, Czaja S, Morscher EW.** Fifteen-year results of the Müller CoCrNiMo straight stem. *Arch Orthop Trauma Surg* 2001;121:38–42.
- 130. Kerboull L, Hamadouche M, Courpied JP, Kerboull M.** Long-term results of Charnley-Kerboull hip arthroplasty in patients younger than 50 years. *Clin Orthop Relat Res* 2004;418:112–118.
- 131. Nich C, Courpied JP, Kerboull M, Postel M, Hamadouche M.** Charnley-Kerboull total hip arthroplasty for osteonecrosis of the femoral head a minimal 10-year follow-up study. *J Arthroplasty* 2006;21:533–540.
- 132. Dutch Arthroplasty Register (LROI).** 2019. [www.lroi-report.nl](http://www.lroi-report.nl) (date last accessed 10 November 2019).
- 133. Partio E, von Bonsdorff H, Wirta J, Avikainen V.** Survival of the Lubinus hip prosthesis: an eight- to 12-year follow-up evaluation of 444 cases. *Clin Orthop Relat Res* 1994;303:140–146.
- 134. Jacobsson SA, Ivarsson I, Djerf K, Wahlström O.** Stem loosening more common with ITH than Lubinus prosthesis: a 5-year clinical and radiographic follow-up of 142 patients. *Acta Orthop Scand* 1995;66:425–431.
- 135. Nivbrant B, Kärrholm J, Söderlund P.** Increased migration of the SHP prosthesis: radiostereometric comparison with the Lubinus SP2 design in 40 cases. *Acta Orthop Scand* 1999;70:569–577.
- 136. Alho A, Lepistö J, Ylinen P, Paavilainen T.** Cemented Lubinus and Furlog total hip endoprosthesis: a 12-year follow-up study of 175 hips comparing the cementing technique. *Arch Orthop Trauma Surg* 2000;120:276–280.
- 137. Catani F, Ensini A, Leardini A, Bragonzoni L, Toksvig-Larsen S, Giannini S.** Migration of cemented stem and restrictor after total hip arthroplasty: a radiostereometry study of 25 patients with Lubinus SP II stem. *J Arthroplasty* 2005;20:244–249.
- 138. Savilahti S, Myllyneva I, Pajamäki KJ, Lindholm TS.** Survival of Lubinus straight (IP) and curved (SP) total hip prostheses in 543 patients after 4–13 years. *Arch Orthop Trauma Surg* 1997;116:10–13.
- 139. Holt G, Hook S, Hubble M.** Revision total hip arthroplasty: the femoral side using cemented implants. *Int Orthop* 2011;35:267–273.
- 140. Amanatullah DF, Pallante GD, Floccari LV, Vasileiadis GI, Trousdale RT.** Revision total hip arthroplasty using the cement-in-cement technique. *Orthopedics* 2017;40:e348–e351.
- 141. Cnudde PH, Kärrholm J, Rolfson O, Timperley AJ, Mohaddes M.** Cement-in-cement revision of the femoral stem: analysis of 1179 first-time revisions in the Swedish Hip Arthroplasty Register. *Bone Joint J* 2017;99-B:27–32.