INTRODUCTION
Calcific aortic valve disease (CAVD) is a formation of tissue similar to bone on the leaflets of the aortic valve (AV). The presence of such calcifications rapidly leads to aortic stenosis (AS), a condition which requires an early intervention; however, patients usually do not present symptoms until the disease has progressed to an advanced stage [2]. It is therefore rare to have a CT scan acquired at the early stages of the disease. Bicuspid Aortic Valve (BAV) is the most common type of congenital heart disease where the valve has only two leaflets rather than the normal three. The most common configuration of BAV, type 1, includes one fused leaflet with two fused segments. BAV is associated with secondary pathologies of the valve and the aorta, such as aortic regurgitation, AS, and ascending aorta dilatation [3]. The progression of CAVD leading to AS in BAV patients is accelerated compared to TAV patients [4]. Transcatheter aortic valve replacement (TAVR) is a relatively new procedure that provides an alternative to open-heart surgical replacement for inoperable patients with severe AS. In this minimally invasive intervention, a stent with a mounted bioprosthetic valve is delivered through the arteries and deployed on the stenotic native valve. Currently, the latest generation FDA-approved TAVR devices are the Edwards Lifesciences Sapien 3 and Medtronic Corevalve Evolut R. In recent years, more centers around the world started to perform TAVR also in BAV patients which raised concerns stemming from the BAV asymmetrical structure and its elliptical annulus and valve orifice. The outcomes of TAVR in BAVs are also highly dependent on the type of device, namely Edwards Sapien valve might require post-implantation balloon dilation to minimize paravalvular leakage (PVL) [5, 6] while Medtronic CoreValve has higher occurrence of post-implantation central regurgitation [6].

CAVD has been studied using numerical tools to investigate the mechanical stress, hemodynamics and kinematics of the valve. One of the main use for patient-specific modeling of CAVD is TAVR procedural planning [7] with studies examining prosthesis deployment and the device design. However, previous TAVR studies did not account for the progression of the disease. Our group studied BAV with Fluid Structure Interaction (FSI) methods [8] to compare tricuspid valve with three morphologies of BAV while other groups also modeled BAVs for similar aims.

METHODS
CT scans of pre-TAVR patient with BAV were collected from our existing database of CAVD scans. A severe AS patient was chosen because of the heavily calcified raphe region, contributing to the assumed TAVR elliptical deployment. Our Reverse Calcification Technique (RCT) was employed for this BAV patient in a similar manner to our previously suggested RCT for TAVs [1]. This technique is based on using pre-TAVR CT scans of AVs to study the calcification progression that leads to the current state. Spatial gradients of the densities in the calcified regions are analyzed at the current late stage (identified from the HU range), and are utilized to predict the progression [1]. For TAV, this technique was validated by obtaining two scans from the same patient during both severe and mild stages (Fig. 1, left). Close agreement was found between the old scan and the RCT prediction from a recent scan.

Idealized geometry of the BAV type 1 anatomy was created for non-fused leaflet angle of 140° and symmetrical fused leaflet. For this
purpose, our existing parametric geometry and mesh generation method [9] was modified for asymmetric BAVs. The fusion of the leaflets is defined as circular arcs that follow the leaflet’s curvature and Bezier curve in the coaptation-belly connection. The native leaflets and root are meshed with shell elements in this model and have native tissue properties. The calcium deposits are tied to the leaflets and have calcium material properties (Fig. 1, center).

Deployment of the two TAVR devices, Sapien 3 and Evolut R (Fig. 1, right), are modeled in the CAVD-BAV anatomy. For Sapien 3, the leaflets and stent were drawn based on publicly available figures from Edwards. The 3D shape of the leaflets was calculated in finite elements (FE) by suturing them to the cuff. The cuff, that was also drawn based on public images, is necessary to estimate the leakage and connect the leaflets and the stent. The stent of the CoreValve was generated based on Bezier curves, resulted in a structured hexahedral mesh. Both stents have ~70,000 elements. The leaflets of the CoreValve were generated based on the stent mesh and meshed with shell elements. The cuffs in both models were modeled with membrane elements. The materials used to model the stents are MP35N alloy and purely superelastic NiTi for the Sapien 3 and Evolut R, respectively. The stents were initially crimped with a cylindrical crimper. The Evolut R deployment is a result of the residual stresses present in the stent after the crimping while gradually pulling the sleeve toward the aorta. The Sapien 3 is deployed by balloon (NovaFlex+) inflation as we previously used for first generation Sapien [10]. The FE solver is SIMULIA Abaqus (Dassault Systèmes, Providence, RI).

The FE analyses of the deployments will be used as predicators of possible complications. The migration of the stents as a result of insufficient anchoring forces will be modeled by recoil phase after the deployment [10]. Post-TAVR diastolic regurgitation in BAVs is compared between Sapien 3 and Evolut R. The leaflets and cuffs are deformed to the final configuration of the deployed stents and the leaflets are then closed by applying transvalvar pressure. Capvidia FlowVison will be used for regurgitation estimation.

RESULTS

The RCT subtraction algorithm was commenced and used to generate various stages of the CAVD disease in BAV. The pre-TAVR stage (Fig. 1, center) was used as the input for this technique and the reverse configurations were generated until reaching the initiation node site. The left column of Fig. 2 shows three of the calculated configurations. An initiation node of the calcification growth appears on the raphe region, a location that is subjected to higher stresses in healthy BAV type 1. The non-fused leaflet has similar arc shaped pattern as in TAVs [1] while the arcs are connected in the fused leaflet.

Preliminary deployment of the Evolut R stent in healthy BAV is shown in the right column of Fig. 2. The resulting deployed configuration was used to deform the leaflets and cuff to the final configuration. The deformed prosthetic leaflets and cuff embed in the final configuration (bottom).

DISCUSSION

In this study we expanded our previously published models of retrospective estimation of CAVD progression and parametric geometry of the aortic root from TAV to BAV morphologies. The RCT was able to generate calcific deposits geometries in various stages but further validation of this technique in BAVs is still required. Similarly, the parametric geometry algorithm needs to be compared with 3D Echo scans. The balloon expandable Sapien 3 assumed the circular configuration of the balloon while the Evolut R adapted to the elliptical shape of the BAV opening, leading to very different hemodynamic during the diastole. The circular Sapien 3 deployment in an elliptical opening may leave gaps between the stent and the root but the outer skirt can help in reducing the severity of the PVL. The highly elliptical deployment of the Evolut R in the calcified BAV might prevent proper coaptation between the bioprosthetic leaflets and a full closure but the “fish mouth” opening of the BAV could be narrow enough to prevent it. Similar deployment models will be solved for previous stages of the disease to estimate the desired occasion for intervention.

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REFERENCES