Computational Finite Element Analyses to Optimize Graft Sizing During Aortic Valve-Sparing Procedure

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Background and aim of the study: **Aortic valve-sparing (AVS) procedures have been introduced to treat ascending aorta dilatation and aortic valve insufficiency in the presence of preserved native aortic valve leaflets. Although the surgical technique has been standardized, the choice of best type and size of Dacron graft to be used remains a matter of debate. Herein are presented preliminary results based on a patient-specific finite element model aimed at optimizing the Dacron prosthesis size and shape. Previously, finite element analysis (FEA) has been applied to investigate medical problems and, in particular, to better evaluate the pathophysiology of the aortic root. To date, however, such methodology has not been applied to the patient-specific evaluation of AVS postoperative results.**

Methods: **The framework of the FEA study included four steps: (i) the creation of a mathematic model of the patient's aortic root; (ii) the creation of a model for two different Dacron grafts (the standard straight graft and a Valsalva graft), with sizes of each type ranging from 24 to 30 mm; (iii) a virtual computer-based simulation of the AVS procedure, using each graft; and (iv) a virtual computer-based simulation of the diastolic closure of the repaired valve and an evaluation of post-implant physiology, based on three parameters: the height of coaptation ratio ($H_C{}^R$); the length of coaptation ratio ($L_C{}^R$); and the distance between the central point of coaptation and the ideal geometrical centre (D_C).**

Results: **The simulation results of post-implant performance of the aortic valve revealed that both $H_C{}^R$ and $L_C{}^R$ were decreased as the graft size was increased, but no significant differences were identified between two types of graft. In contrast, the Valsalva graft, when compared to the standard straight graft, led to a significant reduction in D_C. The results in terms of $H_C{}^R$, $L_C{}^R$ and D_C recommended unequivocally, for the specific case under investigation, that a 30 mm straight graft and a 28 mm Valsalva graft would ensure the most physiological valve behavior for the patient under investigation.**

Conclusion: **In evaluating the potential of a preoperative prediction of the optimal graft size, using FEA, the virtual simulation of the AVS procedure proved to be feasible and useful in predicting the postoperative physiology of the aortic root. In particular, this finite element model might have a clinical impact as may be used to optimize the surgeon's choice of prosthesis size.**

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Aortic valve-sparing (AVS) procedures, as introduced by David in 1992 (1), were designed to treat aortic valve insufficiency caused by dilation of the aortic root, thus preserving the native leaflets. The original technique described by David, known as the 'reimplantation' technique, included an excision of the aortic root and its replacement with a cylindrical straight polyester graft. Subsequently, several modifications of the original technique (2,3), as well as different graft types (4), have been proposed to optimize the postoperative physiological function of the reconstructed aortic root. However, the choice of the best graft type and size to be adopted for any specific patient remains a matter of debate, with several formulae and methods having been presented to guide the surgeon's decision intraoperatively (5-8).

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The aim of the present study was to predict the optimal surgical solution in terms of graft type and size, by performing virtual patient-specific simulations based on finite element analysis (FEA). In the past, many applications of FEA have been reported in the field of cardiovascular medicine (9-11) although, to the present authors' knowledge, the technique has never been adopted to obtain a prediction of postoperative patient-specific results following AVS surgery.

Herein are presented details of the authors' preliminary experience in the development of a patient-specific application of FEA that has been devoted to optimizing the surgeon's choices in terms of graft shape and size with respect to the AVS procedure, thus enhancing the postoperative outcome.

Materials and methods

The FEA model

The FEA model includes four steps which can be summarized as follows:

- The creation of the pathological aortic root model (based on ultrasound measurements in one patient).
- The creation of the prosthetic graft model (two types of Dacron graft, with four sizes for each type).
- A computer-based simulation of the AVS surgical procedure (eight different configurations).
- A computer-based simulation of the diastolic valve behavior for each postoperative configuration.

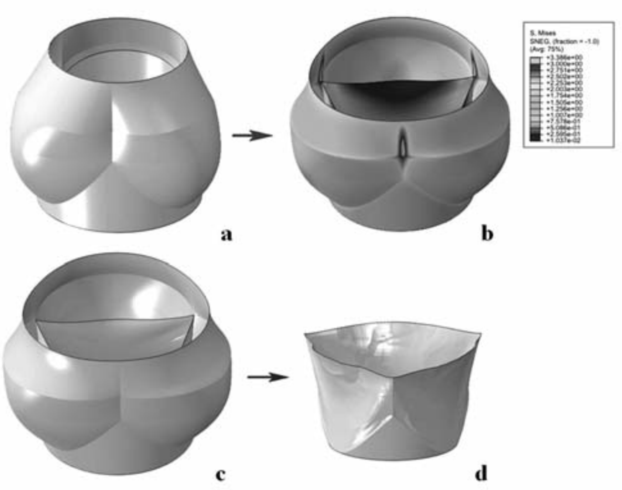

Figure 1: a) A healthy 'parent' model of the aortic root is created based on the Labrosse model. b) The process of dilation is simulated by FEA. Radial displacements are applied to the nodes of the commissures in order to reproduce the pathologic dilation. The von Mises stress pattern is highlighted. c) The pathologic model of the dilated aortic root obtained through a finite element simulation is characterized by the same dimensions measured with echocardiography. d) The native aortic valve, stretched due to dilatation of the aortic root, is extracted from the whole pathologic model.

All simulations were performed using Abaqus software (v. 6.10; Dassault Systèmes, Providence, RI, USA) as the finite element solver. The geometric model of the dilated aortic root was based on direct echocardiographic measurements (diameters of the annulus and sinotubular junction; sinus height; leaflet free margin length; leaflet height).

The first step was to create a healthy aortic root based on the Labrosse model (12) (see Fig. 1a), after which the process of dilation was simulated by applying radial displacements to the nodes of the commissures (see Fig, 1b), as described by Auricchio et al. (13), such that the resulting dimensions agreed with the pathological dimensions evaluated using echocardiography.

The geometric model of the stretched valve was finally obtained by setting to zero the developed internal stresses (Fig. 1c) and by removing the Valsalva sinuses (Fig. 1d).

Thickness values (1.5 mm for the sinuses, 0.5 mm for the leaflets) and material parameters were based on previously reported data (14): a Mooney-Rivlin isotropic hyperelastic model (density = 1000 kg/m^3, C_{10} = 0.5516 MPa, C01 = 0.1379 MPa) was adopted to represent the material behavior. Both, four-node membrane elements (M3D4R) and three-node membrane elements (M3D3) were used to mesh the leaflets, while the Valsalva sinuses were meshed with shell elements (S4R).

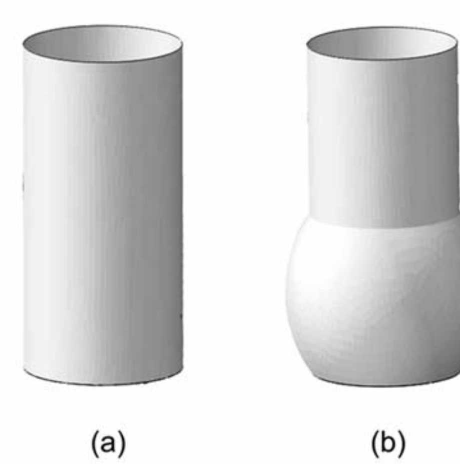

Figure 2: The geometric models of the Dacron grafts adopted for simulation of the AVS procedure. a) The Standard Dacron graft. b) The Valsalva graft.

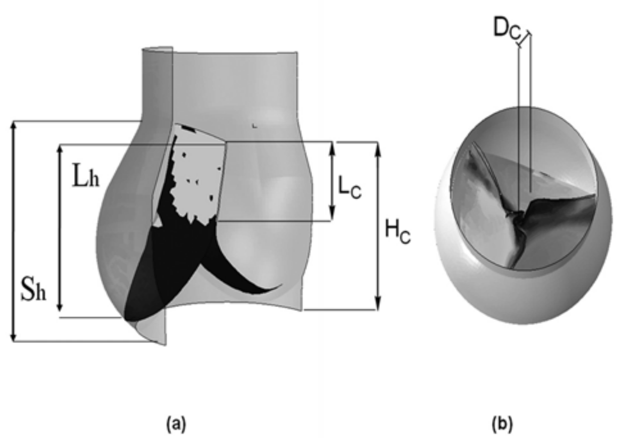

Figure 3: a) Parameters used for evaluation of the postoperative valve performance. HC: Height of coaptation; LC: Length of coaptation; Sh: Sinus height; Lh: Leaflet height. b) A third parameter is used to evaluate the postoperative valve performance. DC: Displacement of coaptation (distance of the top of leaflet coaptation from the geometric center of the aortic root/Dacron tube).

The creation of a finite element model of a possible prosthesis to be used during the surgical procedure was based on company specifications (see Fig. 2). In particular, the prosthesis model was obtained from two different graft types: the standard graft, and the Valsalva graft (Vaskutek Terumo, Renfrewshire, UK); the latter is characterized by a peculiar shape which mimics the presence of the Valsalva sinuses (4). Sizes ranging from 24 to 30 mm were reproduced for both graft types, and the prostheses modeled as rigid bodies meshed with four-node surface elements (SFM3D4R).

The native aortic valve model was then combined with the prosthesis model. In particular, the diameter of the prosthetic device, which was, in the initial configuration, intentionally greater than the real one, was gradually reduced without modifying the prosthesis geometry; displacements were applied to the graft nodes to virtually reproduce the effective surgical procedure. The interaction between the graft and the prosthesis was modeled, adopting a frictionless algorithm. The constraining effect of the applied graft caused these nodes to move through the phases of simulation.

Finally, the performance of the graft implant was evaluated by simulating the postoperative valve closure during diastole. To model the diastolic loading of the aortic root, an 80 mmHg physiological pressure was applied to the leaflets, while the nodes belonging both to the annulus and to the commissures were blocked.

The numerical analyses of both graft placement and valve closure are non-linear problems that involve large deformation and contact. For this reason, quasi-static procedures were used, assuming that inertia forces would not dominate the analysis. Kinetic energy was monitored to ensure that the ratio of kinetic energy to internal energy remained <10%. Finally, a mass scaling strategy was adopted to reduce computational costs. A frictionless general contact algorithm was used in order to handle the interactions between the leaflets.

The optimal size and graft type to be implanted were evaluated on the basis of the prediction of three measurable postoperative parameters:

- Height of coaptation ratio ($H_C{}^R = H_C/Sh \times 100$), defined as the level of the sinus height where the coaptation occurs (H_C, highlighted in Fig. 3a) correlated to the total sinus height, Sh.
- Length of coaptation ratio ($L_C{}^R = L_C/Lh \times 100$), defined as the effective coaptation length (L_C, highlighted again in Fig. 3a) correlated to the leaflet height, Lh.
- Displacement of coaptation (D_C), which should represent a marker of the asymmetric coaptation as it is defined as the distance of the central point of coaptation from the ideal geometric center (see Fig. 3b).

According to the pre-study transthoracic echocardiographic evaluation on patients without aortic valve disease, the most physiological postoperative conditions were identified for: (a) $H_C{}^R$ approaching 100%; (b) $L_C{}^R$ approaching 40%; and (c) minimal D_C.

Results

Based on the results obtained relative to a dilated aortic root of one specific patient, the finite element predictive model showed how the use of a different type and size of graft could have significant influences on the postoperative parameters.

Both $H_C{}^R$ and $L_C{}^R$ were gradually decreased as the graft size was increased (Fig. 4a and b), with the trend being similar regardless of the graft type considered. The value of D_C (Fig. 4c) - and thus the grade of asymmetric coaptation - was conversely reduced as the graft size was increased. In addition, the Valsalva graft appeared to warrant a significant reduction in D_C (Fig. 5) compared to the standard straight graft (Fig. 6), for any size comparison.

According to criteria described previously, a Valsalva graft of 28 mm was identified as the optimal solution. Interestingly, this was used by the surgeon, who was blinded to the results of the numerical simulations, while the engineers were blinded to the surgeon's choice.

The comparison between in-vivo postoperative echocardiographic measurements (both $H_C{}^R$ and $L_C{}^R$) revealed a good match with the FEA prediction.

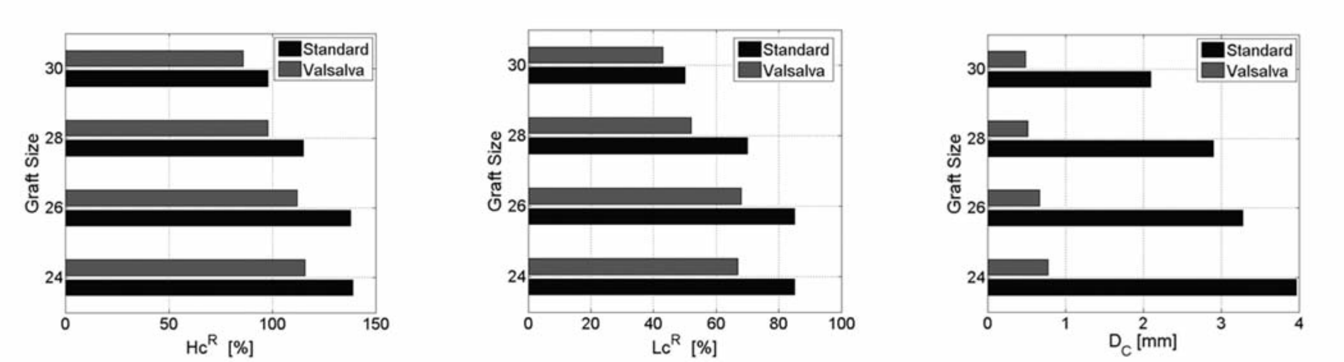

Figure 4: a) Postoperative simulation. Trend of $H_C{}^R$ according to different type and size of graft. $H_C{}^R$: Height of coaptation ratio (see Materials and methods for definition). b) Postoperative simulation. Trend of $L_C{}^R$ according to different type and size of graft. $L_C{}^R$: Length of coaptation ratio (see Materials and methods for definition). c) Postoperative simulation. Trend of D_C according to different type and size of graft. D_C: Displacement of coaptation (see Materials and methods for definition).

Discussion

The preliminary experience of the development of a patient-specific application of FEA to optimize the choice of graft size and type during AVS procedures, thus enhancing postoperative outcome, are reported.

Introduced by David in 1992 (1), the so-called 'valve-sparing' procedures were designed to treat aortic valve insufficiency caused by aortic root dilatation, while preserving the native valve leaflets. The original technique, as described by David, included excision of the aortic root and suturing the native aortic valve inside a cylindrical straight polyester graft. Hence, the technique became popular a 'reimplantation' rather than the 'remodeling' approach that was introduced by Pepper and Yacoub (15) but which did not include reimplantation of the valve inside a graft and, consequently, was reserved for patients without annular dilatation.

Since the lack of Valsalva sinuses has been considered to be a principal cause of suboptimal postoperative results following the reimplantation procedure, further evolutions of this technique have focused on re-creating the physiological function of the Valsalva sinuses. In this respect, Cochran et al. (2) and David (3) presented modified versions of the original techniques that were aimed at restoring the shapes of the sinuses, by using additional sutures. Finally, in 2000 De Paulis et al. (4) introduced a technique that was based on a dedicated graft; this was referred to as a Valsalva graft, and was characterized by a self-expandable region obtained by a 90° rotation of the Dacron corrugations, so as to re-create the Valsalva sinuses.

Based on satisfactory short- and long-term results (16), AVS surgery has become recognized as an effective and extremely useful procedure, even in

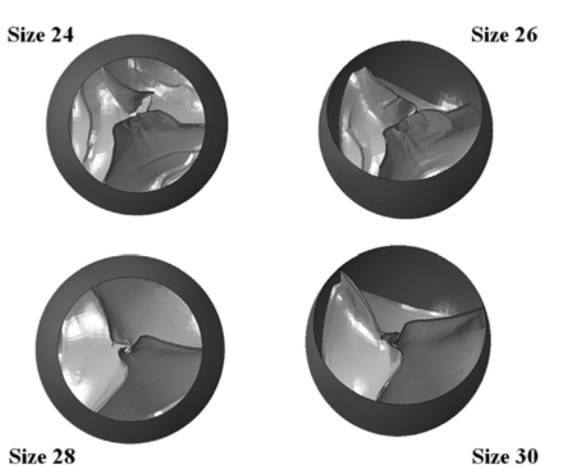

Figure 5: Computer-based simulation results of AVS procedure using Valsalva graft size from 24 mm (upper left) to 30 mm (lower right).

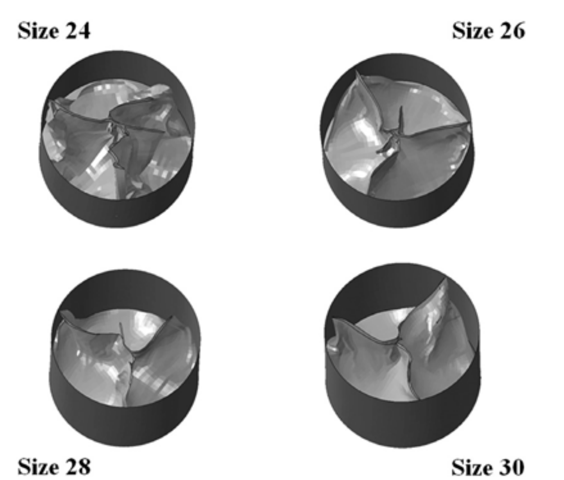

Figure 6: Computer-based simulation results of AVS procedure using standard graft size from 24 mm (upper left) to 30 mm (lower right).

suboptimal series of patients such as those with Marfan syndrome (17). Certain technical aspects related to AVS, however, remain the subject of debate, such as the choice of the shape and size of the Dacron graft - a choice that David and Feindel (1) defined as "…more art than science".

Several studies have reported the pitfalls associated with selecting a better size of graft. For example, Svensson (5) proposed sizing the graft based on an oversizing of the ideal left ventricle outflow tract size, while Maselli et al. (6) introduced a normogram that was based on a mathematical model and took into account the leaflet size; this latter approach should be helpful when calculating the grade of graft oversizing with respect to the aortic annulus dimension (18). However, all of the above-described methods - as well as those of Morishita et al. (7) and Kollar et al. (8) - were based on intraoperative measurements and permitted only an intraoperative selection of the graft. Hence, the decision was taken to evaluate the potential of preoperative prediction of the optimal graft size using FEA.

FEA is a numerical technique for finding approximate solutions of partial differential equations (19,20), and which has been applied to cardiovascular medicine since the late 1990s in order to better understand the pathophysiology of the aortic valve (9). Subsequently, FEA has been focused on the evaluation of the mechanism of aortic insufficiency in complex aortic root pathology (10,11) and, finally, the application of mathematical models has been tested to evaluate the results of surgical procedures in the treatment of aortic root diseases.

Grande et al. (20) had shown previously, by using FEA, that the re-creation of sinuses is important following valve-sparing procedures. This study was focused mainly on the stress/strain distribution in the leaflets and in the aortic wall, and showed that the re-creation of sinuses brought the leaflet stresses closer to normal, but did not provide any further specification. Their results were consistent with the present findings, which confirmed that postoperative physiology is better preserved when using a Valsalva graft.

In contrast, Soncini et al. (21) compared root physiology following a 'remodeling' or a 'reimplantation' technique by using a model that was based on both the closing and opening phases of the valve, and also focused on postoperative leaflet coaptation. Despite showing that a scalloped graft used in the 'remodeling' technique would better preserve the physiological kinematics of leaflets and the extension of the coaptation area, the model of Soncini et al. was not patient-specific, and neither was the Valsalva graft considered for the 'reimplantation' technique. Interestingly, these authors introduced the concept of a dislocation of the nodule of Arrantius as a marker of non-physiological closure of the valve.

To date, however, FEA has not been used to obtain a prediction of postoperative patient-specific results. Consequently, the innovative aspect of the present study consisted of extending the application of finite element models from a descriptive and diagnostic area to an extremely more complex (but potentially valuable) area of predicting surgical results in a patient-specific relationship.

It is believed that the present findings represent an ideal evolution of previous studies, as they have confirmed that a surgical technique which can be used to reconstruct Valsalva sinuses (as in the present study with the use of a Valsalva graft) is preferable as it leads to a more physiological and symmetrical valve closure.

The results of the present study also showed that it is possible to move towards an straightforward preoperative patient-specific identification of the best graft size that is not always easy to identify intraoperatively, as it can be influenced by many factors related to the native aortic root and valve (22). Moreover, the study results were consistent with previous considerations by Maselli et al. (18) with regards to the need of an optimal graft choice to avoid not only a reduced leaflet coaptation (in the case of excessive oversizing) but also contact between the leaflet and the sinus wall during valve opening (in the case of limited oversizing).

Study limitations

The present study incorporated certain limitations common to other FEA-based studies. First, the finite element model did not include any specification on tissue anisotropic elastic properties, and neither was any fluid-structure interaction considered; consequently, no information could be provided regarding retrograde blood flow in the case of aortic valve insufficiency. With regards to the patient-specificity of the model, as echocardiography is heavily operator-dependent and echocardiographic measures might be affected by meaningful errors, encouraging results have been obtained by using computed tomography images to create a patient-specific geometric model of the aortic root, and this should represent a key factor for moving forwards in this direction. Finally, when evaluating the postoperative physiology of the aortic root, certain parameters were applied that had not been validated previously, in an attempt to translate as a numeric variable the grade of asymmetry of leaflet coaptation. Clearly, future developments are necessary in order to further validate the parameters introduced in the present study.

In conclusion, the present study results have clearly confirmed that the application of FEA should be moved forwards to an evaluation of the results of medical procedures. Patient-specific predictions of the surgical procedure, as demonstrated recently with cardiology interventional procedures (23-25), might represent a key factor in future surgical decision-making processes aimed at optimizing the postoperative outcome. Further studies in this respect should, therefore, be encouraged.

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