Flat or Curved Pericardial Aortic Valve Cusps: A Finite Element Study

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Background and aim of the study: **The finite element method (FEM) has frequently been used to investigate the behavior of the aortic valve, but studies on the performance and behavior of free-hand autologous pericardial aortic valves reconstructed using specially designed valve molds have not been performed. The study aim was to demonstrate the effectiveness of a three-dimensional (3-D) cusp of the authors' design (H-Mold) versus a two-dimensional (2-D) (flat) cusp using a FEM to compare stress distribution and leaflet contact properties.**

Methods: **Solid models of the aortic root and valve cusps were constructed using a computer-aided design package. All models had different free edge lengths and surface areas, but a constant leaflet attachment length corresponding to a 19 mm annulus diameter. A static pressure of 80 mmHg was applied to all models.**

Results: **The maximum von Mises stress value in the H-Mold at the cusp commissure was 34.5% lower than the stress value in the flat leaflet, while the contact area in the H-Mold leaflet was 85.7% greater than that of the flat leaflet. The length of leaflet free edge greatly influenced maximum von Mises stress intensity at the commissures, and the contact area between leaflets was mainly affected by the geometric shape of the leaflet and its surface area.**

Conclusion: **3-D leaflet geometry was found positively to influence leaflet stress distribution and coaptation. This geometry should have a significant impact on the reliability and long-term durability of pericardial aortic valve reconstruction.**

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Since the early days of cardiac surgery, human pericardium has been used to repair the aortic valve. The availability, ease of handling, lack of antigenicity, and low cost of autologous pericardium should - at least theoretically - be superior to that of present-day prostheses. Flat pieces of autologous pericardium have been trimmed in different two-dimensional (2-D) shapes to replicate aortic cusps (1), and implanted in patients either free-hand or mounted intraoperatively into a stent (2). No attempt was made to reproduce the normal configuration of the aortic leaflets. Previously, a surgical technique was described for free-hand aortic valve replacement with autologous pericardium molded with a curved shape (3). Although the clinical results obtained were satisfactory, this curved mold did not reflect the correct geometry of the normal aortic leaflets. Progressive changes were introduced until a more anatomic, three-dimensional (3-D) mold (H-Mold) was developed (United States Patent No. 6,491,511). Given the technical difficulties in an in-vivo study of whether cups fashioned with this H-mold were mechanically superior to a flat model, a finite element method (FEM) study of the two types of leaflets was designed.

Recently, Grande et al. (4) reported a FEM study of the human aortic valve and root under normal and abnormal conditions. These authors also used FEM to investigate the effect of aging on the mechanical performance of the aortic root (5), aortic root dilatation (6), and the importance of the sinuses of Valsalva (7).

To date, however, no study has been reported on the mechanical behavior of molded pericardial cusps designed to be sutured free-hand into an aortic root. Neither is any information available on the contribution of cusp shape and dimensions on valve stress variations. It was hypothesized that the most anatomically correct leaflets should perform better and, consequent-

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ly, increase their durability. Thus, a simple FEM was applied to investigate and compare the stress distribution of aortic valve leaflets constructed with 2-D and 3-D molds.

Materials and methods

Valve leaflet modeling

A computer-aided design package (Pro/Engineer; PTC, Inc., Needham, MA, USA) was used to create four aortic valve leaflets of different curvature, surface area, and free edge length. Model 1 was completely flat with a surface area of 261.24 mm^2, and the other three models were curved, with a progressively larger surface area. The surface area was 291.48 mm^2 in model 2, 272.87 mm^2 in model 3, and 320.65 mm^2 in the H-Mold (Table I). In order to ensure uniformity for purposes of comparison, the various leaflets were fitted into 19-mm diameter aortic roots.

The aortic root was constructed assuming a simplified aortic wall as a cylinder with three protruding symmetrical sinuses. Although the aortic root has three asymmetrical sinuses of Valsalva, the sinuses were created using three symmetrical ellipsoidal revolutions to simplify the model. The position of the axis of revolution and the axis of the ellipses were adjusted to correspond to the sinus dimension ratio given by Swanson and Clark (8). The excess ellipsoidal surface at the cylinder's inner side was cut away, leaving three bulges protruding from the cylinder's wall. The dimensions of the constructed sinus of Valsalva followed the data from Thubrikar (9). For an aortic root base of 9.5 mm radius (Rb), the sinus radius was 13.87 mm (1.46 × Rb) and 16.72 mm (1.76 mm × Rb) for the sinus height. Fillets of 4 mm radius were placed between the sinuses and the aortic wall (Fig. 1a) to improve the similarity of the model with the natural aortic root and to avoid any region of stress concentration on the aortic wall.

The H-Mold surface model was created first. Only one of the cusps was used and fitted into the aortic wall. Because a symmetrical aortic root was assumed during simulation, only one cusp of the full aortic root was modeled. From the intersection of the H-Mold leaflet with the aortic wall, a 3-D datum curve was constructed to mark the intersection line (Fig. 1b). This datum curve represented the line of leaflet attachment to the aortic wall. All subsequent models had a similar attachment line. The attachment length of all the aortic leaflets was 22.6 mm. The flat leaflet was created with the same line of attachment as the H-Mold. This leaflet was created to model a pericardial leaflet constructed from a flat template mold. A surface was extruded from the wall of the aortic valve and passed through the attachment line (datum curve) to create the leaflet surface. The flat leaflet had 180° leaflet opening angle (α) and a flat free edge. The general description of the flat leaflet construction is illustrated in Figure 1b.

Besides the H-Mold and the flat model generation, two intermediate models (models 2 and 3) were generated. Their leaflet opening angle ranged between those of the flat and the H-Mold. The leaflet opening angles (α) for models 2 and 3 were 140° and 160°, respectively. The main purpose of generating these intermediate models was to investigate the effect of progressive variations in surface area from the profile of the flat model (α = 180°) toward the modified H-Mold design (α = 120°). All leaflets models had the same leaflet attachment line. The difference between models was that, instead of making one straight extrusion, two extrusions at predefined leaflet opening angles were made from the attachment line (Fig. 1c). The extruded surfaces met at the center and joined together to create a complete leaflet (Fig. 1c). Details of the surface area, free edge length, and von Mises stress of the various models are listed in Table I.

Model assumptions and boundary conditions

The material property of the human pericardium was assumed linear isotropic because it has been found to exhibit a negligible anisotropic characteristic (10). Although the circumferential modulus of elasticity for the aortic wall was slightly different from its radial elasticity, the study assumed that the aortic wall exhibited isotropic material property. Young modulus and Poisson ratio for treated human pericardium and aortic wall were obtained from various reports (5,9-11). The material properties and thicknesses assigned to the models are listed in Table II.

To simulate the coaptation between leaflets, a wall

Table I: Leaflet model area, free edge length, and von Mises stress comparison.

Model	Surface area (mm^2)	Free edge length (mm)	von Mises stress (MPa)	% von Mises stress
Flat	261.24	16.42	0.371	100.00
Model 3	272.87	16.70	0.355	95.69
Model 2	291.48	17.46	0.303	81.67
H-Mold	320.65	21.00	0.243	65.50

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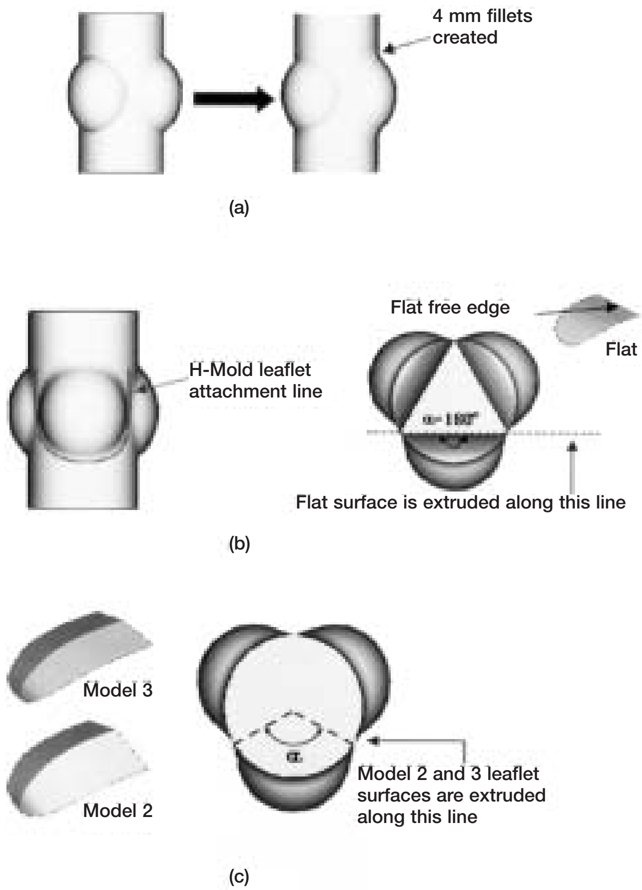

Figure 1: Modeling of aortic valve. a) Creation of sinus fillets; b) flat leaflet construction; c) model 2 and 3 leaflets.

was created at the position where the leaflets should meet (Fig. 2a). Frictionless contact behavior (μ = 0) was set between the leaflets and the aortic wall to mimic the sliding contact behavior between leaflets. The upper and lower annulus rings of the aortic root were constrained in the up-and-down direction (z direction). This situation corresponded to the condition of the aortic wall, which was only allowed to expand radially when blood flowed through it. The locations of the upper and lower annulus rings are shown in Figure 2b. A symmetrical boundary condition was assigned at the symmetry plane of the models (Fig. 2c). This symmetry boundary condition was necessary because the finite element analysis was only carried

Table II: Material properties.

Property	Leaflet	Aortic wall
Thickness (mm)	0.5	1.0
Behavior	Isotropic	Isotropic
Young modulus (MPa)	0.9	6.0
Poisson ratio	0.45	0.45

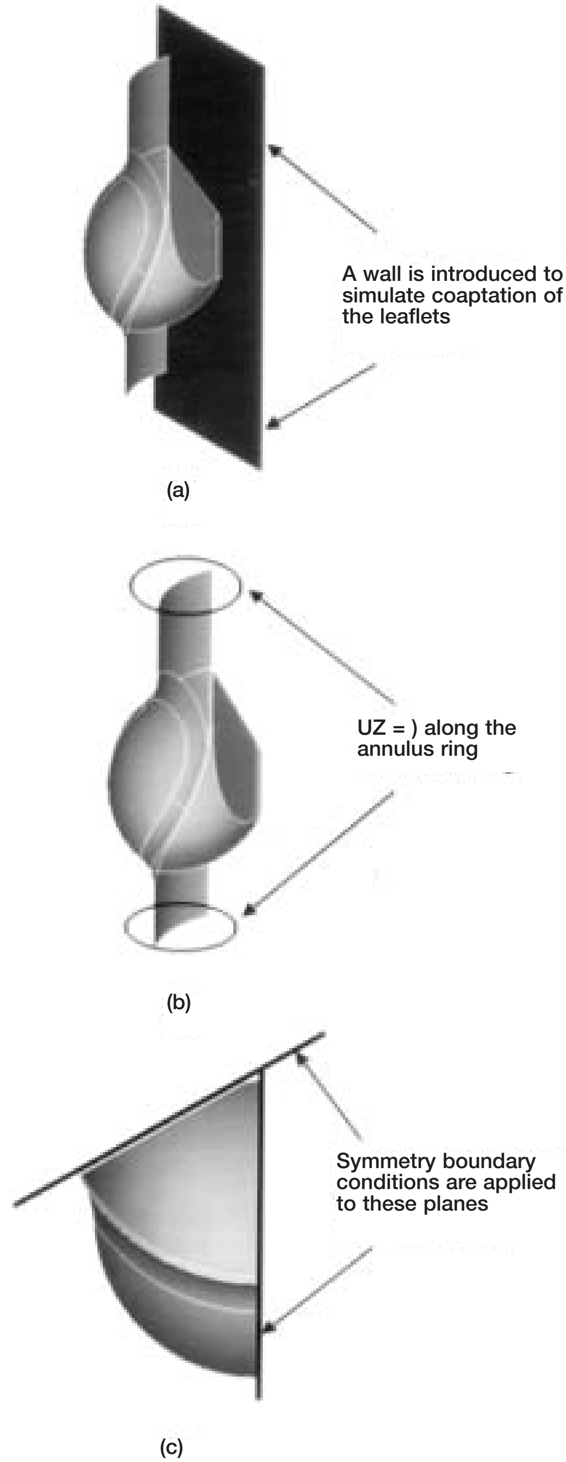

Figure 2: Application of boundary conditions. A) Introduction of wall to simulate contact between the leaflets. b) The annulus rings were constrained in the z direction. c) Symmetry boundary conditions applied to simulate full aortic root loading.

out on the one-sixth aortic root model. A uniform normal pressure load of 80 mmHg was applied to the aortic surface of the valve to simulate the working conditions at end-diastole.

Solution method

Finite element analyses of the models were carried out using the mechanical university high version of ANSYS 5.7 (ANSYS, Inc., Canonsburg, PA, USA) running on an SGI Origin 2000 platform server operating at the Center for Advanced Numerical Engineering Simulation (CANES) at Nanyang Technological University, Singapore. For analysis of the models, static large displacement analysis mode was chosen, and the iteration method was set to Full Newton-Raphson with load increments of 150 to 200 sub-steps.

Results

The region of maximum stress concentration on the leaflets occurred at the commissure. Although all models had their maximum stress region at the commissure, the quantitative values were very different (Table I).

The results illustrated the superiority of the H-Mold compared with the flat leaflet. In terms of maximum von Mises stress, the H-Mold showed a reduction of up to 34.5% at the leaflet commissure. The reason for the higher commissural stress in the flat model versus that in the H-Mold was the difference in displacement that the leaflets must travel before reaching their equilibrium position. Because the flat leaflet was positioned further back from the coaptation wall than the other models, it required a larger displacement when pressurized. Hence, as displacement is proportional to in-plane stress, the flat leaflet would experience higher stress.

A closer examination of the von Mises stress distribution on the leaflet models is shown in Figure 3. This suggested that the von Mises stress reduction may be related to stress distribution on the aortic wall. The stress distribution on the flat model showed that the leaflet had a limited stress-bearing area near the sinus region, whereas in the H-Mold the stress bearing area extended to the entire aortic wall structure. Thus, progressive modification of the flat leaflet towards the H-Mold leaflet appeared to improve the role of the aortic wall stress-sharing effect, thus reducing stresses on the entire leaflet area, especially at the commissures.

The leaflet free edge length also affected the von Mises stress distribution over the leaflet; free edge lengths with respect to increasing von Mises stress are summarized in Table I. These data indicated that, as the leaflet free edge length increased, the von Mises stress at the commissure decreased. Observation of the leaflet's closing process showed that the free edge length always experienced maximum displacement when the leaflet was loaded. It is clear that the leaflet's free edge length would determine a higher strain than the other areas. Because the commissure is the attachment point of the free edge to the leaflet wall, the high strain generated by the free edge length would significantly build up stress at the commissural area. Thus, an increase in leaflet free edge length would reduce its strain and, subsequently, the stress at the commissure.

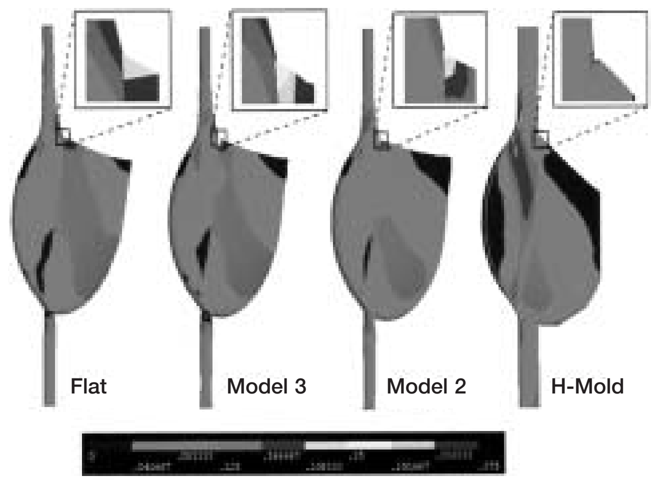

Figure 3: Contours of von Mises stress distribution on models with maximum stress insets. The color code bar shows the von Mises stress ranges of the models (in MPa).

Table III: Contact area comparison.

Model	Contact area (mm^2)	% Contact area	Leaflet surface area (mm^2)	% Leaflet surface area
Flat	37.21	100.00	261.24	100.00
Model 3	44.78	120.34	272.87	104.45
Model 2	56.18	150.98	291.48	111.58
H-Mold	69.09	185.68	320.65	122.74

The coaptation area of the leaflets was gradually increased from the flat leaflet to the H-Mold leaflet (Table III). Coaptation area enhancement was clearly due to the modification in leaflet shape and increased surface area - that is, the closer the geometric shape of the leaflet to the native valve, the better the coaptation area. A large coaptation area was considered desirable as it offered an effective sealing during valve closure and, therefore, better valve competence.

Discussion

Four different aortic valve leaflet models were constructed using different molds, and then studied with FEM. The geometry of the valve leaflets ranged from flat to 3-D designs. The attachment length of each model was kept constant, but the surface area and free edge length varied. To simulate the leaflet's coaptation conditions, a static pressure of 80 mmHg (0.01 MPa) was applied to close the valve. After pressurization, leaflet stress and coaptation characteristics of the different leaflet models were compared and analyzed. Analysis of the models revealed several important findings. First, after loading the aortic leaflets, two stress concentration regions developed, at the aortic leaflet commissure, and at the belly. Second, two geometric parameters were found to affect the stress intensity at the commissure, leaflet belly, and pressure distribution on the aortic root.

Elongation of free edge length reduced stress intensity at the leaflet commissure and over the entire leaflet surface. As the free edge length increased, the commissural and overall leaflet stresses were reduced because the aortic wall shared more stress.

Increases in leaflet surface area reduced the maximum von Mises stress intensity at the leaflet belly. These results suggested that the effective load bearing region of the aortic leaflet was mainly on the belly, and that the leaflet surface area significantly influenced the leaflet coaptation area. Shaping the leaflet geometry to resemble the native aortic cusps would improve leaflet coaptation area.

Comparison between the H-Mold leaflet and the flat leaflet showed the former to have a better overall performance in terms of maximum von Mises stress at high stress regions (commissure and belly) and contact area between leaflets. This comparison also showed that commissural stress in the H-Mold leaflet was 34.5% lower than in the flat mold leaflet, while the contact area in the H-Mold was twice that of the flat leaflet.

Taken together, these findings suggest that the aortic leaflet geometry has a significant impact on the aortic valve von Mises stress distribution and leaflet coaptation properties. Leaflet designs closer to the natural valve should have an important impact on the efficacy and durability of pericardial aortic valves.

Study limitations

As in all finite element analyses, a number of design and material properties must be incorporated into the model. The present study assumed an aortic root with symmetrical sinuses of Valsalva, knowing that the natural root has asymmetric sinuses. This assumption simplified the modeling and analysis by solving one-sixth of the model, and reducing computation time. In addition, the study simulated only the full closure and thus could not predict the opening behavior of each model.

It was also assumed that the material properties of the leaflet and aortic wall were isotropic with uniform thickness, though the thickness of the native leaflet and aortic wall varied with anisotropic modulus of elasticity. For example, the native aortic wall at commissural level was thicker and more fibrous, and therefore better to sustain higher stress. Stress data in the present study might be higher than normal values. The anisotropic behavior of the pericardium was not considered as it has been reported that the orthogonal modulus difference is negligible (10). Similarly, the aortic wall is anisotropic, but was assumed isotropic in the present study. In addition, the induced bending 'pre-stress' in the leaflets during molding was not considered. However, the purpose of the present study was not to calculate the exact stress values of the native aortic valve but rather to identify the best possible leaflet design of a stentless pericardial aortic valve. The comparison between all four models should be valid as all were studied under the same experimental conditions.

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