A numerical model for the analysis of the mechanical behaviour of a leaflet valve prosthesis

A numerical Model for the Analysis of the Mechanical Behaviour of a Leaflet Valve Prosthesis

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INTRODUCTION

For the design study of an improved leaflet valve prosthesis, the quasi-static mechanical behaviour of the Hancock valve prosthesis has been studied in a numerical model. This model was formulated using basic information on such a valve as obtained in earlier studies [1,2]. Modification of the numerical model gives the possibility to forecast the influence of design parameters for the stress distribution. The prediction of the model on the relation between hydrostatic pressure and changes in geometry of the valve prosthesis were compared with an experimentally determined relation.

DESCRIPTION OF THE MODEL

The Hancock prosthesis (250 Aortic,23) is a so-called porcine bioprosthesis (figure 1). It consists of a glutaraldehyde-treated porcine aortic valve, mounted in a polypropene frame. The prosthesis is implanted in the patient by means of a sewing ring. Sewing ring, frame and a small part of the porcine valve are covered with Dacron cloth. For this valve prosthesis a 3-dimensional, geometrically nonlinear model has been developed, using the finite element program MARC [3]. The valve frame is modelled with 2-node beam elements. The thin leaflets of the porcine valve which are reinforced with relatively thick bundles of collagen are modelled with 4-node membrane and 2-node truss elements ,as described by Sauren [4].The sinus wall tissue between leaflets and frame is modelled with membrane elements. All elements have linear elastic material properties. (Young's moduli: frame:1500 N/mm^2, leaflet membrane:2 N/mm^2, collagen bundles:25 N/mm^2). Furthermore it is assumed that the base of the prosthesis is fixed in all directions and that the prosthesis geometry has 120 deg symmetry. Because also the leaflet is symmetrical, only 1/6 part of the valve has to be modelled. The mesh is given in figure 2. The valve is submitted to a uniform pressure load.

RESULTS

The main result of the numerical model is the computed distribution of the maximum principal stresses in the valve prosthesis. Figure 3 shows such a distribution along the lines AE and BF at a pressure load of 12.2 kPa. From this figure it can be seen that the highest stresses, which are directed along the bundles, are located in the collagen bundles. To be able to verify the model experimentally, the displacements of the nodes in the vicinity of the frame top are related to the pressure load. The results on the radial displacements of the nodes 11,21,22 and 16 are shown in figure 4. In this figure, node 11 represents the real frame top and the nodes 21,22 and 16 represent the tissue beneath that frame top. The maximum displacements at 12.2 kPa pressure load are: 2.8,5.2, 6.3 and 5.2 percent for the nodes 11,21,22 and 16 respectively. These values are percentages of the constant valve radius.

EXPERIMENTAL VERIFICATION

The numerically obtained relations between the pressure load and the radial displacements of some nodes in the vicinity of the frame top are compared with experimental relations. The experimental relations are determined as follows. The valve prosthesis is mounted in a rigid valve house (figure 5) such that the base of the valve is fixed. Hydrostatic pressure is applied to the closed valve prosthesis by means of a fluid column the height of which is controlled using a pumping device. First, the pressure load increases quasi-statically up to a level of 19.9 kPa, immediately followed by a decrease until 1.4 kPa. The displacement of the tissue just beneath the frame top corresponding to this pressure variation is determined for each frame top using an inductive measuring technique as developed by van Renterghem [5]. This measuring device consists essentially of 2 small electrical coils. One coil is sutured to the tissue just beneath the frame top whereas the other coil is glued to the nearest opposite wall of the valve house (figure 5). The coil on the valve house transmits a time varying magnetic field which induces a voltage in the coil on the frame top. From the induced voltage the distance in between the 2 coils is derived. In figure 6 a typical pressure-displacement relation is shown. From this figure it can be seen that the pressure-displacement relation shows a remarkable hysteresis loop. The mean displacement of the tissue beneath the frame top at a pressure load of 12.2 kPa, is 5.3,5.4 and 6.5 percent for the 3 tops respectively.

DISCUSSION AND CONCLUSIONS

From this study, it is concluded that the agreement between the numerical and experimental results for the displacement of the tissue beneath the frame top is fair. However some remarks have to be made. Experimentally a hysteresis loop was observed. This possibly can be explained by the viscoelastic material behaviour of frame and leaflet. The difference between the experimentally determined radial displacements of the 3 frame tops is probably mainly caused by the fact that the real valve lacks the symmetry as assumed in the numerical model. In conclusion it can be stated that a reliable numerical model of a leaflet valve prosthesis under quasi-static pressure load has been developed. Although some adjustments have to be made in order to get a better agreement between numerical and experimental results, this model is a useful tool for analyzing the mechanical behaviour of the leaflet valve prosthesis. It permits to build in design specifications to study the influence of these specifications on the stress distribution in the valve prosthesis. This will be the object of the research in the future.

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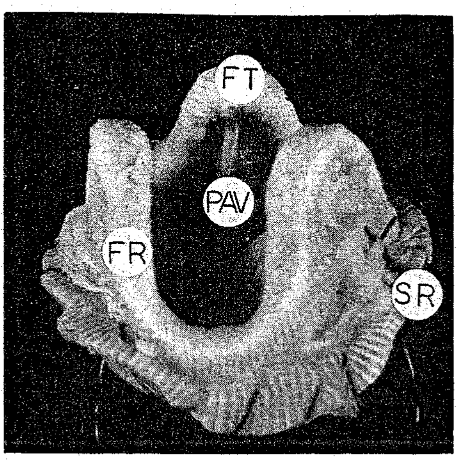

Figure 1 : The considered leaflet valve prosthesis (Hancock 23-Aortic).
PAV = Porcine Aortic Valve
SR = Sewing Ring
FT = Frame Top
FR = Frame

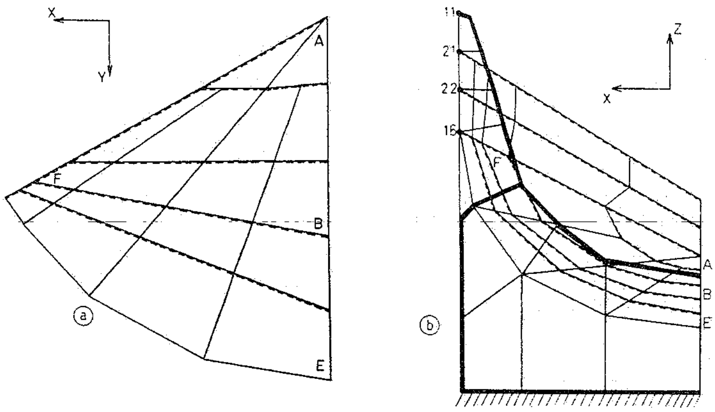

Figure 2 : The mesh for the numerical model.a: view from the upper side showing the leaflet including the bundle structure.b: side view in which also the contour of the frame is visible. ---- truss elements, ―― beam elements (frame). Numbered nodes are referred to in text.

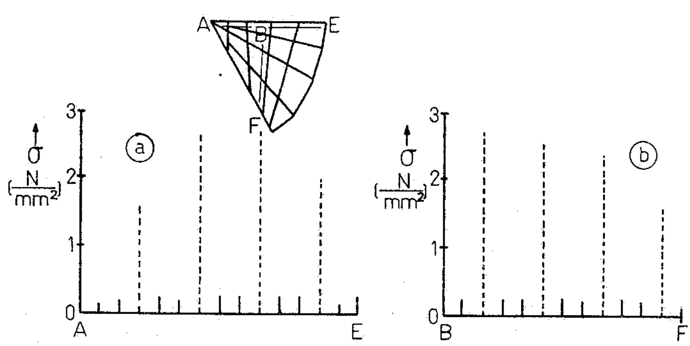

Figure 3 : Stress distribution in the valve leaflet.a: stresses along line AE. b: stresses along line BF. The maximum normal stresses in the membranes are denoted with a solid line while these in the trusses are given with a dotted line.

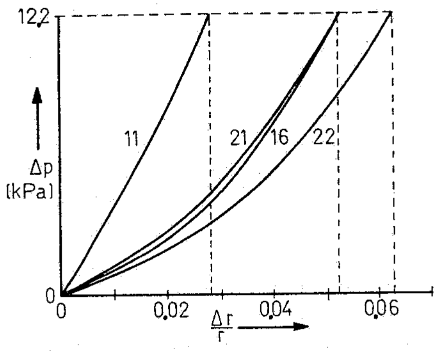

Figure 4 : The relation between the pressure load of the valve and the computed radial displacements of the nodes 11,21,22 and 16. The latter 3 nodes are located just beneath the frame top (figure 2).

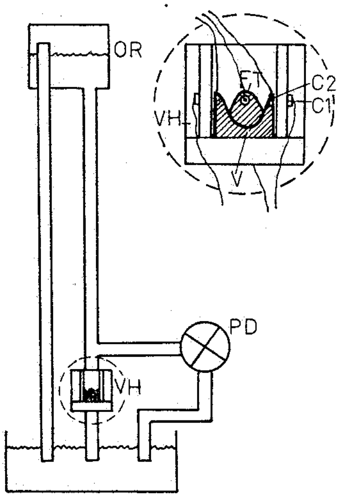

Figure 5 : The experimental set-up.
OR = Overflow Reservoir
PD = Pumping Device
VH = Valve House
C1 = Coil on the valve house
C2 = Coil on the tissue beneath the frame top
FT = Frame top
V = Valve

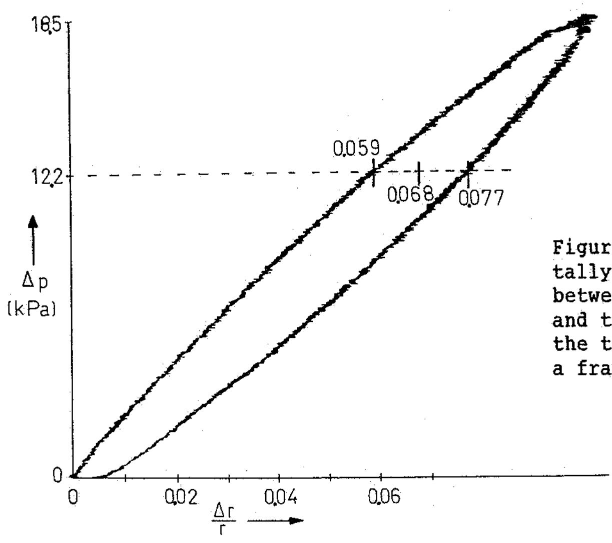

Figure 6 : Typical experimentally observed relation between pressure load and the displacement of the tissue just beneath a frame top