Radiographic Assessment of Leaflet Motion of Gore-Tex Laminate Trileaflet Valves and Hancock Xenograft in Tricuspid Position of Dogs

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SUMMARY Six samples of various thicknesses of Gore-Tex compounds were fashioned into trileaflet valves. A radiopaque marker was placed on the center of the free margin of each cusp, and the prostheses were implanted in the tricuspid position of dogs. Two Hancock valves were studied for comparison. Catheterization revealed that the hemodynamic function was normal in all valves tested. High-speed radiography permitted analysis of leaflet movement throughout the cardiac cycle. Of the six Gore-Tex valves, five opened completely. The cusps of these five valves were fabricated from 4, 6, 8, 10, and 12 layers of Gore-Tex film. The remaining valve, which was fabricated from 15 layers of Gore-Tex film, and both porcine xenograft aortic valves did not open completely. We postulate that the laminates of 12 layers or less of Gore-Tex film are suitable for further study to evaluate their potential applicability in trileaflet cardiac valve prostheses.

SUBSTANTIAL EFFORT has been directed toward duplicating the natural aortic valve configuration as a model for the ideal valve substitute. Minimal flow resistance and turbulence are the principal theoretic advantages of the central orifice design. In practice, however, once the pathologic processes responsible for leaflet stiffening occur, these hemodynamic benefits are lost and function deteriorates. Hence, the question is raised whether the use of materials, which are initially "too stiff" for valve cusp construction, might likewise contribute to valve failure.

Increasing evidence supports the concept that the longevity of a leaflet-type heart valve substitute depends not only on the mechanical strength and biological and chemical characteristics of the materials employed but also on the design, especially the mode of valve function in vivo. Hydrodynamic function of a model aortic valve has been investigated with a pulse-duplicator, or an in vivo ultrasonic technique. We believe that further progress toward a rational choice of an appropriate leaflet material requires documentation of the valve performance characteristics in the beating heart.

In this study, we used stented trileaflet valves fabricated of Gore-Tex laminate. Gore-Tex (or expanded polytetrafluoroethylene) is a new synthetic material that possesses high tensile properties. Its biocompatibility has been studied in arterial and venous grafts. Additionally, Gore-Tex laminate allows use of materials with a wide range of thickness. We used porcine xenograft aortic valves for comparisons. The purpose of this paper is 1) to describe the initial function of these valves in the tricuspid position of dogs assessed by radiopaque markers and high-speed X-ray techniques; 2) to define the thickness of Gore-Tex laminate that is optimal for a flexible leaflet prosthesis; and 3) to discuss the implications of hemodynamics for adequate long-term function.

Material and Methods

Gore-Tex laminate is manufactured by W. L. Gore and Associates. A single film of this polymer, 0.003-mm thick, consists of nodules and fibrils of polytetrafluoroethylene (PTFE) and has uniaxial tensile strength that parallels the fibril content. The tensile strength of a single film is 60,000 psi — approximately 20 times that of conventional PTFE. For use as valve leaflets, several films are laminated in diverse directions to compensate for the absence of the tensile strength in the cross-directional axis and to add strength. The Gore-Tex laminate is nonporous and transparent, unlike the Gore-Tex vascular prosthesis, which is microporous and snowy white. The number of laminated films used in each valve leaflet studied determines the thickness, strength, and stiffness. Six samples constructed from laminates of 4, 6, 8, 10, 12, and 15 layers of Gore-Tex film were studied. These samples ranged from 0.008 to 0.031 mm in thickness as a result of compression during the laminating process.
Each of the sample materials was fashioned into a stented trileaflet valve. The support frames of a cloth-covered titanium ring with three posts and a sewing collar attached to the base ring had the following dimensions: internal orifice diameter 20 mm, implantation diameter 26 mm, net height of the strut 12 mm, and total height of the valve 17 mm.

Two models of the porcine xenograft valve were studied: standard model (342 AV valve) and modified model (350 AV valve). In the latter valve, the right coronary cusp is replaced by a muscle-free noncoronary cusp of another animal. Both valves were size 27 mm: the internal orifice diameter was 20 mm, implantation diameter 35 mm, net height of strut 12 mm, and total height of the valve 22 mm.

Individual cusps of all valves studied were “tagged” with a radiopaque marker. A lead bead (1-mm diameter, 20-mg weight) was wrapped with a piece of Gore-Tex laminate sheet and secured by suture to the center of the leaflet-free edge (fig. 1).

Eight mongrel dogs weighing from 18 to 22 kg were used. With the aid of extracorporeal circulation, the tricuspid valve was excised, and the prosthesis was placed in such a way that the position of each prosthetic cusp coincided as precisely as possible with the position of the excised leaflets of the tricuspid valve. The porcine xenograft was inserted so that the right cusp or its alternative occupied the area of the posterior leaflet of the tricuspid valve. To facilitate orientation of the valve in the heart when viewed on the fluoroscope, the posterior leaflet region was marked with a metallic bead. The prosthesis was anchored in position by using several interrupted stitches and a single running suture.

When cardiopulmonary bypass was discontinued, the peak systemic arterial pressures were 120 mm Hg or higher in all instances. None of the dogs required administration of inotropic agents, and each remained in a stable state during the subsequent X-ray studies. The chest was closed in a routine fashion, and 3 to 4 hours after bypass, the dog was moved to the catheterization laboratory.

While the dog was lying supine in a 30° head-down position, the marker’s movement was recorded with high-speed X-ray facilities: 16-mm cinefilm (240 frames/sec) in three dogs and computer-compatible videotape (60 frames/sec) in five. The images of a circular valve stent were best obtained in the anteroposterior projection. After suitable films were obtained, the dog was repositioned on its side, and films were taken in the lateral projection. Excursion of each individual leaflet from the closed position was assessed by tracking the markers incorporated into the leaflets frame by frame on a stop-action apparatus. The images of the metallic valve stent seldom, if ever, changed their shape throughout an entire cardiac cycle in both anteroposterior and lateral projections and were useful as a landmark for spatial and temporal orientation of the center of the free margins of the cusp.

Concomitantly, catheterization was performed. Pressures in the right atrium and in the right ventricle were simultaneously recorded with transducers (Statham P23 Db) and were measured in centimeters of water. Selective angiography was made during injection of contrast medium (Renovist) into the right ventricle. Electrocardiogram was continuously monitored. When the study was completed, autopsies were done. All prostheses were found to be properly placed. Prosthetic leaflets were free from thrombi. There was no evidence that any anatomic structures of the right ventricle potentially interfered with free leaflet movement.

Results (table 1)

Electrocardiograms showed sinus rhythm in all eight dogs. Premature ventricular contractions were occasionally encountered. The heart rates were between 142 and 180 beats/min. The location of the markers at end systole invariably indicated a reasonable approximation of the free edges of the cusp. Ventriculography confirmed the competence of all beaded valves implanted.

Gore-Tex Laminate Valve

Analysis of the marker’s movement disclosed that the individual cusps commenced motion at various times during each phase of diastole and systole. Simultaneous movement of two cusps was not a rare event, but simultaneous movement of three cusps was never observed. The sequence of leaflet excursion was specific to each valve. An example of sequential cusp movement typically seen (case 3) is illustrated in figure 2. Early in diastole, the cusp located in the septal leaflet region begins to open. A moment later, the second and third cusps open sequentially. All three cusps made the maximal excursion during all cardiac cycles when the dog was in regular rhythm. The cardiac cycle associated with an extrasystole was easily distinguished from that during regular rhythm by the lack of uniformity in the marker’s movement (fig. 2). As expected, each of the three cusps generally showed some reduced excursion during extrasystole.

Sequential cusp movement was also observed during systole. The order of leaflet closure differs from the order of leaflet opening — namely, the cusp that began to close first was the cusp that opened last, and the cusp that closed last was the cusp that began to open first. This reverse relationship was maintained in every cardiac cycle during regular rhythm. Leaflet velocity was not always constant.

**Figure 1.** Beaded valve prosthesis. Small lead bead is sewn to center of each cusp-free edge. Left, Closed position (end-systole). Right, Fully opened position (end-diastole).
Movement was slow at the beginning and became progressively more rapid. This change of velocity was more noticeable in systole than in diastole.

Of the six Gore-Tex laminate valves, five opened completely. Cusps of these five valves were fabricated from each of the laminates of 4, 6, 8, 10 and 12 Gore-Tex films. Catheterization data confirmed normal valvular function (mean right atrial pressure less than 10 cm water). The sixth valve, which was fabricated from the laminate of 15 Gore-Tex films, did not open completely. The cusp located in the septal leaflet region started to open late in diastole, and its excursion varied appreciably from one cardiac cycle to another. Presumably, the anisotropy of leaflet excursion reflects the altering cardiac output in response to respiratory movement. The movement of the other two cusps was excellent. Both of them began to open at a relatively early

### Table 1. Data Pertinent to the Tests on Beaded Valves

<table>
<thead>
<tr>
<th>Valve Description</th>
<th>Thickness (mm)</th>
<th>Heart rate (beats/min)</th>
<th>RAP mean (cm H2O)</th>
<th>RVP (cm H2O)</th>
<th>Regurgitation in ventriculogram</th>
<th>No. of cusps with limited mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gore-Tex trileaflet valve</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 4 layer</td>
<td>0.008</td>
<td>180</td>
<td>7/3 (5)</td>
<td>35/-2, 5</td>
<td>No</td>
<td>0</td>
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<tr>
<td>2 6 layer</td>
<td>0.013</td>
<td>176</td>
<td>14/8 (10)</td>
<td>33/0, 10</td>
<td>No</td>
<td>0</td>
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<tr>
<td>3 8 layer</td>
<td>0.015</td>
<td>142</td>
<td>6/3 (4)</td>
<td>25/-4, -1</td>
<td>No</td>
<td>0</td>
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<tr>
<td>4 10 layer</td>
<td>0.019</td>
<td>177</td>
<td>9/0 (5)</td>
<td>40/-5, 5</td>
<td>No</td>
<td>0</td>
</tr>
<tr>
<td>5 12 layer</td>
<td>0.023</td>
<td>151</td>
<td>7/0 (4)</td>
<td>40/0, 0</td>
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<td>0</td>
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<tr>
<td>6 15 layer</td>
<td>0.031</td>
<td>164</td>
<td>10/-4 (3)</td>
<td>37/-2, 5</td>
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<td>1</td>
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<td>Heterograft aortic valve</td>
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<tr>
<td>1 Model 342 AV valve</td>
<td>144</td>
<td>7/2 (5)</td>
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<td>No</td>
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<tr>
<td>2 Model 350 AV valve</td>
<td>156</td>
<td>12/8 (10)</td>
<td>37/-3, 0</td>
<td>No</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: RAP = right atrial pressure; RVP = right ventricular pressure; systolic/lowest diastolic, end-diastolic.

**Figure 2.** Cinematograms of Gore-Tex laminate valve exhibiting sequential cusp movement. Films are reproduced from 16-mm motion picture (240 frames/sec) and oriented in clockwise direction (arrow). A, P, and S at top frame denote prosthetic cusps located in regions corresponding to anterior, posterior, and septal leaflets of tricuspid valve, respectively. In the bottom frame, complete valve opening is demonstrated. Inset shows film of end-diastole at extrasystole. Note that order of cusp closure differs from the order of cusp opening.
stage of diastole and made a maximal excursion in any cardiac cycle with regular rhythm. Despite incomplete valve opening, the hemodynamic measurements indicated normal valvular function.

**Porcine Xenograft**

No significant difference was noted between the standard model and the modified model. The characteristic pattern of movement of these valves at heart rates of 144 and 156 beats/min is shown in figure 3. Both valves opened incompletely. Only one cusp showed a rapid movement and demonstrated full excursion during each cardiac cycle with regular rhythm. The well-functioning cusp was identified as the left coronary cusp in the standard model and as the original noncoronary cusp in the modified model. These cusps were placed in the region of the septal leaflet and anterior leaflet of the tricuspid valve, respectively. The other two cusps showed little or no movement. In the standard model valve, one of these two cusps opened slightly during some cardiac cycles. It began to open late in diastole, and its excursion was markedly restricted. The remaining cusp showed no visible movement from the closed position.

The simultaneous pressure tracings of the dog with the standard model porcine xenograft are shown in figure 4. A slight increase in pressure gradient late in diastole was demonstrated, possibly explaining the delayed opening of this cusp. In the modified model bioprosthetic valve, only a single cusp functioned, and the role of the other two cusps in valve opening was virtually negligible. Despite remarkable dysfunction of the two cusps, the valve function was hemodynamically normal in both instances. The mean right atrial pressures were 5 and 10 cm of water, and end-diastolic pressure gradients were trivial. Values for right ventricular pressures remained within normal physiologic range.

**Discussion**

This study supports the concept that flexibility or elasticity is an important ingredient in the selection of an ap-
propionate leaflet material. The principal factors determining the hydrodynamic movement of a flexible leaflet are hydraulic stress in place and stiffness of the leaflet. Theoretically, the bending stiffness of plates is proportional to the thickness to the third power.

Experimental evidence indicates that the flexibility or the elasticity of a leaflet is more important when pressures are low. Studies of the stress/strain characteristics by Munth and co-workers demonstrated that the normal aortic leaflet has a marked elastic response to tension of less than 30 mm Hg and then becomes relatively inelastic at higher pressures. The pressure gradient, that is, the principal force causing the valve movement, is a variable determined by the interaction of stroke volume with effective valve orifice. The maximal atrioventricular pressure gradients during diastole are below 10 mm Hg in normal subjects.

Evidence shows that the sequential cusp movement is related to the magnitude of the hydraulic stress. Swales and associates studied the opening characteristics of fascia lata and Silastic trileaflet valves with a steady-state flow rig and found that three cusps of the valves opened in sequence at a low-flow state and required higher flow rates for complete valve opening. Recently, Horowitz and colleagues confirmed that both homograft and heterograft aortic valves showed a consistent pattern of sequential cusp movement at a low-pulsed flow in a test chamber.

The present in vivo study demonstrates that the same cusp of a particular valve opens first during every cardiac cycle. No correlation is found between the first cusp to open and its site in the tricuspid anulus. Inconsistency of the order of leaflet excursion in diastole and systole suggests that the fluid mechanism of valve opening is different from the fluid mechanism of valve closing. In valve opening, there probably is a significant difference in difficulty or ease of initiating motion among the cusps mounted on a common stent; this may reflect the inequalities of size and shape in each cusp, as suggested by Horowitz and his group. Unknown factors seem to influence the valve closure mechanism in the atrioventricular area.

The relative difficulty of any cusp in responding promptly to a small hydraulic stress is a possible explanation for sequential cusp opening. This difficulty is magnified by the central flow characteristics. When one cusp opens early in diastole, the pressure differentials across the valve abruptly decrease. As a consequence, the other one or two cusps, which are functionally stiffer, remain closed or opened partially until the pressure difference is increased to a significant level. If the leaflet is "too stiff" or if the hydraulic stress is "too small," the leaflet will not open fully.

The failure of a particular cusp or cusps to open fully also may be due to tachycardia. If opening of any cusp is delayed, full opening may be prevented by the high heart rate. The inability of two cusps of the porcine xenograft to open fully at heart rates of more than 140 beats/min demonstrated in this study is compatible with the clinical experience. Johnson and associates reported that atrial or ventricular endocardial pacing at a heart rate of 134 to 150 beats/min in six patients undergoing mitral valve replacement with a bioprosthetic heterograft valve resulted in an average increase of the mean gradient of 6 mm Hg, with the mean gradient ranging from 7 to 17 mm Hg at the rapidly paced heart rates.

Although the limited mobility of one or two cusps may not cause hemodynamic valvar dysfunction, ample evidence indicates that abnormal leaflet behavior enhances structural and functional deterioration. In vitro studies of Bellhouse's group demonstrated that the normal aortic valve begins to close during forward flow and requires a small amount of reversed flow for complete closure. If a valve is prevented from opening fully, this control mechanism is lost and the valve receives an impulsive loading on closure. Also, obstruction to the blood flow due to incomplete opening elevates the blood pressure and semi-opened leaflets will inevitably encounter a concentrated stress. Moreover, it was experimentally demonstrated that the stenosed valve produces considerable turbulence. Deleterious effects of turbulence eddy are known to be 1) a higher shear stress, which accelerates fatigue of a leaflet and breakdown of blood cells, and 2) blood stagnation, which may follow, causing thrombus formation.

Platelet aggregation and fibrin deposition on foreign surfaces with subsequent fibrosis are the major etiologic factors of prosthetic cusp stiffening. Therefore, aside from ideal surface properties of the materials employed, essential for a device intended to be thrombus-free is a design that precludes blood stagnation. As an approach to this goal, we propose that the material in a leaflet prosthesis must have sufficiently low inertia to permit extremely rapid action so as to open and close completely at any given condition within the physiologic range.

Echocardiography has been reported to be valuable in assessing leaflet mobility of a fascial valve or porcine xenograft used as replacement for the human mitral valve, but this technique provides information on only one or two cusps. The necessity to assess the mobility of all three cusps at the same time prompted us to employ the current method. Competence of the beaded valves assures us that the loading of a metallic marker did not significantly affect leaflet mobility. In view of the results obtained from this preliminary study, we postulate that the laminates fabricated from 12 or less Gore-Tex films should be a functionally suitable material for construction of an artificial semilunar valve. To further demonstrate the feasibility of use of Gore-Tex laminates in prosthetic valves, chronic animal experimentation is presently being performed in our laboratory.

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The Evolution of Peripartal Heart Failure in Zaria, Nigeria

Some Etiologic Factors

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SUMMARY The subsequent course of 173 women with severe congestive heart failure hospitalized within 6 months of delivery has been analyzed after 4 to 7 year follow-up periods. Forty-seven normotensive women and 50 women hypertensive only during the initial 48 hours have little long term morbidity. Thirty-six women with hypertension initially improved, but many are now showing enlarging cardiac silhouettes. Morbidity is increasing in this group. A similar, less severe pattern is developing in 36 women with intermittent hypertension.

The uniquely high incidence of this condition in Zaria is associated with several locale factors. These Hausa-Fulani women eat large quantities of a local lake salt, kanwa, for 40 days postpartum. The syndrome is markedly more common in the hot rainy season, when evaporative water loss is less, than in the dry season. The first postpartum days are spent confined to bed in a small heated room. Once or twice daily the new mother is given hot baths with branches which have been dipped in boiling water.

The combination of excessive sodium intake and diminished evaporative water excretion seems to precipitate failure in both normotensive and hypertensive patients.

Patients

To avoid confusion, patients 1) with infections requiring antibiotics, 2) with hemoglobins below 6 g per 100 ml, 3) with murmurs which have persisted and are presumed organic, and 4) those in whom only a few follow-up visits are available are not included in this report. The remaining patients were grouped as follows: 1) 47 patients had a normal blood pressure (85 mm Hg diastolic) while in hospital and throughout the follow-up period. They are considered normotensive. 2) 50 patients had blood pressure elevations up to 110 mm Hg diastolic on admission and during the initial 48 hours. No treatment for hypertension was given, no evidence of hypertensive vascular disease was detected on initial physical examination, and all 50 of these patients have remained normotensive subsequent to this initial hypertension. 3) A third group includes 36 women who were hypertensive in the hospital and on almost all subsequent occasions. 4) Group 4 consists of 36 patients in whom blood pressure has been intermittently elevated; 5) and finally, in group 5 are four patients who were initially normotensive but have developed hypertension during this 4–7 year surveillance period. The clinical characteristics of these five groups are given in table 1. The clinical presentation was remarkably uniform, with jugular venous distention, bilateral pulmonary rales, cardiomegaly with loud gallop, tense ascites, and anasarca.
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