In vitro investigation of aortic valve annuloplasty using prosthetic ring devices

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Abstract

Objectives: The remodeling of the dilated valve annulus with a prosthetic ring for the repair of valve insufficiency is a well-established concept in mitral valve surgery, and may also be suitable for aortic valve reconstruction. In this study, two models of prosthetic aortic annuloplasty devices were investigated. Methods: Fresh porcine aortic roots (n = 16) were investigated in a pulsatile flow simulator after patch dilatation of the annulus and subsequent reconstruction using both an external and an internal prosthetic ring. For each configuration, leakage was determined by ultrasonic flow measurements and leaflet co-aptation by transesophageal echocardiography. In addition, valves’ motions were recorded by high-speed video. Results: By the use of the prosthetic annuloplasty rings, leakage volumes decreased significantly compared with the dilated root, more pronounced with the intra-annular ring. Similarly, the co-aptation height of the leaflets increased. Pressure gradients were not significantly influenced by the ring application, but leaflet motion patterns changed from the usual trapezoid to a more rectangular opening characteristic, visible at both echocardiographic and high-speed video analysis. Conclusions: The reconstruction of a dilated aortic valve annulus using external and internal ring devices is feasible and effective for reduction of regurgitation at which the internal ring provides a greater potential to decrease valve insufficiency.

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Keywords: Aortic annuloplasty; Aortic valve repair; Device

1. Introduction

In the surgical management of aortic valve diseases, the replacement of the diseased valve is the most common procedure. In case of aortic insufficiency (AI), however, aortic valve repair gains increasing interest because this pathology occurs frequently secondary to dilatation of the aortic root and/or annulus [1], often with unaffected cusps; hence, preserving the native aortic valve is a worthwhile approach. Reconstruction strategies indeed are surgically challenging, which may be one reason for the infrequent use [2]. Another aspect could be a lack of prosthetic support.

In mitral valve surgery, resizing of the dilated valve annulus with a prosthetic ring is a well-established concept in the correction of valve insufficiency and such procedure may also be suitable for the reconstruction of aortic valves. A certain number of techniques using external or subvalvular strips for aortic annuloplasty in combination with leaflet correction or aortic root replacement were described [3–5], but few complete devices are known [6–8], which may provide a technically simplified and standardized surgical technique in future.

In this study, we investigated two different approaches of prosthetic aortic annuloplasty in an in vitro model, using both an external and intra-annular ring.

2. Material and methods

2.1. Annuloplasty devices

The external annuloplasty device consisted of a custom-made open circular metal ring surrounding approximately two-thirds of the aortic circumference, with a Dacron cover for suturing and flexible connection parts at the open ends of the metal ring, which were guided below the coronary arteries and bound with each other between the left and right sinus (Fig. 1, right). The intra-annular ring was constructed of a flexible, flat, wire frame in a closed, circular configuration surrounded with a thin woven Dacron layer (Fig. 1, left). To avoid impact of the ativoventricular conduction system, both annuloplasty rings incorporated a triangular notch between the right and non-coronary sinus.
2.2. Dilatated aortic annulus model

Aortic roots were carefully dissected from pig hearts from a local slaughterhouse within 4 h of slaughter. The ascending aorta was cut 3 cm above the sinotubular junction. Then, the left-ventricular muscle and the anterior mitral valve leaflet were removed and a Dacron tube was sutured to these structures for mounting the root in the test circuit, leaving roughly 1 cm of tissue between this prosthetic mounting tube and the aortic annulus. The coronary arteries were ligated. The next three incisions were made below the valve commissures (Fig. 2, left) and rhombus-shaped patches of aortic wall tissue were sutured in-between (Fig. 2, right) to achieve a 30% increase of the respective aortic annulus diameter.

2.3. Hemodynamic measurements

The dilatated aortic roots were mounted inside a pulsatile flow simulator providing physiological flow conditions [9] and run at a heart rate of 64 cycles min⁻¹ with a stroke volume of 60 ml for a systemic pressure of 125/80 mmHg. The test fluid consisted of physiological saline solution. Tests were performed with 16 specimens in dilated configuration, and subsequent reconstruction was undertaken with both external and intra-annular ring devices. The order of ring implantation was interchanged randomly to minimize possible impact of the application procedure.

For each configuration, pressure gradients and regurgitation volumes were determined by means of Envec Ceracore M pressure transducers (Endress + Hauser, Maulburg, Germany) and a TS410 ultrasonic flow meter (Transonic Systems Inc., Ithaca, NY, USA), respectively. Leaflet co-apptation was visualized and measured by transesophageal echocardiography during which the ultrasonic probe was placed adjacent to the aortic roots in the surrounding fluid reservoir. In addition, valve motions were recorded with a Motionscope HR-1000 high-speed camera (Redlake Imaging Corp., Morgan Hill, CA, USA) positioned straight above the valve and analyzed digitally.

2.4. Statistical analysis

Data were expressed as mean ± standard deviation. Comparisons of hemodynamics between the groups were performed using the Friedman test. Aortic valve opening and closure characteristics were tested with the chi-square test for cross-table relationship.

3. Results

The results of the hemodynamic measurements are shown in Table 1. By the use of the prosthetic annuloplasty rings, leakage volumes decreased significantly compared with the dilatated root \( p = 0.017 \) for the external and \( p = 0.006 \) for the intra-annular ring, more pronounced with the intra-annular ring \( p = 0.005 \). Further, leaflet co-apptation height increased in this way \( p = 0.043 \) for both. Thereby, mean and peak pressure gradients were not significantly influenced. Visualization of aortic valve movements showed some different patterns of leaflet displacement following ring application, from the common trapezoid to a rather rectangular course (Fig. 3), although it was statistically ambiguous.

4. Discussion

In this study, we could demonstrate that the application of prosthetic ring devices is suitable to restore valve competence in case of aortic root annulus dilatation.

The concept of tightening the aortic base to correct aortic valve insufficiency was first described by Taylor and colleagues in 1958 [10], with a silk suture line along the aortic annulus. Other techniques were the subcommissural annuloplasty with suture constricting of the interleaflet triangle [11], plication of the aortic sinus [12], or sub-

![Fig. 1. Photographs of the external (right) and intra-annular (left) aortic annuloplasty devices used in this study.](image)

![Fig. 2. Preparation of the aortic root (left) and dilatation of the annulus by rhombus shaped patches (right).](image)

<table>
<thead>
<tr>
<th>Dilated annulus</th>
<th>External</th>
<th>Intra-annular</th>
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<tbody>
<tr>
<td>( \Delta P_{\text{mean}} ) [mmHg]</td>
<td>3.63 ± 0.67</td>
<td>4.07 ± 0.61</td>
</tr>
<tr>
<td>( \Delta P_{\text{peak}} ) [mmHg]</td>
<td>9.07 ± 1.49</td>
<td>10.67 ± 1.39</td>
</tr>
<tr>
<td>( V_{\text{closure}} ) [ml]</td>
<td>5.53 ± 0.91</td>
<td>5.07 ± 1.28</td>
</tr>
<tr>
<td>( V_{\text{leak}} ) [ml]</td>
<td>2.08 ± 3.22</td>
<td>1.19 ± 1.16</td>
</tr>
<tr>
<td>( H_{\text{coapt}} ) [mm]</td>
<td>4.1 ± 2.4</td>
<td>5.4 ± 3.1</td>
</tr>
</tbody>
</table>

Table 1. Hemodynamics and leaflet coaptation of the dilatated aortic root and subsequent annuloplasty with ring devices. \( \Delta P_{\text{mean}} \) — mean pressure gradient; \( \Delta P_{\text{peak}} \) — peak pressure gradient; \( V_{\text{closure}} \) — closing volume; \( V_{\text{leak}} \) — leakage volume during diastole; \( H_{\text{coapt}} \) — leaflet coaptation height.
valvular-placed U-stitches [13]. In recent years also, a number of annuloplasty techniques were introduced using external or intra-annular prosthetic strips [3–5]. All these methods undoubtedly serve the purpose but are technically difficult. The use of prefabricated prosthetic annuloplasty devices may help to facilitate the surgical application.

Two different approaches were investigated in this study. First, an extra-aortic ring device, fixed externally close to the aortic root base, with the advantage to go without cardiac arrest and second, an intra-annular ring device implemented comparable to the widely used mitral annuloplasty rings.

By the use of both prosthetic rings, diastolic leakage volumes decreased significantly compared with the dilated root. This fact was supported by the concomitant increase in leaflet coaptation height at which both, volume decrease and coaptation increase, were more pronounced for the intra-annular ring. For the latter, we could observe a complete elimination of valve insufficiency in certain cases. Fortunately, pressure gradients were not influenced by the implantation of either annuloplasty rings. Though correction of AI proceeded successfully, movements of the valve cusps were influenced. In the dilated configuration leaflet, displacement followed the specific trapezoid pattern of the native aortic valve. After ring annuloplasty, the closing motion during systole became less pronounced and leaflets’ movements more unsteady in some valves, possibly due to a degree of annular stiffening by the prosthetic device. Similar alterations could be observed in valve-sparing aortic root replacement [14], but seem to be of minor clinical relevance.

As a matter of fact, the experimental set-up has limitations. To investigate the particular influence of the ring reconstruction on valve hemodynamics, we have performed a separate aortic annulus patch dilatation, whereas in patients with AI, it is often associated with a dilatated sinotubular junction also. In that case, the results of the annuloplasty may be less distinct. Furthermore, in the in vitro model, only acute effects of such prosthetic annuloplasty can be investigated; thus, chronic animal studies will be needed to evaluate long-term behaviors.

Anatomically, the aortic annulus is not represented as a circular ring but a crown-shaped structure; hence, an analogous configuration of annuloplasty devices may be more appropriate. Rankin recently introduces such a ‘hemispherical’ frame [8], with also successful results. However, in the present study, we used an intra-annular ring with only a single commissural ridge, considering potential mismatch at implantation due to individual variations in the patient’s root geometry, in particular unequal commissural distances [15].

As an exclusive procedure, subvalvular aortic annuloplasty only comprises a small aspect within the field of aortic valve repair, as annulus dilatation is a minor cause of AI, nearly 6% of all cases [1]. Nevertheless, prosthetic devices, as presented in this study, enlarge the surgical options by standardized tools. In case of accompanying pathologies of the aortic valve and root, these annuloplasty rings could also be combined with other root-correction procedures and leaflet-reconstruction techniques; thus, they may provide the potential to aid the routinely use of valve repair versus replacement.

Nevertheless, both devices might offer some challenges in their clinical use. For the extra-aortic ring, particular care must be taken by the preparation of the coronary arteries and the guidance of the ring underneath to avoid damage or restriction. Further, a proper suturing method has to be determined. The intra-annular ring was fixed similar to the base suture line in the reimplantation technique for valve-sparing aortic replacement; hence, an adequate placing of the ring with enough space to the leaflets should be uncomplicated. However, the application and long-term stability of both extra-aortic and intra-annular rings have to be further evaluated in vivo.

In conclusion, the reconstruction of a dilated aortic valve annulus using prosthetic ring devices has proven to be feasible. Whether internal or external rings should be used has to be discussed. However, the intra-annular ring provides greater potential to decrease valve insufficiency.

References


