The influence of size mismatch on the hemodynamic performance of the pulmonary autograft in vitro

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Abstract

Objectives: We established an in vitro model to investigate the effect of size mismatch between the aortic and pulmonary root on the hydrodynamic performance and leaflet motion of the pulmonary autograft. Methods: Ten fresh porcine pulmonary roots (annulus diameter: 19–25 mm) were tested in a pulsatile flow simulator. The autografts then were implanted in fresh porcine aortic roots (annulus diameter: 19–30 mm) and retested in the flow simulator. Three roots were oversized by 21–39%, three were undersized by 32–45% and there were four size for size implantations. The external diameter of the roots and autografts was measured at the sinotubular junction at hydrostatic pressures of 0–120 mmHg. The transvalvular gradient and regurgitation were also measured and the effective orifice area was calculated. The leaflet motion was recorded on video. Results: The fresh pulmonary roots were more compliant than the fresh aortic roots (46 ± 8.4% vs. 35 ± 7.8% dilatation from 0 to 120 mmHg). The group of matching size autografts dilated by 43 ± 4.9% in the same pressure range. The external diameter of the undersized autografts was 10 ± 2.1% bigger than before implantation at 0 pressure and then the dilatation was 40 ± 5.3% at 120 mmHg. The oversized implantation made the autografts 11 ± 9.4% smaller in their relaxed state, but then they dilated by 65 ± 11% as the pressure increased to 120 mmHg, resulting in a net dilatation of 54% over the original undilated state. The under or oversizing had little effect on the pressure gradient measured across the valves (5.6 ± 2.57 mmHg before, 6.3 ± 3.27 mmHg after implantation). Only the oversized valves showed significantly higher gradients than the native pulmonary valves. The effective orifice area of the undersized autografts was slightly bigger and the oversized autografts was slightly smaller after implantation, although the differences were not significant. The size mismatch did not cause regurgitation on the valves. The video images showed very low-open leaflet-bending deformation, both on the fresh pulmonary and the autograft valves. Conclusion: Under or oversizing the pulmonary autograft up to 40% of the annulus diameter did not affect the hydrodynamic parameters significantly. The compliance of the autograft root was able to compensate for the size mismatch without adversely influencing the valve performance. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Pulmonary autograft; Size mismatch; Hydrodynamic parameters; Leaflet motion

1. Introduction

The pulmonary autograft is potentially the best aortic valve substitute due its excellent hemodynamic performance, long-term durability with very low valve related complications and proven growth potential [1,2]. Nearly 30 years after the original report of Donald Ross [3] its advantages have been realized and indications for the Ross procedure have been expanding in recent years. Despite the more widespread use of the pulmonary autograft as an aortic root replacement, little attention has been paid to the biomechanics of the pulmonary valve and root in the systemic circulation. On the other hand, there has been continuous debate about the effect of size mismatch between the aortic annulus and the pulmonary autograft on the valve function.

We have established an in vitro model of the Ross procedure to investigate the hydrodynamic parameters of the
The pulmonary valve and the autograft root under systemic pressures and to analyze the effect of size mismatch on the valve function and leaflet motion.

2. Materials and methods

Ten various size fresh porcine pulmonary roots, were implanted in different size fresh porcine aortic roots.

2.1. Pulmonary and aortic roots

The pulmonary and aortic roots were dissected out from fresh pig hearts, stored at 4°C in normal saline and used within 24 h. The external diameter of the aortic and pulmonary roots was measured at the sinotubular junction at hydrostatic pressures of 0, 30, 60, 80, 100 and 120 mmHg using digital vernier calipers. The annulus size was measured on all the pulmonary and aortic roots by passing an obturator through the annulus from the ventricular side. The annulus diameter of the pulmonary roots was ranging from 19 to 25 mm, the host aortic annulus size was 19–30 mm in diameter. Three autografts were oversized by 21–39%, three were undersized by 32–45% and there were four size for size implantations.

2.2. Technique of autograft implantation

The right ventricular outflow tract muscle was thinned off to approximately 2 mm in thickness and trimmed 2 mm below the nadir of the cusps and was used as a pulmonary root cylinder. The aortic valves were excised from the host aortic roots. The aortic wall was trimmed off, approximately, 2–3 mm above the annulus and commissures to get a scalloped-shape host annulus preparation. The pulmonary root cylinder was then implanted intra-annularly using continuous 4/0 polypropylene suture in such a way that the autograft’s commissures were in alignment with the host’s commissural attachment. After implantation the external diameter of the autograft was measured at the sinotubular junction at hydrostatic pressures of 0, 30, 60, 80, 100 and 120 mmHg using digital vernier calipers.

2.3. Hydrodynamic testing

The pulmonary roots and autografts were tested in a pulsatile flow simulator, details of which have been described previously [4]. The flow simulator consisted of two rigid cylindrical test sections for each of the mitral and aortic valves, a compliance chamber, peripheral resistance and an atrial reservoir. The system was driven by a servo controlled piston pump. The roots were mounted in place of the rigid aortic valve section and tested at a rate of 72 cycles/min with a stroke volume of 70 ml for a systemic pressure of 120/80 mmHg. The pressure-difference across the root, was measured directly by a differential transducer and the flow was measured with an electromagnetic flow meter positioned downstream of the root. Pressure, flow, pump displacement and velocity signals were collected digitally for a period of 10 s at a sampling frequency of 200 Hz and stored on a disk for analysis using an IBM PS/2 computer. The data were ensemble averaged to create one cycle, and valve function was analyzed using this averaged waveform. The effective orifice area (EOA) was calculated using the formula: $\text{EOA} = \frac{Q}{\sqrt{\Delta p}}$ (where $Q$ is the root mean square forward flow in ml/s and $\Delta p$ is the mean pressure drop during forward flow in mmHg). Valve leaflet movements were recorded with a video camera positioned axial to the flow through the roots to determine the configuration of the open valve leaflets. A spigot of the same diameter as that of
the actual root in its distended state, allowed a video recording of the leaflet motions of the entire valve, including the commissural area. The open leaflet bending deformation was determined from the still image of the fully open position of the valve in mid-systole using an image analysis system. The open leaflet deformation at the commissures was quantified by taking three points along the leaflet edge in the region of the maximum deformation (Fig. 1). The spatial deviation of the centre point (BD) from the straight line formed by joining the two end points (AC) was used as a measure of leaflet deformation [5]. The BD/BC was used as a leaflet bending deformation index (BDI). BDI was quantified at all three commissures and the average of the data was given as a characteristic of the valve. The mean and standard deviation of the data were calculated. Statistical analysis was performed by Student’s t-test. Statistical significance was taken at the 5% level ($P = 0.05$).

3. Results

The distensibility of the fresh aortic and fresh pulmonary roots and the fresh free-standing pulmonary autografts is shown in Fig. 2. In the pressure range of 0 to 120 mmHg the fresh pulmonary root was a lot more compliant than the fresh aortic root. The external diameter of the fresh pulmonary roots increased 46 ± 8.4% as the pressure rose from 0 to 120 mmHg as against 35 ± 7.8% dilatation for the fresh aortic roots. The pressure related dilatation was nearly linear for the fresh aortic roots up to 120 mmHg, whereas, the pulmonary root was highly compliant in its normal pressure range of 0 to 30 mmHg, after which it was less compliant. In the normal resting systemic pressure range (between 80 and 120 mmHg) the aortic root dilated 10 ± 3.5%, while the pulmonary root’s dilatation was only 3 ± 1.6%. The compliance of the autograft roots was similar to that of the pulmonary roots.

In Fig. 3, we compared the elasticity curve of the oversized, undersized and matching size autografts with the elasticity of the fresh pulmonary root. The size for size implanted autografts were nearly as compliant as the fresh pulmonary root with an overall dilatation of 43 ± 4.9%. The external diameter of the oversized autografts was 11 ± 9.4% smaller after implantation than before at 0 pressure, but then they dilated by 65 ± 11% as the pressure increased to 120 mmHg, resulting in a net dilatation of 54% over the original undilated state. The undersized implantation made the autografts 10 ± 2.1% bigger in their relaxed state and the dilatation was 40 ± 5.3% at 120 mmHg.

Table 1 shows the effect of size mismatch of the autografts on the measured pressure gradients compared with the gradients on the native pulmonary roots. The transvalvular pressure gradients measured on the native pulmonary roots and the differently sized pulmonary autografts

<table>
<thead>
<tr>
<th></th>
<th>Pulmonary root (mmHg)</th>
<th>Autograft (mmHg)</th>
<th>t-Test ($P =$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oversized</td>
<td>4.13 ± 0.7</td>
<td>6.86 ± 1.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Size for size</td>
<td>6.85 ± 2.5</td>
<td>6.65 ± 4.5</td>
<td>0.47</td>
</tr>
<tr>
<td>Undersized</td>
<td>5.40 ± 3.1</td>
<td>5.26 ± 2.2</td>
<td>0.48</td>
</tr>
</tbody>
</table>
ular gradient on the undersized autograft was slightly lower than on the native pulmonary root, although the difference was not significant. However, the oversized autografts produced, significantly higher gradients after implantation than before ($P = 0.01$).

In Table 2, we summarized the results of the calculated effective orifice area of the autografts in comparison to the native pulmonary roots. The orifice area of the undersized autografts was slightly bigger, while the oversized autografts showed smaller orifice area, but unlike the pressure drop this difference did not quite reach statistical significance.

Regurgitation was not found on any of the implanted autografts regardless the size mismatch. Fig. 4 shows the autograft which was 45% undersized (20 mm pulmonary root implanted in a 29 mm aortic root) in diastole, and the valve was still competent.

Table 3. shows the open leaflet BDIs of the autografts before and after implantation. The native pulmonary valves and all the implanted autografts showed full valve opening and very low leaflet deformation. The size mismatch did not alter, significantly, the open leaflet BDI (Figs. 5–7).

4. Discussion

In the last four decades a continuous effort has been made to develop improved heart valve substitutes. In the aortic position the pulmonary autograft probably comes closest to meeting the requirements: excellent hemodynamic performance, no need for anticoagulation and growth potential. The idea of implanting autologous pulmonary valve in the systemic circulation dates back to the early 1960s, when Lower and Shumway implanted it first in the descending aorta, then used it as an aortic valve substitute experimentally [6,7]. In 1967 Donald Ross reported the first clinical application of the procedure [3]. However, due to the technical simplicity of implanting the newly developed and rapidly improving mechanical and biological prostheses and to the relatively high early reoperation rate of the original series [8], only a few surgeons continued to perform this complex operation. In 1971, Geens et al., investigated the relationship of the pulmonary autograft and the coronary

![Fig. 3. The dilatation of the native pulmonary roots in the pressure range of 0 to 120 mmHg.](https://academic.oup.com/ejcts/article-abstract/15/3/294/455142)
circulation, and outlined the importance of preserving the first septal perforator of the left anterior descending coronary artery [9]. In 1986, Ross introduced the free standing autograft root replacement technique, which helps in preserving the natural valve geometry [10]. Refinements in the surgical technique and improvement in myocardial protection decreased the operative mortality and the early reoperation rate to acceptable levels [11]. In 1991 Ross again reported excellent long-term autograft durability [12], which findings were supported by other investigators [13,14]. In 1994, Elkins demonstrated the evidence of growth potential of the autograft in children [15]. These findings together with the increasing number of valve and anticoagulant related complications after conventional valve replacements directed the interest to the pulmonary autograft. In 1996 the International Registry of the Ross Procedure had registered over 2500 autograft implantations worldwide [16]. Despite the expanding indications for the Ross procedure [17] and the more widespread use of the autograft it still remains uncertain, whether gross size mismatch is a contraindication of the procedure.

In our series we investigated the behaviour of the pulmonary autograft under “ideal” and extreme sizing conditions. Our sizing technique was based on the most common and simplest method: the annulus diameter was measured by different size obturators. That also means that, due to the thickness of the right ventricular outflow tract muscle (approximately 2 mm), in the case of size for size implantation, the host aortic annulus accommodated an autograft of similar size, which had an external diameter at least 4 mm larger. For the same reason the undersizing was less severe, but the oversizing was more severe in our series than the actual numbers represented. Whatever the conditions, the autografts maintained their excellent hemodynamic performance regardless of size mismatch. Only the oversized autografts produced, significantly higher gradients after implantation than before, however, these autografts were squeezed into 19–21 mm aortic roots. Interestingly, the transvalvular gradient and effective orifice area was still superior to any other valve replacement device for this size of aorta, including the stemless porcine aortic valve (comparative studies in our laboratory). Although the transvalvular gradient was significantly higher on the oversized autografts, the leaflet deformation was not any worse than the native pulmonary valve. The possible explanation is that the free standing autograft root maintains its distensibility

Table 3
The open leaflet bending deformation indices of the native pulmonary roots and the differently sized pulmonary autografts

<table>
<thead>
<tr>
<th></th>
<th>Pulmonary root</th>
<th>Autograft</th>
<th>t-Test (P = )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oversized</td>
<td>0.06 ± 0.3</td>
<td>0.08 ± 0.03</td>
<td>0.24</td>
</tr>
<tr>
<td>Size for size</td>
<td>0.06 ± 0.3</td>
<td>0.07 ± 0.03</td>
<td>0.34</td>
</tr>
<tr>
<td>Undersized</td>
<td>0.05 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>0.19</td>
</tr>
</tbody>
</table>
after implantation. The external diameter of the sinotubular junction was somewhat different at the oversized and undersized valves at 0 pressure, but then the pressure-dilatation curve of the autografts was quite similar to the native pulmonary root (Fig. 4). One of the three roots was responsible for the slightly different curve of the oversized autografts, as
it showed extreme distensibility with a dilatation of 78% at 120 mmHg. The capability for dilatation at the sinotubular junction is an important determinant of the normal valve function and the low-open leaflet-bending deformation of the semilunar valves, as it was documented by Brewer et al. [18]. On the other hand, the pulmonary root’s dilatation was nearly exponential as the pressure increased. It means that higher systemic pressures will not cause acute valve incompetence due to over dilatation of the autograft.

5. Conclusion

In our series the size mismatch between the pulmonary root and the aortic root did not affect, significantly, the hemodynamic performance and leaflet motion of the pulmonary autograft in vitro. The extreme distensibility of the pulmonary root was preserved after implantation and compensated for the size mismatch. The pulmonary roots could not be overdilated even at higher pressures due their nonlinear response to increasing hydrostatic pressures. All implanted autografts were competent regardless of the size mismatch.

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References


Fig. 7. An oversized pulmonary autograft in its open position.


