Quantification of Pulmonary Autograft Characteristics using Magnetic Resonance Imaging

Scott A. Reid[1], Peter G. Walker[1], John Fisher[1], Zsolt L. Nagy[2], John P. Ridgway[2], Mohan U. Sivananthan[2], Kevin G. Watterson[2]

[1]*School of Mechanical Engineering, University of Leeds,* [2]*Yorkshire Heart Centre, Leeds General Infirmary, Leeds, UK*

Background and aim of the study: **The diameters and distensibility of the native pulmonary root and their effect on pulmonary autograft performance were examined pre- and postoperatively using cardiac ultrasound and magnetic resonance imaging (MRI).**

Methods: **Eight patients undergoing the Ross procedure were prospectively involved. The diameters of the native aortic, native pulmonary and autograft roots were measured at the level of the annulus, sinus, sinotubular junction and in the main root using MRI through the cardiac cycle. Ultrasound was also used to estimate the degree of regurgitation, both pre- and postoperatively.**

Results: **The pulmonary root implanted into the systemic circulation increased in size but decreased in distensibility significantly at the sinus, sinotubular junction and main root, but not at the annulus. Postoperatively, the pulmonary autograft annulus showed a similar size and distensibility to that of the native aortic annulus. A wide range of aortic annular sizes (22-30 mm) produced clinically competent valves postoperatively. All undersized pulmonary valves showed only trivial regurgitation postoperatively. Although there was no clear correlation between root shape and valve insufficiency, two patients with mild and moderate autograft regurgitation both had divergent pulmonary roots (diameter at sinotubular junction > annulus diameter) preoperatively.**

Conclusion: **The pulmonary autograft using the root replacement technique functioned well in all but one case. The shape of the native pulmonary root may be a determinant of early autograft regurgitation, as well as the diameter and the size mismatch between the great arteries.**

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The pulmonary autograft, or Ross procedure, is now a widely accepted treatment for aortic valve disease, especially in children and young adults. During its 35-year history, the early and long-term results of this method have considerably improved due to the better myocardial protection and refinements in surgical technique (1,2). Currently, root replacement is more popular than the original subcoronary approach (3). However, debate continues on the indications and contraindications for the procedure. There are conflicting opinions about the importance of factors such as the diameter of the aortic annulus, the size mismatch of the great vessels, and the aortic and pulmonary root geometry (3-6). Hence, there is a requirement for a reliable method by which autograft performance may be assessed on a quantitative basis.

Address for correspondence:
Mr. Kevin G. Watterson, D floor Jubilee Wing, Yorkshire Heart Centre, Calverley Street, Leeds LS1 3EX, UK
e-mail: kevin.watterson@leedsth.nhs.uk

The pulmonary autograft has already been investigated using ultrasound and magnetic resonance imaging (MRI) (7-9). Although in recent years echocardiography has become the 'gold standard' for the non-invasive measurement of aortic root characteristics, little can be visualized in the native pulmonary root with this technique. Potentially, MRI allows detailed morphological and hemodynamic assessment of both the aortic and pulmonary roots. The aim of the present study was therefore to quantify the effects of the size and morphology of the aortic and pulmonary roots on hemodynamic performance of the autograft, both pre- and postoperatively, using ultrasound and MRI.

Clinical material and methods

Patients

The study group consisted of eight patients (six males, two females; mean age 22 years; range: 13 to 35 years) who had been listed for cardiac surgery with clinically diagnosed congenital aortic valve disease. The patients were scheduled for aortic valve surgery using the pulmonary autograft (Table I). The study protocol was approved by the local Ethics Committee, and informed consent was obtained to conduct the MRI and ultrasound investigations. The patients were imaged on the day before surgery and at three months postoperatively using MRI and ultrasound.

Surgical technique

All operations were performed via a midline sternotomy with cardiopulmonary bypass (CPB) and moderate hypothermia. After opening the pericardium, the diameters of the aorta and the main pulmonary artery were measured approximately 5 cm above the annulus in systole (maximum diameter) as a comparison for the MRI measurements. The heart was arrested by cold blood cardioplegia. The coronary arteries and aortic annulus were thoroughly inspected, after which the aortic valve was excised and the pulmonary autograft carefully harvested. The coronary ostia were mobilized with an aortic wall button. In this particular series of patients, the autograft was implanted intra-annularly with 4-0 continuous polypropylene suture interrupted at each commissure without any reinforcement. After the inflow portion had been sewn into the host annulus, the coronary arteries were reimplanted in the autograft, without distortion. The distal end of the autograft was joined to the ascending aorta with continuous 4-0 polypropylene suture in such a way that any disparity between the distal end of the autograft and the proximal end of the aorta was equalized by the stitches. To complete the operation, a fresh-frozen pulmonary homograft was implanted to reconstruct the right ventricular outflow tract. CPB was discontinued and the chest closed in such a way as to allow a window above the autograft free of sternal wires that allowed MRI to be carried out.

MRI

All patients were imaged using an ACS-NT Philips (Philips Medical Systems, Best, The Netherlands) 1.5 T MRI scanner (Release 6 software) using either a body or cardiac imaging coil. To quantify the pulmonary and aortic root sizes, a block of six sagittal (pulmonary position) and coronal (aortic position) cine MRI slices were obtained perpendicular to the annular plane (pixel size 1.04 × 1.04 mm, slice thickness 4 mm). Fifteen phases or images were obtained over one heartbeat to provide temporal diameter changes.

To quantify pulmonary autograft hemodynamics, a single velocity-encoded slice was obtained 0.5 cm distal to the autograft annulus. The slice was orientated perpendicular to the root, and the through-plane (main flow direction) velocity was quantified (pixel size 1.17 × 1.17 mm, slice thickness 6 mm, velocity range ± 150 cm/s). Around 22 phases or images were obtained over one heartbeat, depending upon the patient's heart rate.

Ultrasound imaging

Ultrasound scanning was carried out on an Acuson Sequoia™ 512 Ultrasound system (Acuson Corporation, Mountain View, CA, USA). A 3V2c ultrasound vector array probe with a footprint size of 19 mm was used to assess qualitatively the valvular hemodynamics both pre- and postoperatively. Using a parasternal long- and short-axis and an apical long-axis view of the autograft, the degree of valvular regurgitation was assessed based on regurgitant jet size according to standard protocols. A grading of trivial, mild, moderate or severe was awarded.

MRI data analysis

Pulmonary, aortic and autograft diameter and dilatation measurements

The pulmonary, aortic and autograft root diameters were quantified at the annular, mid-sinus, sinotubular

Table I: Patient information and preoperative pulmonary valve regurgitation (PPVR) measured by ultrasound.

Patient no.	Age (years)	Sex	Congenital condition	Grade of PPVR	Surgical procedure
1	14	M	AS	None	Ross
2	25	M	AS	None	Ross
3	13	M	AS	Trivial	Ross
4	25	F	Severe AR	Trivial	Ross
5	15	M	AS	Trivial	Ross
6	27	F	AS	Mild	Ross
7	35	M	AS	None	Ross
8	22	M	AS + LVOTO	None	Ross + septal myectomy

AR: Aortic regurgitation; AS: Aortic stenosis; LVOTO: Left ventricular outflow tract obstruction; PV: Pulmonary valve.

junction and main root (5 cm distal to the annulus) levels from the MRI images at normal systemic arterial blood pressures. Any motion of the root relative to the stationary MRI images would produce an apparent change in root diameter. Therefore, the slice containing the maximum root diameter at each of the four levels was identified at each period during the cardiac cycle. From this curve of diameter against time, the maximum and minimum diameters during the cardiac cycle were obtained.

Root distensibility was calculated from the maximum (d_{max}) and minimum (d_{min}) diameters using the following equation:

$$\% \text{ Distensibility} = \frac{d_{max} - d_{min}}{d_{max}} \times 100$$

A paired Student's *t*-test was used to test significant diameter and dilatation changes.

Valve shape and size mismatch

Valve mismatch was calculated in order to investigate the effect of annular mismatch on the hemodynamic performance of the autograft. This was achieved by calculating the ratio of the average pulmonary valve annulus diameter to that of the average aortic valve annulus diameter. Valvular shape was also determined by obtaining the ratio of the average sinotubular junction to the annulus diameter in the pulmonary autograft both pre- and postoperatively. A convergent root would have a ratio <1 (annulus > sinotubular junction), whereas a divergent root would have a ratio >1 (annulus < sinotubular junction).

Results

The MRI measurements of the aortic and main pulmonary artery diameters were compared to the intraoperative measurements. The intraoperative diameters were slightly larger than the MRI measurements (23.7 ± 1.25 versus 22.2 ± 1.91 mm for the pulmonary roots, and 37.7 ± 3.35 versus 35.7 ± 3.43 mm for the aortic roots), though the differences did not reach the level of significance ($p = 0.08$ and $p = 0.28$ for the pulmonary and aortic roots, respectively).

Values of diameter and distensibility are listed in Tables II-IV. The maximum diameter measurements (in systole) showed that the native pulmonary root was significantly ($p \leq 0.05$) smaller than the native aortic root, except at the annulus level. When transposed to the aortic position, the autograft increased in maximum diameter, although significance was only evident at the root and sinus levels. The autograft maximum diameters remained less than that of the aortic root, except at the annulus level, where it actually became slightly bigger. In other words, during systole the autograft root did not expand to the same size as the native aortic root (Table II).

The minimum diameter measurements (in diastole) also showed that the native pulmonary root was significantly ($p \leq 0.05$) smaller than the native aortic root, except at the annulus level. When transposed to the

Table II: Maximum diameter (mm) of the native pulmonary roots, native aortic roots and autograft roots measured at mid systole.

Location	Native pulmonary root	Native aortic root	Autograft root
Root (5 cm above annular level)	22 ± 2	35.7 ± 3.4 p = 0.01	32.5 ± 2.3 p = 0.007 p* = 0.43
Sinotubular junction	26 ± 3.5	31.1 ± 4. p = 0.043	28.9 ± 1.4 p = 0.25 p* = 0.16
Mid-sinus	31.7 ± 2.6	41 ± 7.8 p = 0.043	37.8 ± 7.3 p = 0.023 p* = 0.09
Annulus	26.7 ± 1.9	28 ± 4.4 p = 0.2	29.2 ± 6.3 p = 0.19 p* = 0.26

p, versus native pulmonary root diameter.
p*, versus native aortic root diameter.

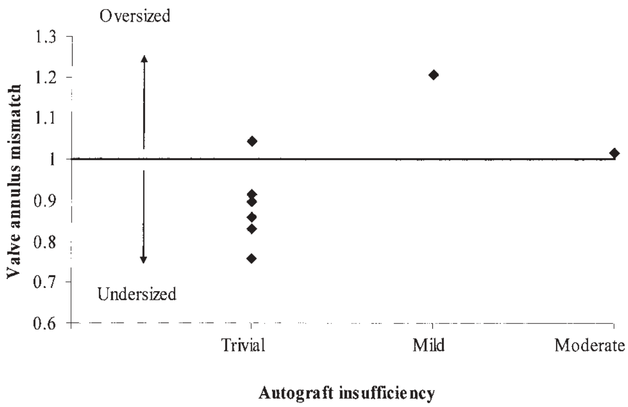

Figure 1: Pulmonary and autograft valve annulus mismatch against autograft regurgitation.

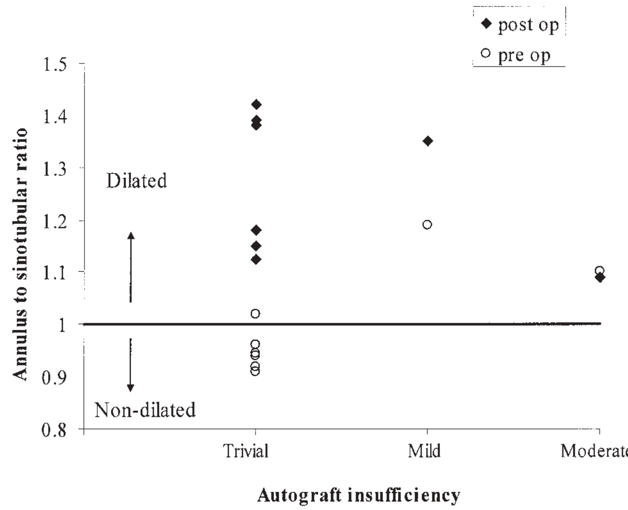

Figure 2: The annulus to sinotubular junction ratio of the native pulmonary and autograft roots against autograft regurgitation.

aortic position, the autograft significantly increased in minimum diameter at all levels except at the annulus, where there was a non-significant increase in diameter. The autograft minimum diameters differed from the maximum diameter results in that they were comparable to the native aortic root measurements. In other words, during diastole, the autograft root diameter was nearly the same size as the aortic root (Table III).

The distensibility measurements (Table IV) showed that the native pulmonary root exhibited greater distensibility than the native aortic root, though these results were only significant at the sinus level. The autograft, however, exhibited a reduction in distensibility when compared to both the pulmonary and aortic roots. Compared to the native pulmonary root, distensibility of the autograft was reduced by around 30-50%, except at the annulus level, where no significant difference was found in distensibility.

Ultrasound assessment of the pulmonary and autograft valves showed that, preoperatively, all valves but one had trivial or no regurgitation (see Table I). Postoperatively, only one valve had moderate regurgitation, whilst all others had either trivial or mild regurgitation. The relationship between postoperative regurgitant grading of the autograft and the pre- and postoperative annulus diameter is shown in Table V.

Table III: Minimum diameter (mm) of the native pulmonary roots, native aortic roots and autograft roots measured at mid-diastole.

Location	Native pulmonary root	Native aortic root	Autograft root
Root (5 cm above annular level)	16.7 ± 1.7	29.4 ± 4.0 p = 0.002	28.6 ± 1.2 p = 0.001 p* = 0.39
Sinotubular junction	20.2 ± 2.8	25.7 ± 3.3 p = 0.006	26.5 ± 1.4 p = 0.01 p* = 0.36
Mid-sinus	25.1 ± 2.2	34.7 ± 7.2 p = 0.008	34.5 ± 5.8 p = 0.008 p* = 0.38
Annulus	19.8 ± 1.6	21.0 ± 3.1 p = 0.11	23.1 ± 4.2 p = 0.12 p* = 0.37

p, versus native pulmonary root diameter.
p*, versus native aortic root diameter.

Table IV: Distensibility of the native pulmonary roots, the native aortic roots and the autograft roots.*

Location	Native pulmonary root	Native aortic root	Autograft root
Root (5 cm above annular level)	23.5 ± 6.2	18 ± 4.4	11.8 ± 3.6** p = 0.037
Sinotubular junction	22.4 ± 4.3	20.6 ± 8.5	8.3 ± 4.1** p = 0.003
Mid-sinus	20.8 ± 6.3	15.4 ± 7.1** p = 0.034	8.6 ± 2** p = 0.001
Annulus	25.7 ± 5.0	24.6 ± 6.3	21.4 ± 5.0

Distensibility = %
** $p < 0.05$ versus native pulmonary root.

Overall, no correlation was found between annulus size and regurgitant grading. In particular, there was a relatively large range of pre- and postoperative annulus diameters (22-30 mm) with clinically competent valves. However, the two autografts with mild and moderate regurgitation both had relatively small aortic and autograft annulus diameters before and after surgery.

When comparing the preoperative pulmonary and aortic annulus diameters within each patient (size mismatch), it was found that all undersized pulmonary valves (pulmonary annulus diameter < aortic annulus diameter) showed only trivial regurgitation. However, in the two patients with mild or moderate autograft regurgitation, the valves were either matched or oversized (pulmonary annulus diameter ≥ aortic annulus diameter), although the Fisher Exact significance test did not show any significant difference between the undersized and oversized autografts in terms of valvular regurgitation ($p = 0.11$) (Fig. 1).

Figure 2 shows that all autograft roots were slightly divergent (sinotubular diameter > annular diameter) postoperatively, and no correlation was found between the degree of divergence postoperatively and the degree of autograft regurgitation. However, both pulmonary roots which were divergent preoperatively, exhibited mild or moderate regurgitation after implantation as an autograft.

Discussion

The Ross procedure has become increasingly popular during the past decade for the treatment of aortic valve disease in young patients due to the excellent mid- and long-term results obtained and the unrestricted life quality of patients postoperatively. The full root replacement technique was introduced by Donald Ross in 1974, and most surgeons have adopted the newer technique (10). By using the root replacement technique, the anatomical integrity of the pulmonary

Table V: Native pulmonary and autograft annulus diameters and pre- and postoperative valvular regurgitation as measured by ultrasound.

Patient no.	Pulmonary annulus diameter (preoperative)	Grade of preoperative pulmonary regurgitation	Autograft annulus diameter (postoperative)	Grade of autograft regurgitation
1	24.9	None	20.7	Mild
2	22.2	None	26.8	Trivial
3	22.8	Trivial	30.1	Trivial
4	24.4	Trivial	26.7	Trivial
5	25.5	Trivial	26.9	Trivial
6	22.3	Mild	21.4	Trivial
7	22.6	None	25.2	Trivial
8	21.3	None	21.0	Moderate

root is preserved, and this results in improved autograft valve function, as well as helping to compensate for any size mismatch between the great vessels (11,12). Despite these advantages, occasional reports are made of early autograft dilatation or aneurysm formation after the root replacement technique (13,14). In the present study, the native aortic and pulmonary and autograft root dimensions were measured using MRI to examine preoperative variables that might influence postoperative autograft performance.

The results obtained supported previous findings that the pulmonary root, after implantation into the high-pressure systemic circulation, dilated during the entire cardiac cycle at the level of the sinus, the sinotubular junction, and in the main root (15,16). This may well be attributed to the fact that the minimum diameter measurements of the autograft were made at the systemic diastolic pressure of 70-80 mmHg, whilst the maximum diameter of the pulmonary root was measured at the systolic pulmonary pressure of ~30 mmHg. However, despite the significant increase in pulmonary root diameter in the aortic position, it did not reach the maximum dimensions of the native aortic root. Previous morphological investigations showed that the aortic wall and sinuses were thicker because of a larger amount of collagen and smooth muscle cells that resulted in differing elastic properties of the pulmonary root compared to the aortic root (17). Thus, there may be a morphological basis for the findings that the autograft root is less distensible than the native aortic root at systemic pressures.

The results presented also showed that the pulmonary valve annulus did not increase in size significantly after implantation as an autograft. This may be due to the aortic annulus ring, which helps maintain the dimensions of the autograft annulus even under systemic conditions. Interestingly, the autograft annulus diameter was found to be slightly larger than that of the native aortic valve annulus, though the differences did not reach the level of significance. Most likely, after excision of the thickened aortic valve - which sometimes was calcified, thereby restricting the elasticity of the native aortic annulus - it increased in size compared to its original diameter.

The results of in-vitro hydrodynamic measurements showed that the native pulmonary root is more distensible than the native aortic root (18,19). When the pulmonary root was implanted into the aortic position, there was a decrease in distensibility at the sinus, the sinotubular junction and in the main root at systemic pressures. The loss of functional elasticity of the autograft root under systemic conditions is vital in maintaining normal leaflet coaptation and valve competence, as was concluded by Nagy et al. on the basis of their previous in-vitro model (18). Interestingly, at the annulus, distensibility of the autograft was similar to that of the native aortic valve, which helps to maintain the excellent hemodynamic performance of the autograft. This also means that the continuous Prolene sutures did not fix the tissues, but allowed at least a 20% dilatation of the annulus during systole. Overall, the pulmonary autograft is most distensible at the annulus and less so further downstream in the root.

There is also debate about the importance of the absolute size of the aortic annulus. Some surgeons have raised concerns about the feasibility of the Ross procedure in cases where the aortic annulus diameter is >27 mm (20). In the present small series there was no clear correlation between annulus size and the degree of regurgitation. In fact, there was a wide range of aortic annulus sizes, in which the pulmonary autograft was clinically competent after implantation. However, the fact that the two autografts with mild to moderate regurgitation were small sizes indicates that some factor other than annulus size might have an important role on autograft competence.

The size mismatch between the native pulmonary and aortic valve annuli is also believed to have an important impact on the outcome of the procedure, and most surgeons avoid undersizing the autograft to prevent early regurgitation. In a previous in-vitro study, no correlation was found between size mismatch (oversized and undersized autografts) and the hydrodynamic performance of the pulmonary autograft (21). In the present study, all undersized autografts showed only trivial regurgitation postoperatively. However, the patient with moderate autograft regurgitation had a matching annular size, and the other autograft with mild regurgitation was slightly oversized.

The morphology of the pulmonary root and autograft could be an important factor in early and late autograft competence. David et al. (22) found that size mismatch between the autograft annulus and sinotubular junction would lead to valve incompetence. These authors also found that autografts with dilatation of the sinuses - but not the sinotubular junction - did not show signs of regurgitation (22). The present results suggest that preoperative assessment of the pulmonary root shape may be an aid to predicting early autograft failure: both patients with autograft regurgitation on echocardiography and MRI had divergent pulmonary roots (sinotubular junction > annulus) preoperatively secondary to elevated pulmonary pressures.

The long-term results of the Ross procedure are generally satisfactory, apart from the few cases when early autograft dilatation leads to aortic regurgitation. It is therefore crucial for the surgeon to choose another procedure in those cases when early dilatation might develop. The aim of the present study was to identify preoperative determinants for early autograft dilatation and failure. The results obtained suggested that preoperatively divergent pulmonary roots may be more prone to dilate postoperatively under systemic pressures. The only patient who developed early autograft dilatation and moderate regurgitation in the whole series of over 40 patients had a divergent pulmonary root preoperatively. Interestingly, on removal of the cross-clamp at operation, the autograft in this patient dilated immediately much more than normal. This dilatation has since progressed and reoperation will be necessary in the future. The other patient with a divergent pulmonary root continues to have only mild autograft regurgitation. Therefore, the shape of the pulmonary root will need further detailed investigation in the future to better define its significance. MRI may have the potential to identify such patients preoperatively using a detailed investigation including pulmonary artery geometry and wall thickness. This would allow identification of these occasional patients who are clearly not suitable to the Ross procedure.

Study limitations

There were important limitations of the present study. It is clear that eight patients was not a sufficient number from which to draw significant conclusions, but it was proven that the MRI was suitable for detailed morphological assessment of the pulmonary autograft, both pre- and postoperatively. In addition, the follow up time was short, and longer follow up will be necessary to assess long-term autograft performance.

In conclusion, the pulmonary autograft dilated significantly after implantation in the systemic circulation at the sinus, sinotubular junction and in the main root through the whole cardiac cycle. There was also a significant reduction in the functional elasticity of the autograft root. However, the autograft annulus did not change significantly in size, and also maintained its distensibility during the entire cardiac cycle. The aortic annulus diameter and the size mismatch between the aortic and pulmonary valve annuli did not play an important role in early autograft competence in this small series. However, the shape of the native pulmonary root may be a useful indicator to predict early autograft regurgitation: both incompetent autograft roots were divergent (diameter at the sinotubular junction > diameter of the annulus) preoperatively.

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