SURGERY FOR ACQUIRED CARDIOVASCULAR DISEASE

DILATION OF THE PULMONARY AUTOGRAFT AFTER THE ROSS PROCEDURE

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Objective: Dilation of pulmonary autograft after the Ross procedure is being recognized with increasing frequency. This study was undertaken to examine the extent of this problem and factors that may be associated with it. **Methods:** The clinical, operative, and echocardiographic data of 118 patients who underwent the Ross procedure were reviewed. The mean age of 79 men and 39 women was 34 ± 9 years, range 17 to 57 years. Bicuspid or other congenital aortic valve disease was present in 81% of patients. The pulmonary autograft was sutured as a valve in the subcoronary position in 2 patients, as a root inside of the aortic root in 45, and was used for complete aortic root replacement in 71. Teflon felt was not used to buttress the proximal or the distal anastomosis of the pulmonary autograft. The diameters of the sinuses of Valsalva, aortic anulus, and sinotubular junction were measured early and late after the operation with echocardiography. The mean follow-up was 44 months. **Results:** The diameter of the sinuses of Valsalva increased from 31.4 ± 0.4 mm to 33.7 ± 0.5 mm ($P = .01$). Analysis of covariance revealed a significant change over time in this diameter, as well as a difference between operative techniques, with replacement of the aortic root being associated with a higher risk of dilation ($P = .0006$). In 13 patients the diameter ranged from 40 to 51 mm. The diameter of the aortic anulus decreased in most patients and increased in 15, but there was no interaction between these changes and the operative technique. The diameter of the sinotubular junction increased in patients who had aortic root replacement and decreased in patients who had aortic root inclusion ($P = .007$). Moderate aortic insufficiency developed in 7 patients, and 3 required replacement of the pulmonary autograft. All patients with moderate aortic insufficiency had dilation of the aortic anulus and/or sinotubular junction. **Conclusions:** Dilation of the pulmonary autograft after the Ross procedure may occur because of an intrinsic abnormality of the pulmonary root in patients with congenital aortic valve disease. The technique of aortic root replacement is associated with a higher risk of dilation of the sinuses of Valsalva and sinotubular junction than the technique of aortic root inclusion. (J Thorac Cardiovasc Surg 2000; 119:210-20)

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Aortic valve replacement with a pulmonary autograft was originally performed by implanting the pulmonary valve inside the aortic root in the subcoronary position.^{1,2} The pulmonary autograft also has been implanted inside the aortic root as an entire root (the so-called root inclusion technique) or as a complete aortic root replacement. The latter technique has become the preferred method of performing the Ross procedure because it appears to be associated with the lowest risk of aortic insufficiency (AI) and pulmonary autograft failure.³⁻⁶ Although the pulmonary root may have an inherent ability to adapt itself to the mechanical stress of the aortic root in most patients, pulmonary autografts have failed because of technical errors, prolapsed cusps, and dilation of the root.^{7,8} Dilation of the sinuses of Valsalva of a semilunar valve does not cause valve insufficiency.⁹ Dilation of the sinotubular junction and/or aortic anulus pulls the cusps apart and causes valve insufficiency.⁸⁻¹⁰

A referral of an outside patient in whom a pulmonary autograft aneurysm and severe AI developed after the Ross procedure prompted us to review our experience to determine the magnitude of this problem and the factors that may play a role in dilation of the pulmonary autograft.

Patients and methods

From 1990 to 1997, 118 patients with a mean age of 34 ± 9 years, range 17 to 57 years, underwent the Ross procedure at Toronto General Hospital. Table I shows the clinical profile of these patients.

Operations were performed with normothermic cardiopulmonary bypass and antegrade cold blood cardioplegia for myocardial protection. The diameters of the aortic anulus and sinotubular junction were measured with metric sizers after excision of the diseased aortic valve in all but the first 4 patients. The sinotubular junction of the pulmonary autograft was also measured, and the diameter of the pulmonary anulus was estimated to be 10% larger than the diameter of the sinotubular junction.^{11,12} If the diameter of the aortic anulus was more than 2 mm larger than the diameter of the pulmonary anulus, the aortic anulus was surgically reduced before the pulmonary autograft was sutured in the left ventricular outflow tract.¹² Similarly, if the aortic sinotubular junction was larger than the pulmonary sinotubular junction by more than 2 mm, the aortic sinotubular junction and ascending aorta were plicated before the autograft was sutured within the aortic root or to the ascending aorta.¹² The diameters of the aortic anulus and sinotubular junction were recorded in all but the first 4 patients in this series.

The pulmonary autograft was implanted inside the aortic root in the subcoronary position in 2 patients. The root inclusion technique was used in 45 and root replacement in 71. A strip of Teflon felt was not used in the annular or distal anas-

Table I. Clinical data on 118 patients who underwent the Ross procedure

	No.	%
Sex		
Male	69	67
Female	39	33
Heart rhythm: sinus	118	100
New York Heart Association functional class		
I	18	15
II	76	64
III	16	14
IV	8	7
Left ventricular ejection fraction		
≥60%	64	54
40%-59%	42	36
21%-39%	12	10
≤20%	0	
Previous aortic valve surgery		
Repair	13	11
Replacement	9	8
Aortic valve lesion		
Stenosis	67	57
Insufficiency	43	36
Mixed	8	7
Aortic valve pathology		
Bicuspid	84	71
Other congenital	12	10
Rheumatic	3	2.5
Tricuspid calcific	1	0.8
Tricuspid incompetent, nonrheumatic	9	7.6
Prosthetic valve	9	7.6

tomoses of the pulmonary autograft with the aortic anulus or the ascending aorta.

The right ventricular outflow tract was reconstructed with a pulmonary valve homograft in all but the first patient of this series, who had an aortic valve homograft. Table II summarizes the operative data.

All patients have been examined by the referring cardiologist annually and had an echocardiogram at their institution. No patient has been lost to follow-up, which extended from 12 to 96 months (mean 44 months).

All operations were performed with transesophageal Doppler echocardiography. All patients had a transthoracic echocardiogram 1 week after the operation, and 82 patients had an echocardiogram at our hospital during the last follow-up visit for the purpose of this study. The diameters of the aortic anulus, sinotubular junction, and sinuses of Valsalva were measured. Echocardiographic examinations from other institutions were also reviewed but only used for measurement of the diameter of the sinuses of Valsalva.

It is not possible to accurately measure the diameters of the aortic anulus and sinotubular junction with echocardiography soon after the Ross procedure because of edema, hematoma, and other factors related to the trauma of the operation. An experienced sonographer measured both the internal and

Table II. Operative data on 118 patients who underwent the Ross procedure

	No.	%
Operative technique		
Subcoronary implantation	2	1.7
Root inclusion	45	38
Root replacement	71	60
Surgically measured diameters before reduction (mm)		
Aortic anulus		
Mean	27 ± 4	
Range	17-36	
Aortic sinotubular junction		
Mean	27 ± 4	
Range	16-40	
Pulmonary anulus*		
Mean	24 ± 2	
Range	19-27	
Pulmonary sinotubular junction		
Mean	21 ± 2	
Range	17-24	
Reduction of aortic anulus or sinotubular junction		
None	46	39
Reduction of aortic anulus	41	35
Sinotubular junction	9	8
Both	22	18
Additional procedures		
Replacement of ascending aorta	5	4.2
Resection of subaortic membrane + myectomy	3	2.5
Mitral valve repair	3	2.5
Septal myectomy†	1	0.8
Coronary artery bypass†	3	2.5
Pulmonary valve replacement		
Aortic valve homograft	1	0.8
Pulmonary valve homograft	117	99
Aortic crossclamp time (min)	124 ± 15	
Cardiopulmonary bypass time (min)	143 ± 25	

*Estimated to be 10% larger than the diameter of the sinotubular junction.

†Unplanned additional procedures.

external diameters of the aortic anulus and of the sinotubular junction. These diameters were compared with those obtained by direct measurement during the operation. The external diameters were larger and the internal diameters were smaller than those obtained during the operation. The mean values between the internal and external diameters were 1 to 3 mm smaller than those obtained during the operation. For this reason, the mean values were used as early diameters of the aortic anulus and sinotubular junction. Only the internal diameters were measured in the late echocardiographic studies.

Statistical analysis. Data were managed in dBASEIV data sets and analyzed with the SAS for PC statistical program (SAS Language Guide for Personal Computers, SAS Institute Inc, Cary, NC, 1988).

Data are presented as means ± standard errors in text and figures and as mean ± standard deviation in tables. The early and late diameters of the pulmonary autograft were evaluated

by two methods. Analysis of covariance was used to evaluate the main effects of operative technique (aortic root inclusion vs aortic root replacement), time, and the interaction of technique versus time. PROC MIXED was also used as corroborating longitudinal analysis. Statistical significance was set at $\alpha = .05$.

Time-related events such as late survival, reoperations, and development of AI were calculated by the Kaplan-Meier method.

Results

Dilation of the pulmonary autograft

Sinuses of Valsalva. A total of 111 patients had early and late measurements of the diameter of the sinuses of Valsalva. The diameter of the sinuses of Valsalva exceeded the normal limit of 39 mm in 13 patients, in whom it ranged from 40 to 51 mm. All these 13 patients had bicuspid aortic valve, and the Ross procedure had been performed by the technique of aortic root replacement.

The diameter of the sinuses of Valsalva increased from 31.4 ± 0.4 mm to 33.7 ± 0.5 mm ($P = .01$), as illustrated in the *upper panel* of Fig 1. Analysis of covariance showed a significant change over time in the diameter of the sinus of Valsalva, as well as a significant difference between operative techniques, with replacement associated with a higher risk of dilation as shown in the *lower panel* of Fig 1. The diameter of the sinuses of Valsalva increased from 32.2 ± 0.5 mm to 35.0 ± 0.6 mm in patients who had the technique of aortic root replacement and from 30.2 ± 0.5 mm to 31.5 ± 0.8 mm in those who had the technique of aortic root inclusion. Table III shows the results of the mixed linear model.

Aortic anulus. Eighty-two patients had early and late measurements of the diameter of the aortic anulus. The diameter of the aortic anulus decreased in 67 patients and increased in 15.

The diameter of the aortic anulus decreased from 26.2 ± 0.3 mm to 23.6 ± 0.4 mm ($P < .01$). The *upper panel* of Fig 2 shows the changes in diameter of the aortic anulus in all patients, and the *lower panel* shows the changes in patients who had the Ross procedure (done by two different operative techniques). There was no significant time or operative difference in the change in the aortic anulus diameter by PROC MIXED (Table IV), but there was a significant time effect by analysis of covariance ($P = .004$, *lower panel* of Fig 2).

Sinotubular junction. Eighty-two patients had early and late measurements of the diameter of the sinotubular junction. The sinotubular junction of the pulmonary autograft could not be identified echocardiographically

Fig 1. Upper panel: The diameter of the sinuses of Valsalva (SV) increased with time ($P = .01$). Lower panel: Analysis of covariance (ANOCOVA) showed that the increase in the diameter of the sinuses of Valsalva was significantly greater in patients who had aortic root replacement (dotted line) than in those who had aortic root inclusion (solid line).

on the late studies in 10 (12.3%) patients because its diameter had become identical to or exceeded that of the sinuses of Valsalva. The typical shape of a semilunar root was lost in those patients. All these patients had bicuspid aortic valve and had had aortic root replacement.

The upper panel of Fig 3 shows the diameters of the sinotubular junction of all 82 patients studied. It measured 29.1 ± 0.3 mm early and 29.1 ± 0.6 mm in the late postoperative period. The lower panel of Fig 3 shows the diameters of the sinotubular junction in patients who had the technique of aortic root replacement (29.5 ± 0.4 mm early and 30.6 ± 0.8 mm late) and the technique of aortic root inclusion (28.7 ± 0.5 mm early and 26.7 ± 0.8 mm late). There was a significant interaction between time and operative technique for the change in the diameters of the sinotubular junction (Table V and lower panel of Fig 3). The technique of aortic root replacement was associated with increased dilation over time.

Clinical outcomes

Early and late mortality. One operative death occurred due to myocardial infarction and one late

Table III. Analysis of variance for changes in diameter of the sinuses of Valsalva

Effect	Regression coefficient	95% CI	P value
Intercept	30.1	28.9, 31.3	.0001
Replacement	2.00	0.45, 3.55	.012
Months	0.048	0.01, 0.09	.016
Months $\cdot$ replacement	0.029	-0.02, 0.08	.25

Months = The number of months for which a predicted diameter is being calculated; replacement = 0 for the inclusion technique and 1 for the replacement technique; CI = confidence interval. The diameters of the pulmonary autograft can be calculated for any postoperative time interval from the data in Tables III to V from the formula:

Diameter (mm) = $\beta_0 + \beta(\text{Replacement}) + \beta(\text{Months}) + \beta(\text{Replacement} \times \text{Months})$

where β_0 = the intercept, $\beta(\text{Replacement})$ = the regression coefficient for replacement, $\beta(\text{Months})$ = the regression coefficient for months (to be multiplied by the number of months), and $\beta(\text{Replacement} \times \text{Months})$ = the interaction regression coefficient (to be multiplied by "replacement" [0/1] $\times$ the number of months).

death due to a mountain climbing accident. The actuarial survival including the operative death was $97\% \pm 1\%$ at 6 years.

Fig 2. *Upper panel:* The diameter of the pulmonary autograft anulus (AA) decreased with time. *Lower panel:* The operative technique had no effect on changes in the diameter of the aortic anulus.

Table IV. Analysis of variance for changes in diameter of the aortic anulus

Effect	Regression coefficient	95% CI	P value
Intercept	25.2	24.2, 26.6	.0001
Replacement	0.072	—1.40, 1.54	.9
Months	—0.024	—0.07, 0.02	.25
Months · replacement	—0.007	—0.06, 0.05	.25

For legend, see Table III.

Reoperations on the pulmonary autograft. Four patients have required reoperation on the pulmonary autograft. In the first patient, moderate AI developed as a result of acute dilation of the entire pulmonary autograft 2 weeks after aortic root replacement. He underwent re-replacement of the aortic root with an aortic homograft.

In the second patient, who had had aortic root replacement, a false aneurysm developed between the mitral valve and the pulmonary autograft without AI. This was diagnosed on a routine echocardiographic

examination. The false aneurysm was successfully repaired with preservation of the pulmonary autograft.

A third patient had partial detachment of the proximal suture line of the pulmonary autograft and moderate AI, which were detected on a routine echocardiographic study 3 years after the operation. The technique of aortic root inclusion had been used. Dilation of the aortic anulus was thought to be the cause of this complication. This patient had aortic valve replacement with a mechanical valve.

A fourth patient needed mitral valve repair for mitral regurgitation resulting from advanced myxomatous disease of both leaflets 5 years after aortic root replacement with a pulmonary autograft. The mitral valve repair failed and since he had moderate AI and a dilated pulmonary autograft at 45 mm, both the mitral and the aortic valves were replaced.

These 4 patients survived reoperation. The freedom from reoperation on the pulmonary autograft was 91% $\pm$ 5% at 6 years.

AI. Transthoracic Doppler echocardiography in 117 patients before hospital discharge revealed no AI in 24

Fig 3. Upper panel: The diameter of the sinotubular junction (STJ) did not change with time. Lower panel: Analysis of covariance (ANOCOVA) showed that the diameter of the sinotubular junction increased in patients who had aortic root replacement (dotted line), whereas it decreased in those who had aortic root inclusion (solid line).

patients, trivial AI in 81, mild AI in 11, and moderate in 1. At the most recent study in 116 patients, including those echocardiograms done before reoperations on the pulmonary autograft, there was no AI in 18 patients, trivial in 59, mild AI in 32, and moderate in 7. Three of the 7 patients with moderate AI have undergone replacement of the pulmonary autograft (described earlier).

All patients with moderate AI had dilation of the aortic anulus and/or sinotubular junction. We could not establish a relation between the degree of dilation and the development of AI.

The freedom from moderate AI including patients who had reoperations was $92\% \pm 3\%$ at 6 years.

Functional status. At the latest follow-up visit, 113 patients were alive with their pulmonary autograft in place. Of those, 110 had no cardiac symptoms and were in New York Heart Association functional class I, and 3 patients were in functional class II.

Table V. Analysis of variance for changes in the diameter of the sinotubular junction

Effect	Regression coefficient	95% CI	P value
Intercept	28.1	26.9, 29.3	.0001
Replacement	0.912	—0.64, .47	.25
Months	—0.018	—0.06, .03	.4
Months · replacement	0.073	0.02, .13	.011

For legend, see Table III.

Discussion

Aortic valve replacement with a pulmonary autograft is a complex operation that provides excellent functional results in most patients, but it can also cause serious complications in some. As the experience with this operation increases, its merits and limitations become more evident.

Our study indicates that the pulmonary autograft

dilates in certain patients with bicuspid and other congenital aortic valve anomalies. We found that the technique of aortic root replacement was associated with a higher risk of dilation of the sinuses of Valsalva and sinotubular junction than the technique of aortic root inclusion. As expected, the operative technique had no effect on annular dilation. Unfortunately, our patients had only one early and one late measurement of the pulmonary autograft and it was not possible to determine other predictors of dilation. For the same reason, Figs 1 through 3 showed linear changes in the diameters of the pulmonary autograft, which in fact may be nonlinear.

Hokken and associates¹³ measured the diameters of the pulmonary autograft with echocardiography at various time intervals after the Ross procedure and found a significant increase in the diameters of the aortic anulus and sinuses of Valsalva. In most cases, dilation occurred during the first 10 postoperative days. During a mean follow-up of 2.3 years, the aortic anulus increased from 26.4 mm to 31.5 mm in 22 patients, and the diameter of the sinuses of Valsalva increased from 36.5 mm to 43.9 mm in 17 patients.¹³ Although those investigators claimed that no patient had severe AI develop (they did not address the issue of dilation of the sinotubular junction) and none required a reoperation, some of their patients had a pulmonary autograft with a transverse diameter of 55 mm. By most surgeons' criterion, an aortic root of 55 mm is an aneurysm that warrants surgical repair.¹⁰

Dilation of the pulmonary autograft is probably the most common cause of failure of the Ross procedure.^{8,14,15} Moritz and associates¹⁴ reduced the diameter of the aortic anulus and wrapped the pulmonary autograft with an absorbable mesh in a few patients as an attempt to prevent postoperative AI. Pacifico and colleagues¹⁵ described an operative technique whereby the entire pulmonary autograft was wrapped with glutaraldehyde-fixed bovine pericardium to prevent dilation. Elkins, Lane, and McCue⁸ reported a freedom from reoperation on the pulmonary autograft of $92\% \pm 3\%$ at 5 years. Eleven of 206 patients who had the Ross procedure required reoperation on the pulmonary autograft from 2 to 62 months after the operation.⁸ Those investigators believed that annular dilation was the principal cause of AI in 6 of their patients.

We initially believed that dilation of the pulmonary autograft occurred because of mismatch between the diameters of the anulus and sinotubular junction of the aortic root and those of the pulmonary root.¹² This happened early on in our experience with the Ross procedure when a fairly acute dilation of the pulmonary

autograft and AI developed in a patient.¹² We solved the problem of early dilation of the annular and sinotubular junction and AI by surgically reducing the diameters of the aortic anulus and ascending aorta to that of the pulmonary root.¹² However, continued follow-up of our patients revealed that these surgical maneuvers did not prevent late dilation of the pulmonary autograft in certain patients with bicuspid and other congenital aortic valve disease.

It has been demonstrated that dilation of the sinuses of Valsalva without concomitant dilation of the sinotubular junction does not cause AI.^{9,10} That is why patients with isolated sinus of Valsalva aneurysm do not have AI. Dilation of the sinotubular junction causes AI because it pulls the commissures of the aortic valve away from the center of the aortic root, preventing coaptation of the cusps.^{9,10} Dilation of the aortic anulus can also cause AI because it flattens the scalloped shape of the aortic anulus, preventing coaptation of the cusps.¹⁰

The diameters of the sinotubular junction and of the aortic anulus are related to the size of the aortic valve cusps.^{10,11} The components of the pulmonary root have the same geometric relationships as the aortic root.¹⁰⁻¹² Thus the diameter of the sinotubular junction and the diameter of the pulmonary anulus are related to the size of the pulmonary cusps. Although it is difficult to measure the diameter of the pulmonary anulus because it is attached to distensible right ventricular muscle, the diameter of the sinotubular junction can be easily measured with metric sizers. The geometric relationship between these two components in a semilunar valve indicates that the diameter of the anulus is approximately 10% to 20% larger than the diameter of the sinotubular junction.^{10,12} The diameter of the aortic root should also be measured during the performance of the Ross procedure. We firmly believe that mismatch between the diameters of the aortic root and of the pulmonary root causes AI.¹² For this reason, the aortic anulus should be reduced to the diameter of the pulmonary anulus if it is larger, and the same principle applies to the sinotubular junction.

We have not used a Teflon strip to buttress the proximal or distal anastomoses of the pulmonary autograft. However, our data suggest that it may be safer to do so to prevent dilation of the aortic anulus, as well as of the sinotubular junction. This maneuver would prevent dilation of the aortic anulus and sinotubular junction but would not prevent dilation of the sinuses of Valsalva when the Ross procedure is performed by the technique of aortic root replacement. We showed that the technique of aortic root inclusion prevents or at

least retards dilation of the sinuses of Valsalva and sinotubular junction. This operative technique is more complex than the one of aortic root replacement because the autograft has to be perfectly aligned within the aortic root to prevent AI. In addition, fixation of the aortic anulus with a strip of Teflon is not advisable because it alters the geometry of the anulus of the pulmonary valve when the inclusion technique is used. The aortic anulus can be fixed with a strip of Dacron fabric applied on the outside of its fibrous component.¹² These are probably the reasons why Elkins and associates⁵ found the technique of aortic root inclusion to be associated with a higher risk of AI than the technique of aortic root replacement, which they recommended. Presently, most surgeons prefer the technique of aortic root replacement when performing the Ross procedure.⁶

Bicuspid aortic valve is the most common cause of aortic valve disease in children and young adults in North America.¹⁶⁻¹⁹ Young patients with bicuspid aortic valve frequently have a dilated aortic root because of premature degenerative disease of the aortic root and ascending aorta.^{16,20} Erdheim's cystic medial necrosis has been described in the arterial wall of the ascending aorta and pulmonary artery in these patients.^{19,20} We found that degenerative changes in the media of the pulmonary artery are common in normal subjects, but they are more severe in patients with bicuspid aortic valve disease than in those with normal or diseased tricuspid aortic valve.²⁰ The pulmonary root may have inadequate elastic fibers and fibrillin in its media to adapt itself to the mechanical stress of the aortic root. For these reasons, it may be more appropriate to use subcoronary implantation to perform the Ross procedure when the pulmonary and the aortic roots have similar geometry and the aortic root inclusion technique in patients in whom the aortic root is larger than the pulmonary root. In these patients, a band of Dacron fabric should probably be used on the outside of the aortic anulus and the sinotubular junction to prevent late dilation. Fixation of these structures with Dacron fabric may be inappropriate in children.

Limitations of the study

Although we have no doubt that dilation and even aneurysm formation of the pulmonary autograft is a potential complication of the Ross procedure, our study contains several shortcomings. It is difficult to accurately measure the diameter of the aortic anulus and of the sinotubular junction soon after the Ross procedure with echocardiography. We chose to use the average values of the internal and external diameters in the

early studies as the most unbiased estimates because they were only slightly smaller than those values obtained by direct measurement at the time of operation. Another major shortcoming of this study is that we had only two echocardiographic studies per patient, one early and one late. Therefore, although the results in Figs 1 through 3 appear to be linear, it is highly probably that they are, in fact, nonlinear. Sequential examinations on the same patient would have provided a clearer temporal definition of dilation of the pulmonary autograft. We have since initiated such a study and ideally will be able to determine the factors associated with pulmonary autograft dilation.

Most of our patients had congenital aortic valve disease, an entity that is often associated with premature degenerative changes of the ascending aorta and pulmonary artery,^{19,20} and our conclusions are valid only for this patient population. Finally, all operations were performed by a single surgeon who has a certain bias regarding the functional anatomy of the aortic and pulmonary roots and may have introduced confounding factors that could not be assessed.

REFERENCES

1. Lower RR, Stofer RC, Shumway NE. Autotransplantation of the pulmonary valve into the aorta. *J Thorac Cardiovasc Surg* 1960; 39:680-7.
2. Ross DN. Replacement of the aortic and mitral valves with pulmonary autograft. *Lancet* 1967;2:956-8.
3. Stelzer P, Jones DJ, Elkins RC. Aortic root replacement with pulmonary autograft. *Circulation* 1989;80(Suppl):III209-13.
4. Kouchoukos NT, Davila-Roman VG, Spray TL, Murphy SF, Perrillo JB. Replacement of aortic root with a pulmonary autograft in children and young adults with aortic valve disease. *N Engl J Med* 1994;330:1-6.
5. Elkins RC, Knott-Craig CJ, Ward KE, Lane MM. The Ross operation in children: 10-year experience. *Ann Thorac Surg* 1998;65:496-502.
6. Oury JH, Hiro SP, Maxwell JM, Lamberti JJ, Duran CMG. The Ross procedure: current registry results. *Ann Thorac Surg* 1998; 66:S162-5.
7. Chambers JC, Somerville J, Stone S, Ross DN. Pulmonary autograft procedure for valve disease: long-term results of the pioneer series. *Circulation* 1997;96:2206-14.
8. Elkins RC, Lane MM, McCue C. Pulmonary autograft reoperation: incidence and management. *Ann Thorac Surg* 1996;62:450-5.
9. Furukawa K, Ohteki H, Cao ZL, et al. Does dilatation of the sinotubular junction cause aortic regurgitation? *Ann Thorac Surg* 1999;68:949-53.
10. David TE. Surgery of the aortic valve. *Curr Probl Surg* 1999; 36: 421-504.
11. Kunzelman KS, Grande KJ, David TE, Cochran RP, Verrier ED. Aortic root and valve relationship: impact on surgical repair. *J Thorac Cardiovasc Surg* 1994;55:162-70.
12. David TE, Omran A, Webb G, Rakowski H, Armstrong S, Sun Z. Geometric mismatch of the aortic and pulmonary roots causes

- aortic insufficiency after the Ross procedure. *J Thorac Cardiovasc Surg* 1996;112:1231-9.
13. Hokken RB, Bogers AJJ, Taams MA, et al. Does the pulmonary autograft in the aortic position in adults increase in diameter? An echocardiographic study. *J Thorac Cardiovasc Surg* 1998;113:667-74.
 14. Moritz A, Domanig E, Marx M, et al. Pulmonary autograft valve replacement in the dilated and asymmetric aortic root. *Eur J Cardiothorac Surg* 1993;7:405-8.
 15. Pacifico AD, Kirklin JK, McGiffin DC, Matter GJ, Nanda NC, Diethelm AG. The Ross procedure—early echocardiographic comparison of different operative techniques. *J Heart Valve Dis* 1994;3:365-70.
 16. Sadee A, Becker AE, Verheul HA, et al. Aortic valve regurgitation and the congenitally bicuspid aortic valve: a clinico-pathological correlation. *Br Heart J* 1992;67:439-41.
 17. Dare AJ, Veinot JP, Edwards WD, Tazelaar HD, Schaff HV. New observations on the etiology of aortic valve disease: a surgical pathology study on 236 cases from 1990. *Hum Pathol* 1993;24:1330-8.
 18. Hahn RT, Roman MJ, Mogtader AH, Devenaux RB. Association of aortic root dilation with regurgitant, stenotic and functionally normal bicuspid aortic valves. *J Am Coll Cardiol* 1992;19:283-8.
 19. McKusick VA. Association of congenital bicuspid aortic valve and Erdheim's cystic medial necrosis. *Lancet* 1972;1:1026-7.
 20. de Sa MPL, Moshkovitz Y, Butany J, David TE. Histologic abnormalities of the ascending aorta and pulmonary trunk in patients with bicuspid aortic valve disease: clinical relevance to the Ross procedure. *J Thorac Cardiovasc Surg* 1999;118:588-96.

Discussion

Dr Nicholas T. Kouchoukos (*St Louis, Mo*). Dr David and his colleagues, in their continuing and careful follow-up of patients who have had the Ross operation, have proposed yet another mechanism for the development of postoperative AI, dilatation of the sinotubular junction. This presumably is the result of inherent structural abnormalities of the pulmonary artery that are identical to those present in the aortas of patients with bicuspid aortic valves.

In a presentation before this Association 3 years ago, Dr David postulated that correction of any substantial geometric mismatch between the aortic and pulmonary valves would prevent AI. He and his colleagues reduced the diameter of the aortic anulus, the sinotubular junction, or both, in approximately two thirds of their patients. Despite these reductions, further follow-up has demonstrated dilatation, which is defined as an increase in diameter of the sinotubular junction and/or sinuses of Valsalva by serial echocardiographic studies. In both of these locations the dilatation occurred with approximately equal frequency whether or not the patient had reduction of the aortic anulus and/or the sinotubular junction. Not surprisingly, use of the root inclusion technique was protective against dilatation of the sinotubular junction and the sinuses, and Dr David recommends use of this technique whenever possible. It is of interest, however, that one of the three reoperations for AI occurred in a patient in whom the root inclusion technique was used.

Our own experience differs somewhat from that of Dr

David. We have performed sequential echocardiographic studies in our patients at 6- to 12-month intervals after the operation, and these have been interpreted by a single cardiologist. We perform annular reduction infrequently but in almost all cases tailor or replace the ascending aorta to conform to the size of the pulmonary artery and buttress the suture line between them with a felt strip. We do not perform the Ross operation in patients with an aortic anulus diameter of 30 mm or more.

Among 56 patients with serial measurements, 22 of whom have been followed up for more than 5 years, the sinotubular diameter increased by more than 20% in only 13% of the patients and the sinus diameter increased in 23%. We observed no significantly greater incidence of AI among these patients than among the remaining patients with no or lesser increases in these dimensions. Among the 22 patients with the longest follow-up, we have been unable to demonstrate a correlation between the severity or progression of AI and dilatation of the neo-aortic sinuses.

Histologic abnormalities of the ascending aorta are present in many patients with bicuspid aortic valves. In another study to be presented at this meeting, Dr David and his colleagues have demonstrated that similar structural abnormalities exist in the pulmonary arteries of many patients with bicuspid aortic valves, and they postulate that these abnormalities are most likely responsible for dilatation of the neo-aortic root and the development of AI. This is an intriguing hypothesis. However, a correlation between the severity of these changes in the pulmonary artery and the development of root dilatation and AI has not yet been demonstrated.

I have several questions. How did you determine that the value of 20% constituted a significant increase in the diameters of the sinotubular junction and of the sinuses of Valsalva?

What was the mean interval between the echocardiographic measurements? Is it possible that interobserver variability by your cardiologists could have produced errors in these measurements?

The great majority of patients currently undergoing the Ross operation have bicuspid aortic valves or congenital aortic valve disease. On the basis of your study, are you now recommending that the root replacement technique be abandoned in favor of the root inclusion technique in all of these patients? If not, in which patients should root replacement still be used?

If the root inclusion technique is used, is there not the potential for dilatation of the sinotubular junction and the development of AI as the native ascending aorta enlarges?

This important paper emphasizes the need for continuing critical evaluation of patients who have undergone the Ross operation to further refine the selection criteria and improve the late outcomes.

Dr David. Thank you, Dr Kouchoukos. I carefully stated that there could be bias that I could not detect in this study. All operations were performed by me, and we all have our own biases toward things we do. Perhaps these are the confounding factors that I could not detect in this study.

All echocardiograms included in this study were performed

at the hospital and reviewed by two cardiologists, both very experienced sonographers. I chose 20% as the amount of dilation that is significant because of our work in functional anatomy of the aortic root and that of other investigators. An interesting study by Dr Furukawa and colleagues on the role of the sinotubular junction and sinuses of Valsalva on the development of AI is being published in *The Annals of Thoracic Surgery*. Those investigators showed that dilation of the sinotubular junction caused AI, whereas dilation of the sinuses of Valsalva does not.

I believe we should abandon the technique of aortic root replacement in patients with bicuspid aortic valve. I am convinced, and one of our fellows will be presenting his work on this subject at the Lillehei Forum,²⁰ that most patients with bicuspid aortic valve have advanced degenerative changes in the arterial wall of the pulmonary trunk. By using the aortic inclusion technique, we may protect the pulmonary autograft from excessive dilation.

Finally, we should use a strip of Teflon felt on the inflow anastomosis between the left ventricular outflow tract and the pulmonary autograft and do the same or use a circumferential strip of Dacron graft at the level of its sinotubular junction, on the outside of the aorta.

Mr Donald N. Ross (*London, United Kingdom*). I enjoyed your paper very much. I was worried that you were going to shoot me down, but I am still here.

The first 251 patients in whom we did this operation had subcoronary implants. In fact, that was the original operation, and perhaps it has been misconstrued. However, the subcoronary operation was a big headache for us to achieve a competent valve both with it and the homograft. Once we had achieved that, those patients and their valves have withstood the test of time very well. My colleague, Dr Somerville in London, has followed them up over 30 years.

When the freestanding root was introduced with the homograft, everyone adopted it enthusiastically because of its competence and applied it automatically to the autograft. I wonder whether that was a mistake. From what you are saying, there may be some inherent disadvantages in using the root technique all the time. I am interested to hear that you are thinking in terms of inclusion roots in selected cases, in which the pathology progresses to aortic wall dilatation.

I think many people, and I am sure this does not apply to you, misapply the aortic root technique and put the valve in a supra-annular position quite unsupported. Even if it is technically correct, there are still cases in which the root perhaps should not be used. For instance, if there is a very small aortic root, we all agree that at least a relieving incision is necessary and perhaps also a Konno operation. In the presence of a satisfactory match, and this is usual, the root is probably appropriate, but what we still do not know is the effect of systemic pressure on the pulmonary artery wall. The problem arises when the root is markedly enlarged. I think we should abandon some of those operations and do a biopsy of the aortic root, retaining the pulmonary valve for a later day.

Would you recommend doing multicenter randomized

studies of the freestanding root, subcoronary, and inclusion root techniques in this operation or for the series of diseases that are quite new to me, such as the bicuspid valve and its aortic wall pathology? I am grateful that you have brought this information to my attention.

Dr David. Thank you very much, Mr Ross. This study was not meant to show that the Ross procedure is a bad operation. I think it is a wonderful operation, and that is what I would choose for myself if I needed an aortic valve replacement, although I may be a bit too old for it. I believe it is an excellent option for children and young adults, and I will continue to do it.

The question I am raising is whether the pulmonary arterial wall is strong enough to endure systemic pressure for the duration of the patient's life. The pulmonary root dilated in some. In my patients, I will do the Ross procedure by implanting the pulmonary autograft in the subcoronary position if the aortic and pulmonary roots have similar geometry and as an aortic inclusion technique in those in whom the aortic root is larger than the pulmonary root. In addition, the sinotubular junction of the pulmonary root should be fixed with a piece of Dacron graft to prevent dilation.

Dr Ronald C. Elkins (*Oklahoma City, Okla*). Dr David, you have raised an issue that concerns everyone who places the pulmonary valve in the systemic circulation. The dilatation that you have identified has been identified in patients who have undergone an arterial switch procedure, it has been identified in patients who have undergone a Damus-Kaye-Stansel procedure, and it clearly occurs in those patients who have a first-stage Norwood operation. The interesting thing about that is that the incidence of reoperation on the autograft is very low in all these groups of patients, including the Ross patients and those who have a root replacement.

If we look at the aortic valve disease—unicuspid, bicuspid, or tricuspid—we are unable to show any difference in terms of our total experience of over 350 patients in the incidence of postoperative AI or changes involved in terms of the aortic sinus or the aortic anulus. We do strongly believe that if the root replacement technique is to be used, one must fix the size of the aortic anulus when it is appropriately dilated, except in the very young child, as well as the size of the sinotubular junction.

I have two questions for you. In a patient with significant sinus dilatation of the pulmonary artery and normal autograft valve function, at what size would you recommend reoperation on that autograft? I am presently observing one patient with significant dilatation of the sinus and I would like to know your recommendation about that.

Second, when you look at the improved early results (ie, freedom from acute intervention) and the late long-term results of the root replacement, do you really feel comfortable in recommending that we move backward in terms of 10-year success of the operation, where at 10 years there is a significant improvement of root replacement over intra-aortic implants in terms of freedom from autograft valve dysfunction?

Dr David. Thank you, Dr Elkins. You were the one who

stimulated me to begin to do the Ross procedure in young patients.

The problem is that the autograft often dilates after the operation. Both the sinotubular junction and the sinuses of Valsalva dilate. Dilation of the sinotubular junction is more worrisome because it affects valve competence. Dilation of the sinuses of Valsalva simply causes an aneurysm. I have been aggressive in repairing aortic root and ascending aortic aneurysms and I believe these patients should be treated in the same fashion.

I have 3 patients with a neo-aortic root in excess of 50 mm in diameter, and I am planning to reoperate on them. I am hoping to be able to save the valves and perform an operation like the aortic valve-sparing operations that I have described in the past. I think these patients should be reoperated on when the sinuses of Valsalva exceed 55 mm in transverse diameter.

I disagree with you that the technique of aortic root inclusion is associated with higher incidence of late AI. If you open the aortic root along the noncoronary aortic sinus, all the way down to the aortic anulus, it is possible to secure the pulmonary autograft inside the aortic root without disturbing its geometry. I used this technique early in my experience and almost exclusively during the past year, and AI is not more prevalent in those patients than in those who had aortic root replacement. The only difference is that aortic root dilation is more common in the group who had aortic root replacement.

Dr James H. Oury (*Missoula, Mont*). I think this paper could be taken as a caution or even possibly as a call to abandon the operation. I am glad to hear you say that you certainly would not abandon it. I think it is a very good operation.

My opinion is that we need to improve technique. Since that has already been discussed, I will not elaborate any further except to make one point: in our series of Ross procedures, which now numbers 147, we have used the root replacement on all but 3 patients. There was no hospital mortality in this series. We have had 3 explants of the autograft,

so our actuarial survival is also 97%. In all of these cases we used annular plication and external support for the anulus, as well as the sinotubular junction. We initially did this because of some bleeding problems distally and quickly found that it not only eliminated the problem but also stabilized the sinotubular junction, as you have indicated. At follow-up, echocardiography showed progressive dilatation, mainly sinus dilatation, in about 10%.

I think your paper is very important in identifying a percentage of these operations that should be done as a subcoronary or as an inclusion technique. Could you further define what percentage of your cases you would now do as an inclusion or as a subcoronary procedure? Also, on the explanted cases, did you actually demonstrate viability of the explanted tissue?

Dr David. Stabilization of the sinotubular junction with a piece of Dacron graft is a new idea that we may have to incorporate in this operation. However, this technique could not be applied to children because it would prevent autograft growth.

In 3 patients who have been reoperated on, 2 of mine and 1 from another institution, the arterial wall of the autograft was viable but histologic examination revealed advanced elastic fragmentation and cystic medial necrosis; furthermore, both the gross and microscopic appearances were indistinguishable from that of degenerative aortic root aneurysm.

Like you, I do not plan to abandon the operation, but I will avoid performing it as a total root replacement. I started doing the Ross procedure by implanting the pulmonary valve in the subcoronary position, then changed to the aortic root inclusion technique, and later to aortic root replacement when Dr Elkins found a higher rate of AI with the two previous techniques. Last year I went back to the two initial techniques. If the aortic root cannot be used to wrap the pulmonary autograft, I use an autologous pericardial patch to close the aortotomy along the noncoronary sinus. I believe the pulmonary sinuses need some external support to prevent dilation.