Aortic root and valve relationships

Impact on surgical repair

A surgical procedure has recently been described for patients with aortic incompetence caused by annular dilation, but with normal aortic leaflets. The dilated aortic root is replaced with a Dacron graft, and the native aortic valve is resuspended within the graft. Matching the size and shape of the graft to the size of the leaflets may have significant effects on valve closure and leaflet stress and thus on the longevity of the repair. To define the relationship of native aortic root structure to leaflet size, we morphologically examined normal human aortic roots ($n = 10$) and valve leaflets and applied mathematic analyses to the results. Our data show that the root has a consistent shape with varying size and that there is a definable mathematic relationship between root diameter and clinically measurable leaflet dimensions. We derived an equation that allows calculation of the appropriate diameter of the root at the sinus of Valsalva level from leaflet heights and perimeters. The diameter of the graft at the sinotubular junction and base should follow the relationship of the normalized root dimensions, either by tailoring of the graft or by new graft design. The current data imply that the graft should incorporate sinuses for proper valve closure and for sharing stress with the leaflets. Application of these results will allow prosthetic graft design to more closely resemble the native aorta. These new grafts should improve physiologic function of the valve, reduce leaflet stress, and increase the durability of the repair. (J THORAC CARDIOVASC SURG 1994;107:162-70)

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Aortic valve insufficiency occurs secondary to both congenital and acquired disease processes. Abnormalities of either the aortic valve leaflets, the aortic root, or both may be responsible for the resulting valve incompetence. The single most common cause of aortic valve insufficiency in North America currently is annular dilation.^{1,2} The prevalence of annular dilation increased from 17% before 1980 to 37% in 1980 in a group of patients treated surgically for aortic valve insufficiency.² Conventional

treatment for annular dilation has generally been composite replacement of the ascending aorta with a synthetic graft, replacement of the native aortic valve with a prosthetic valve, and reimplantation of the coronary arteries into the graft.

However, in some patients the aortic leaflets are anatomically normal, with the primary pathologic conditions confined to the anulus and ascending aorta. In these patients, valve replacement may not be necessary. Because multiple complications such as hemolysis, thromboembolic or anticoagulation-related events, and mechanical failure are associated with aortic valve replacement,³⁻⁷ preservation of the native valve should be a priority whenever possible. David and Feindel⁸ have recently described such a procedure, in which the dilated aortic root is replaced with a Dacron graft and the native aortic valve is resuspended within the graft.

The short-term clinical results in a small number of patients have been encouraging, yet several concerns remain with the procedure. Inasmuch as the native valve is to be spared, matching the graft size and shape to the size of the leaflets may have significant effects on valve

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Fig. 1. Schematic representation of four levels of aortic root where measurements were taken.

Table 1. Human aortic root measurements

Level	Orifice area (cm ²)	Diameter (mm)*	Diameter (mm)†	Thickness (mm)	Interlevel distance (mm)
STJ ₁	3.40 ± 0.38	21.1 ± 1.0	20.6 ± 1.0	1.9 ± 0.2	10.0 ± 0.0
STJ ₀	2.98 ± 0.32‡	18.9 ± 0.9‡	19.3 ± 0.9‡	1.8 ± 0.2	7.3 ± 0.4
SINUS	4.49 ± 0.40§	22.4 ± 1.7§	23.7 ± 1.0§	1.3 ± 0.1	62.4 ± 0.4
BASE	4.24 ± 0.44	23.4 ± 1.2	23.0 ± 1.1	0.8 ± 0.1	

Values given as mean plus or minus standard error of the mean.

*Measured from specimen.

†Calculated from orifice area.

‡STJ₀ < STJ₁, < SINUS, < BASE, $p < 0.05$, ANOVA.

§SINUS > STJ₁, > STJ₀, $p < 0.05$, ANOVA.

closure, leaflet stress, and thus longevity of the repair. The relationship of native aortic root size and shape to leaflet size and shape has not been defined.

The present study was designed to answer two questions: first, does the human aortic root have a standard shape with varying size, and, second, is there a constant definable relationship between the root and clinically measurable leaflet dimensions? To begin to answer these questions, we morphologically examined normal human aortic roots and valve leaflets and applied mathematic analyses to the results. Application of the results may allow prosthetic graft design to more closely resemble the native aorta. This should improve physiologic function of the valve, reduce leaflet stress, and increase the long-term durability of the repair.

Methods

The structure of the aortic root and valve was examined in cryopreserved normal adult human specimens obtained from a local tissue bank ($n = 10$). The research was approved by the Human Subjects Committee at the University of Washington. In all cases the donor cardiac anatomy was normal, but the root specimens were unsuitable for transplant because of insulin-dependent diabetes, abnormal clotting profiles, bacterial contam-

ination of the specimen, and other reasons. The donor group included one woman and nine men. Mean age was 39 ± 12 years (range = 18 to 54). The specimens were thawed according to tissue bank protocol and prepared for measurement by trimming the ascending aorta to 1 cm above the sinotubular junction (STJ).

Root dimensions. The aortic root was sectioned sequentially for measurement at four levels: 1 cm above the STJ (STJ₁), at the STJ (STJ₀), at the center of the sinuses of Valsalva (SINUS), and at the base attachment of the root (BASE) (Fig. 1). The distance between levels was measured to the nearest millimeter. Inner and outer diameter and wall thickness of the aortic root were measured with a flexible ruler to the nearest 0.5 mm. These measurements were taken at reproducible locations above the right and left coronary ostia and the corresponding noncoronary area. The cut edge of the cross section was then dyed with methylene blue and imprinted onto white paper. The orifice area was determined by digitizing the inner perimeter of the imprint with the use of a computerized morphometric analysis program (Morpho, ESD Software/Advanced Quonset Technology Seattle, Wash.). A second inner diameter measurement was then calculated from this digitized area assuming a circular cross section. This method was used to normalize for the irregular shape of the root below the STJ.

Root data analysis. To clarify the size relationships among the four aortic root levels, means and standard errors were calculated for orifice area, inner diameter, and wall thickness at each level. To determine whether diameter variations among the

Fig. 2. Schematic representation of measurements taken from each of leaflets while still attached to aortic wall.

Table II. Normalized human aortic root dimensions

Level	Diameter	Interlevel distance
STJ ₁	0.87 ± 0.02	0.44 ± 0.01
STJ ₀	0.81 ± 0.02*	0.32 ± 0.01
SINUS	1.00 ± 0.00†	0.26 ± 0.01
BASE	0.97 ± 0.02	

Values are unitless; mean plus or minus standard error of the mean.

*STJ₀ < STJ₁, < SINUS, < BASE, $p < 0.05$, ANOVA.

†SINUS > STJ₁, > STJ₀, $p < 0.05$, ANOVA.

four levels were consistent with changing root size, the inner diameter, wall thickness, and distance between measurement levels were nondimensionalized. This was accomplished for each specimen by dividing every measurement by the diameter at the SINUS level. As a result, the diameter at the SINUS level is represented by a value of one, and all other values are represented by a fraction or percentage of this number. Statistical analysis (one-way analysis of variance [ANOVA]) was done to analyze the variation of orifice area and diameter at the four levels.

Leaflet dimensions. Before the aortic root was sectioned through at the SINUS level, the root was opened between the right and noncoronary leaflets. While the leaflets were still intact, the leaflet height, commissural height, free margin length, and attached edge length were measured for the right, left, and noncoronary leaflets (Fig. 2). Measurements were taken by laying a suture along the specified dimension and comparing the suture length to a ruler (to the nearest 0.5 mm). The leaflet was then excised from the root, and the free margin and attached edges traced and subsequently digitized for calculation of leaflet area. The perimeters (P) of the intact valve leaflets were calculated by adding the free margin (L_{fm}) and attached edge (L_{ae}) lengths ($P = L_{fm} + L_{ae}$).

Leaflet data analysis. Means and standard errors of the leaflet measurements (leaflet height, free margin length, attached edge length, commissural height, perimeters, and leaflet area) were first calculated individually for the right, left, and noncoronary leaflets across all 10 specimens. Statistical analysis (one-way ANOVA) was done to determine any signif-

icant differences on the basis of leaflet position. Next, the average values for the right, left, and noncoronary measurements were calculated within each individual specimen.

Root/valve leaflet relationships. Our purpose in calculating leaflet dimensions was to identify predictors of root size. For each specimen, one of the root dimensions (either orifice area or diameter) at each of the four levels was plotted against one of the averaged leaflet dimensions (leaflet height, free margin length, attached edge length, commissural height, perimeters, or leaflet area). Mathematic curve fitting (linear, polynomial, exponential, or logarithmic) was done and regression analysis was performed to determine the level of correlation.

Results

Root dimensions. The root measurements are given in Table I. The first diameter listed is the measured average from the intact specimens, and the second diameter listed is calculated from the orifice area. This was done as a way to normalize for the irregular shape of the orifice at the BASE and SINUS levels. In terms of both orifice area and related diameter, the aortic root was narrowest at the STJ₀ level and widest at the SINUS level (one-way ANOVA, $p < 0.05$). Wall thickness also varied with the measurement level; it was a maximum at the STJ₁ level and decreased progressively toward the BASE level. Additionally, the wall thickness was variable within each cross section. The wall was thickest near the commissures and thinnest at the middle of the sinuses.

To determine whether the variations in diameter were consistent with changing root size, the inner diameter, wall thickness, and distance between measurement levels were nondimensionalized for each specimen (Table II). The standard error associated with each level was very small, which indicates a very consistent root shape for all sizes. A better understanding of the root shape is gained when these values are shown graphically (Fig. 3).

Leaflet dimensions. The results of the measurements of leaflet dimensions are shown in Table III. Consistent

Fig. 3. Shape of nonpressurized human aortic root, on basis of dimensions that have been normalized to overall size of specimen. Values are unitless.

Table III. Human aortic leaflet dimensions

	Right	Left	Noncoronary	Average
Height (cm)	1.33 ± 0.06	1.39 ± 0.08	1.37 ± 0.04	1.36 ± 0.06
Free margin length (cm)	3.30 ± 0.14	3.15 ± 0.14*	3.27 ± 0.13	3.24 ± 0.13
Attached edge length (cm)	4.64 ± 0.20	4.76 ± 0.22	4.81 ± 0.16	4.74 ± 0.19
Perimeter (cm)	7.94 ± 0.33	7.91 ± 0.35	8.08 ± 0.28	7.98 ± 0.31
Area (cm ²)	2.97 ± 0.17	3.09 ± 0.27	3.17 ± 0.18	3.07 ± 0.21

Values given as mean plus or minus standard error of the mean.

* $p < 0.05$, left < right, left < noncoronary, one-way ANOVA.

with previously published observations, there is some variation in size among leaflets.⁹⁻¹¹ Overall, the noncoronary leaflet tends to be the largest of the three leaflets, and the right tends to be the smallest; however, most of these differences are not statistically significant.

Orifice/leaflet relationships. Our purpose in calculating leaflet dimensions was to identify predictors of root size. Thus we examined numeric relationships between root orifice area and leaflet measurements. One of the root dimensions at each of the four levels was plotted against one of the averaged leaflet dimensions, and curves were fit to the data. The best correlation was demonstrated for orifice area versus total leaflet area. In all cases the relationship is linear, with correlation coefficients ranging from 0.86 to 0.94.

Thus the root orifice area at varying levels correlates with total leaflet area. However, our purpose was to define a relationship of root dimensions to *clinically measurable* leaflet dimensions, and area cannot be measured in the intact valve. We plotted leaflet area versus leaflet height, edge lengths, or perimeter to determine whether we could

calculate leaflet area from one of these dimensions. We found that the relationships had a low level of correlation or were nonlinear. We then sought to define a new variable that could be calculated from leaflet measurements. We defined an area analog (AA, units in square centimeters) as follows: $AA = \frac{1}{2} \cdot PH_L$ (where P = perimeter and H_L = leaflet height).

To determine the level of correlation, the measured leaflet areas were plotted versus the calculated area analog (on both an individual leaflet and average basis; Fig. 4). For individual leaflets, regression analysis showed the relationship of the measured area to the area analog to be linear, with a correlation coefficient of 0.90. If the average measured area is plotted versus the average area analog for each specimen, better correlation is demonstrated, with a coefficient of 0.96. The area analog allowed us to calculate leaflet area from dimensions that are clinically measurable in an intact valve.

To verify that the new derived measurement (area analog) could be used as a predictor of root size, the orifice area was plotted versus leaflet area analog (Fig. 5).

Fig. 4. Leaflet area versus area analog. A, Each value corresponds to an individual leaflet; B, each value corresponds to average leaflet area or area analog for each specimen. Linear regression equations and coefficients are given.

Regression analysis showed the relationships to be linear, with correlation coefficients ranging from 0.88 to 0.93. Thus orifice area is related to clinical measures of leaflet size. On the basis of these results, the appropriate diameter of the root can be calculated by combining three equations. The first is the known geometric relationship of area to diameter:

$$OA = \pi D^2/4 \quad (1)$$

where D = diameter and OA = orifice area. The second is the regression equation calculated for the relationship of orifice area to leaflet area analog (at the SINUS level):

$$OA = -0.18691 + 0.85933 (AA)_{Ave} \quad (2)$$

where AA = area analog. The third is the definition of area analog:

$$AA = \frac{1}{2} \cdot PH_L \quad (3)$$

where P = perimeter and H_L = leaflet height. Substituting equation 3 into 2, and subsequently equation 2 into 1, and solving for diameter gives:

$$D = 0.740 \sqrt{(PH_L)_{Ave} - 0.435} \quad (4)$$

To calculate the diameter of the root at the SINUS level, one would measure the height and perimeters of each leaflet, take the average of the product ($P \cdot H_L$), and plug the value into the formula (all values in centimeters). This equation was applied to the morphologic data obtained in this study. The average predicted diameter was slightly lower than the average measured diameter

with less than half a millimeter standard error (average difference was -0.11 ± 0.48 mm). A simple linear regression was performed on $D_p = \beta_1 D_m$ to determine the relation of the predicted diameter (D_p) to the measured diameter (D_m), where β_1 is the slope of the regression line. The analysis demonstrated a significant relation between the predicted and measured values, with β_1 equal to 1.00159 and an R value of 0.998 (Fig. 6). In addition to the raw data and regression line, 95% confidence limits are given.

The equation can be represented in table form, where the calculated diameter is rounded off to the nearest millimeter (Table IV). Thus, with averaged measurements of leaflet perimeters and height, the appropriate aortic root diameter at the SINUS level can be easily calculated.

Discussion

If annular dilation is the primary pathologic process leading to aortic valve incompetence, preservation of the leaflets avoids many of the potential complications of prosthetic valve replacement. David and Feindel⁸ have recently reported such a surgical technique for correction of aortic incompetence caused by annular dilation, with sparing of the aortic valve. The dilated aortic root is replaced with a Dacron graft, and the native aortic valve is resuspended within the graft, similar to the technique used to insert a freehand homograft valve. Reducing the size of the dilated aortic anulus is accomplished by selecting an appropriately sized graft, smaller than the diseased anulus.

Fig. 5. Orifice area versus area analog. A, At STJ and 1 cm above; B, at sinus and base. Linear regression equations and coefficients are given.

Fig. 6. Diameter values predicted by algebraic equation (on basis of leaflet perimeter and height) versus measured diameter from human specimens at sinus level. CL, confidence limits.

To achieve valve competence with resuspension of the native valve within the prosthetic graft, predictable matching of graft diameter to leaflet size is essential. This match will affect immediate valve competence, leaflet

stress, and preservation of long-term valve function. Our study was designed to define the relationship between root size and shape versus leaflet dimensions. Morphologic examination of normal adult human aortic roots and

Table IV. Calculation of SINUS diameter from averaged leaflet perimeter and height

Height (cm)	Perimeter (cm)															
	7.0	7.2	7.4	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	9.4	9.6	9.8	10
1.0	16	17	17	17	17	18	18	18	18	19	19	19	19	20	20	20
1.1	17	18	18	18	18	19	19	19	20	20	20	20	21	21	21	21
1.2	18	19	19	19	19	20	20	20	21	21	21	21	22	22	22	22
1.3	19	19	20	20	20	21	21	21	22	22	22	22	23	23	23	23
1.4	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	24
1.5	21	21	21	22	22	22	23	23	23	24	24	24	25	25	25	25
1.6	22	22	22	23	23	23	24	24	24	25	25	25	25	26	26	26
1.7	22	23	23	23	24	24	24	25	25	25	26	26	26	27	27	27
1.8	23	23	24	24	24	25	25	26	26	26	27	27	27	28	28	28
1.9	24	24	25	25	25	26	26	26	27	27	27	28	28	28	29	29
2.0	24	25	25	26	26	26	27	27	27	28	28	29	29	29	30	30
2.1	25	26	26	26	27	27	27	28	28	29	29	29	30	30	30	31

valve leaflets and mathematic analysis showed that, first, the root has a consistent shape with varying size and, second, there is a definable mathematic relationship between root diameter and clinically measurable leaflet dimensions. Application of the results should allow us to make the graft design more closely resemble the native aorta, to improve physiologic function of the valve and long-term durability of the repair.

Root shape. The shape of the human aortic root was found to be consistent, over a wide range of sizes. The diameter and orifice area of the root were always greatest at the level of the sinuses. The diameter decreased slightly at the BASE level (97% compared with SINUS level) and decreased significantly at the STJ₀ level (81%). The presence of the sinuses of Valsalva does affect aortic valve function, because of the effects on fluid flow, as well as stress distribution in the leaflets.

The importance of the sinuses and their role in creation of fluid eddy currents was recognized as early as 1513 by Leonardo da Vinci.¹² The role of the sinuses has since been further examined by Bellhouse^{13, 14} with a fluid dynamics model. The model demonstrates the formation of fluid flow eddies and explains the effects on opening and closing of the leaflets. According to Bellhouse's model, early in systole the leaflets move toward the sinuses and vortices form between the leaflet and sinus wall. Flow enters at the ridge of the STJ, curls along the wall, and then flows back into the main stream. On valve opening, these eddies prevent the aortic leaflets from impacting on the aortic wall. The eddies also promote valve closure. After peak systole, the eddies force the leaflets to move away from the wall with increasing speed, and the valve is almost closed before the end of systole. A significant finding from the model was that the initial vortices formed even if the shape of the sinuses was altered. This implies

that the sinus ridge, not the shape of the sinuses, is the most important factor in causing initial fluid flow eddies.

Though the exact shape of the sinus may not have a direct effect on initial eddy formation, it does affect valve function in other ways. The importance of sinus curvature and its effect on stress distribution with the leaflets has been studied with the use of marker fluoroscopy techniques in dogs.¹⁵ It has been observed that the diastolic shape of the sinuses is nearly spherical and the shape of the leaflets is cylindrical (in the load-bearing area).¹⁶ By engineering analysis, the stress carried by the leaflets in diastole was calculated to be four times as high as the stress in the sinuses. If the leaflet stress was not shared with the sinuses, the sinus walls would be pulled inward during diastole. The marker studies demonstrated that the sinus walls move outward instead, implying that part of the load on the leaflets is taken up by the sinus walls. This stress sharing decreases the stress and the wear on the leaflets.

The importance of the sinus shape and the presence of a distinct sinus ridge can be examined in relation to the surgical technique for replacement of the aortic root with preservation of the leaflets. In the present technique, a straight tube graft without sinus components is used as a root replacement. This approach raises several theoretic problems. With respect to fluid flow, the lack of sinuses in this graft may not allow for optimal opening and closure of the native valve. With no distinct sinus ridge, fluid flow eddies may not form as readily behind the leaflets. On opening, the leaflets may be more likely to impact on the graft wall, subjecting them to potential damage. In addition, a delay in eddy formation would delay initiation of valve closure, and some regurgitation may result. With respect to stress sharing, a straight tube graft root replacement may not be geometrically suited to take up

stress from the leaflets. Abnormal stress on the leaflets may decrease the potential longevity of the repair. An optimal design for root replacement would incorporate sinuses and a sinus ridge to promote proper valve opening and closure, as well as decreased stress on the leaflets.

Relationship of root size to leaflet dimensions. To use any root replacement design, we need to know the relationship between normal root shape and leaflet dimensions. Our investigation defined the mathematic relationship between root diameter at the SINUS level and clinically measurable leaflet dimensions (perimeter and height). Initial analysis of the data demonstrated good correlation between the orifice area of the aortic root and leaflet area. However, leaflet area cannot be easily measured in an intact valve. We needed a way to determine leaflet area from obtainable measurements. Regression analysis showed that leaflet area could not be accurately calculated from leaflet height, perimeter, free margin length, or attached edge length alone. The relationships between area and each linear dimension were generally nonlinear and did not demonstrate a high degree of correlation.

To have a term that would be in the same units of area, and that could be calculated from other leaflet dimensions, we defined an area analog ($\frac{1}{2} \cdot \text{perimeter} \cdot \text{height}$). Regression analysis between measured leaflet area and the calculated area analog demonstrated excellent correlation. Thus the area analog can be substituted for the measured area. The relationships between orifice area and leaflet area analog were defined by regression analysis. Using the regression equation at the SINUS level, the area analog equation, and the relationship of area to diameter, we derived an equation that allows calculation of the appropriate diameter at the SINUS level. With this one equation, a few measurements of the leaflets can be made in vivo and the diameter can be calculated from the equation, or more simply from a table (Table IV). The appropriate diameter of the root replacement at the BASE and STJ₀ levels would then be a percentage of the calculated diameter at the SINUS level (97% and 81%, respectively).

Study limitations. The limitation of this study is that the measurements of the aortic root were taken from nonpressurized, excised specimens. It is known that the aortic root expands under pressure, and compliance of the aorta has been reported to be as high as 18.2%.^{17, 18} (Compliance was reported as percent change in diameter per 100 mm Hg.) At a physiologic pressure of 120 mm Hg, the diameter of aorta may increase as much as 20%. Thus the mathematic relationship of root diameter to leaflet dimensions will change under pressure.

If the material replacement for the aortic root had the

mechanical properties similar to that of the aorta, a graft could be designed on the basis of the nonpressurized measurements, knowing that the graft would expand with pressure. However, the current available graft materials (Dacron fabric and expanded polytetrafluoroethylene) have reported compliance values from 1% to 2%.¹⁹⁻²¹ At 120 mm Hg, the graft would undergo only small changes in diameter, on the order of 2% to 3%. The compliance mismatch will result in a stress concentration at the aorta/graft anastomosis and may lead to dehiscence of the anastomosis. In addition, the lack of graft extensibility may decrease the potential for stress sharing with the leaflets. Both of these effects will decrease the longevity of the repair. The data reported in this paper refer only to the relationship of root shape with leaflet dimensions in the nondynamic state. We are currently using magnetic resonance imaging and finite element analysis to further define the relationship in dynamic functioning states.

Conclusions. Aortic incompetence secondary to aortic root dilation has posed a difficult problem for the surgeon and the biomedical engineer. Initial efforts were aimed at replacing the valve and aorta with a composite graft incorporating an artificial graft and valve prosthesis. Excellent results have been obtained. However, there are compelling reasons to consider sparing the aortic valve whenever possible; multiple complications such as hemolysis, thromboembolic or anticoagulation-related events, and mechanical failure are associated with aortic valve replacement. An innovative means of correcting annular dilation to correct aortic incompetence while preserving the aortic valve has been described. Initial clinical cases have shown this to be an acceptable surgical procedure. However, the challenge now exists for the surgeon and biomedical engineer to make the graft design more closely resemble the native aorta, to improve physiologic function of the valve and the long-term durability of the repair. We have defined a mathematic relationship between root size and leaflet dimensions. To determine the appropriate diameter of the graft replacement at the sinus level, one can measure the leaflet height and perimeter and plug these dimensions into the formula derived from known equations and regression analysis. The diameter of the graft at the STJ and base should follow the relationship of the normalized root dimensions, either by tailoring the graft or by new graft design. The current data imply that the graft should incorporate sinuses. Resulting fluid flow eddies will promote proper valve closure and will lessen leaflet impact during opening. Additionally, properly shaped sinuses will allow stress sharing with the leaflets. These factors should increase the longevity of the repair. Finally, to optimize the procedure, we must look to new material designs that more closely mimic the natural

aorta. We hope that combining magnetic resonance imaging and finite element analysis will help us in optimizing graft design.

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