Two-Dimensional Echocardiographic Aortic Root Dimensions in Normal Children and Adults

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Two-dimensional echocardiography is increasingly used to measure aortic root dimensions, which provide prognostic information in aortic regurgitation and the Marfan syndome. Aortic root dilatation is currently detected by nomograms based on M-mode echocardiographic data. Aortic root diameters measured by 2-dimensional echocardiography at the anulus, sinuses of Valsalva, supraaortic ridge and proximal ascending aorta in 135 normal adults and 52 normal children were compared with age, gender, body habitus, blood pressure and stroke volume, and with M-mode findings and normal limits. Two-dimensional measurements at the sinuses of Valsalva were larger than M-mode aortic root values ($p < 0.001$), and use of 2-dimensional values with M-mode nomograms falsely diagnosed aortic dilatation in 40% of normal children and 19% of normal adults. Two-dimensional measurements at the sinuses closely correlated with body surface area in children ($r = 0.93$, $p < 0.0005$), moderately in adults younger than 40 years of age ($r = 0.71$, $p < 0.0005$) and weakly in older adults ($r = 0.40$, $p < 0.0005$). In adults, gender influenced aortic root size at all levels ($p < 0.001$), but dimensions were similar when indexed for body surface area. Age strongly influenced supraaortic ridge and ascending aortic diameters; blood pressure and stroke volume had no independent effect on aortic size.

In conclusion, (1) 2-dimensional echocardiographic aortic root dimensions are influenced by age and body size but not by blood pressure; (2) aortic root dilatation is overdiagnosed when aortic diameter at the sinuses of Valsalva is compared with M-mode nomograms; (3) nomograms comparing aortic diameter with body surface area should be used in children; and (4) although use of nomograms based on body size in adults should maximize sensitivity for aortic dilatation, 98% specificity is attained by use of an upper normal limit of 2.1 cm/m² for aortic diameter at the sinuses of Valsalva in both men and women.

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Two-dimensional echocardiography readily visualizes the aortic root and is increasingly used to measure aortic dimensions. Dilatation extending above the sinuses of Valsalva to involve the supraaortic ridge has been shown to be of prognostic significance in both aortic regurgitation and in the Marfan syndrome.[1-3] However, partition values and nomograms standardly used to detect aortic dilatation by echocardiography in children and adults are based on M-mode data.[4-6] Available 2-dimensional echocardiographic studies of normal subjects are limited by small sample size[7,8] and incomplete measurements.[7,9] Hence, we compared aortic root dimensions measured by 2-dimensional echocardiography at 4 levels from the valve anulus to the ascending aorta in a large population of normal infants, children and adults with age, gender, indexes of body size, blood pressure and stroke volume, and to M-mode echocardiographic dimensions. Nomograms and partition values for upper normal limits of 2-dimensional echocardiographic aortic measurements are presented.

METHODS

Subjects: The study population consisted of 52 normal infants and children, and 135 normal adults studied in the Pediatric and Adult Echocardiography Laboratories at the New York Hospital-Cornell Medical Center. The 28 boys and 24 girls ranged in age from 1 month to 15 years (mean 9 ± 5 years). Body surface area ranged from 0.18 to 1.99 m² (mean 1.11 ± 0.44). The clinical records and echocardiograms were reviewed by a pediatric cardiologist to verify normality. In most instances, echocardiograms had been performed to exclude forms of congenital heart disease. The normal adult population consisted of 68 men and 67 women from 20 to 74 years of age (mean 43 ± 15). Body surface area ranged from 1.29 to 2.40 m² (mean 1.85 ± 0.22), and was significantly greater in men (1.99 ± 0.15 vs 1.70 ± 0.16 m², $p < 0.001$). Blood pressure was determined in all adults by cuff sphygmomanometry in the supine position after echocardiography. Average pressures were

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TABLE I Relation of Aortic Root Diameters to Age, Body Habitus and Hemodynamic Variables in Adults by Univariate Analysis

	Anulus		Sinuses of Valsalva		Supraaortic Ridge		Proximal Ascending Aorta	
	r Value	p Value	r Value	p Value	r Value	p Value	r Value	p Value
Age	0.12	NS	0.40	<0.0005	0.44	<0.0005	0.67	<0.0005
Body surface area	0.68	<0.0005	0.50	<0.0005	0.44	<0.0005	0.37	<0.0005
Height	0.58	<0.0005	0.44	<0.0005	0.37	<0.0005	0.30	<0.0005
Weight	0.60	<0.0005	0.43	<0.0005	0.39	<0.0005	0.33	<0.0005
Body mass index	0.26	<0.005	0.18	<0.05	0.18	<0.05	0.17	<0.05
Systolic blood pressure	0.19	<0.05	0.21	<0.01	0.23	<0.01	0.29	<0.001
Diastolic blood pressure	0.17	<0.05	0.26	<0.005	0.27	<0.005	0.26	<0.005
Stroke volume	0.45	<0.005	0.26	<0.005	0.25	<0.005	0.18	<0.05

NS = not significant.

126 ± 14/77 ± 9 mm Hg, with no difference between men and women. The normal adults were members of a healthy, employed population, and unaffected relatives and spouses of patients evaluated in ongoing family studies of mitral prolapse and the Marfan syndrome.[10-12] Body mass index (weight in kg/[height in m^2]) was calculated in adults as an index of obesity.[13]

Echocardiography: Echocardiograms were performed in the left decubitus position by an experienced technologist. M-mode tracings were obtained in adults using 2-dimensional guidance. Up to 6 cycles of the aortic root and left ventricle were marked on M-mode tracings according to the recommendations of the American Society of Echocardiography,[14] and measured and averaged using a commercially available digitizing tablet. Left ventricular stroke volume was calculated using the Teichholz correction,[15] a method validated by comparison with invasive measurements.[16] Using a Diasonics CardioRevue Center (Diasonics, Inc.), 2-dimensional measurements of the aortic root were made at end-diastole in parasternal long-axis views at 4 levels: (1) anulus (defined echocardiographically as the hinge points of the aortic cusps); (2) sinuses of Valsalva; (3) supraaortic ridge; and (4) proximal ascending aorta[1] (Figure 1). Measurements were made perpendicular to the long axis of the aorta using the leading edge technique in views showing the largest aortic diameters. Aortic root measurements were also made in short-axis views at the level of the valve leaflets.

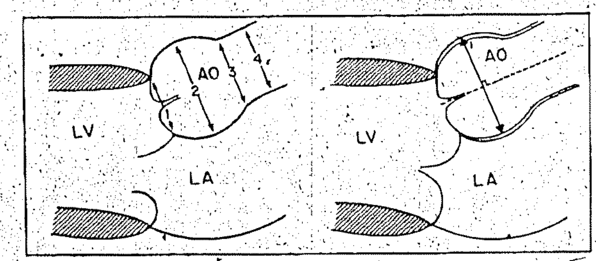

FIGURE 1. ***Left,*** **schematic illustration of the aortic root in the 2-dimensional parasternal long-axis view. Measurements were obtained at 4 levels, including the anulus, sinuses of Valsalva, supraaortic ridge and proximal ascending aorta.** ***Right,*** **measurements were made perpendicular to the long axis of the aorta using the leading edge technique. Ao = aorta; LA = left atrium; LV = left ventricle.**

Statistical analyses: Mean values are presented with 1 standard deviation as the index of dispersion and were compared using the unpaired Student *t* test. The relation between continuous variables was tested by linear regression analysis. Independence of relation was determined by stepwise multiple linear regression. Approximately 95% normal confidence limits were derived as 2 standard errors of the estimate for aortic root dimensions above and below the regression line of the variable with body size. For the relations between aortic diameter at the sinuses of Valsalva and supraaortic ridge (Figures 2 to 5), these confidence intervals encompassed 350 of 359 (97%) of data points, whereas only 2 of 359 (0.6%) of normal values fell above normal limits.

RESULTS

Comparison of M-mode and 2-dimensional values: Highly significant relations were found between M-mode values and 2-dimensional measurements ($p < 0.0005$ for all comparisons) in the parasternal long-axis view at the level of the anulus ($r = 0.60$), sinuses of Valsalva ($r = 0.83$), supraaortic ridge ($r = 0.74$) and proximal ascending aorta ($r = 0.69$), as well as in the short-axis measurements at the level of the aortic valve ($r = 0.80$). Nonetheless, 2-dimensional measurements were systematically larger than those made by M-mode echocardiography (3.17 ± 0.39 at the sinuses of Valsalva, and 3.09 ± 0.42 cm on short axis vs 2.98 ± 0.39 cm by M-mode, $p < 0.001$ and $p < 0.05$, respectively). Use of standard M-mode nomograms[4,5] to compare aortic root dimension at the sinuses of Valsalva with body surface area resulted in false positive diagnoses of aortic dilatation in 21 of 52 (40%) normal children and 25 of 135 (19%) normal adults.

Aortic root dimensions in children: Aortic dimensions at all levels in infants and children correlated closely with both age ($r = 0.87$ to 0.90, $p < 0.0005$) and body surface area ($r = 0.90$ to 0.93, $p < 0.0005$). In multivariate analyses, body surface area was the only independent predictor of aortic dimensions. Age, body surface area and aortic root dimensions at each level and the relations among these variables were similar in boys and girls. The individual data points and nomograms relating body surface area to aortic root diameters at the sinuses of Valsalva and the supraaortic ridge are shown in Figures 2 and 3.

Aortic root dimensions in adults: Two-dimensional aortic diameters in adults correlated strongly with age, body surface area, height and weight, and less well with hemodynamic parameters, that is, systolic and diastolic blood pressures and stroke volume (Table I). Aortic anular diameter correlated most closely with body surface area and with cardiac pump performance, as measured by left ventricular stroke volume, whereas ascending aortic diameter related most closely to age, and nearly as closely to systolic blood pressure as to body surface area. Multivariate analysis indicated that body surface area was the most important independent determinant of aortic diameter at the anulus and sinuses of Valsalva, whereas age most strongly influenced supraaortic ridge and proximal ascending aortic diameters (Table II). Blood pressure and stroke volume had no independent effect on aortic size at any level. Use of body mass index and height as independent indexes of body size in multivariate analyses revealed that height was more closely related to aortic dimensions, although it did not improve the univariate relations between body surface area and aortic root diameter; in additional analyses, aortic diameter was more closely related to height than weight at all levels except the valve anulus.

The influence of age on the relation of body surface area to normal limits for aortic diameter at the sinuses of Valsalva and supraaortic ridge is shown in Figures 4 and 5. Two-dimensional measurements at the sinuses and supraaortic ridge were more strongly related to body surface area in adults younger than 40 years of age ($r = 0.71$ and 0.66, respectively, both $p < 0.0005$)

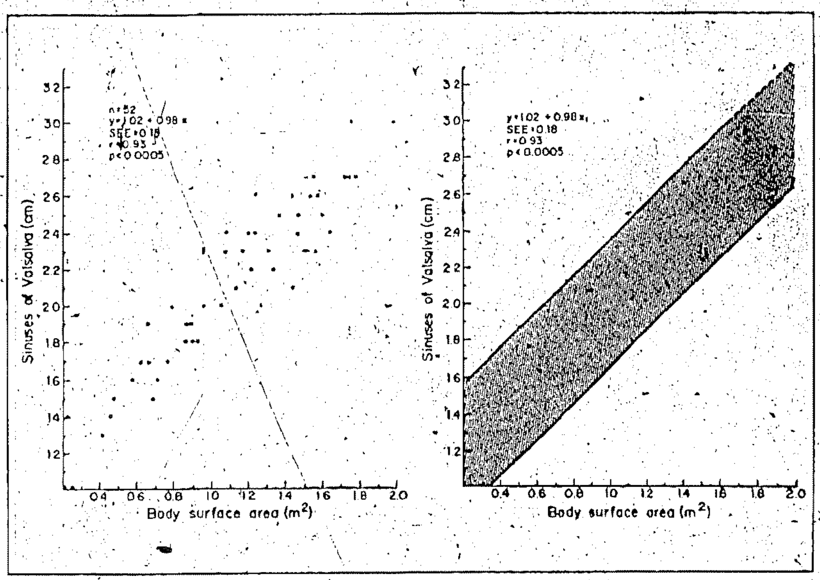

FIGURE 2. ***Left,*** **relation of body surface area to aortic root diameter at the sinuses of Valsalva in normal infants and children.** ***Right,*** **95% normal confidence limits for aortic root diameter at the sinuses of Valsalva in relation to body surface area in infants and children.**

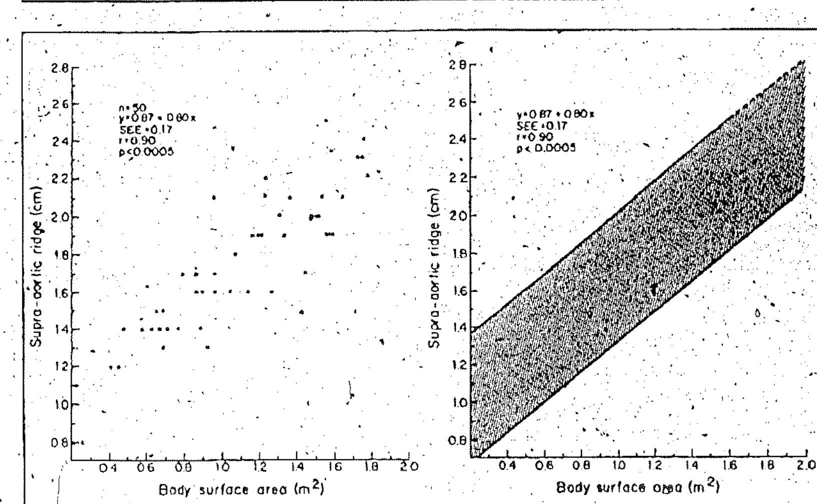

FIGURE 3. ***Left,*** **relation of body surface area to aortic root diameter at the supraaortic ridge in normal infants and children.** ***Right,*** **95% normal confidence limits for aortic root diameter at the supraaortic ridge in relation to body surface area in infants and children.**

TABLE II Relation of Aortic Diameters to Age, Body Habitus and Hemodynamic Parameters in Adults by Multivariate Analysis*

Level of Aorta	Variable	Percent Contribution	Multiple r	F Value
Anulus	BSA	45	0.67	108.7
	Age	2	0.69	7.2
	BMI	2	0.71	6.0
Sinuses of Valsalva	BSA	23	0.48	27.7
	Age	17	0.63	44.9
	Weight	4	0.66	8.9
Supraaortic ridge	Age	19	0.44	42.4
	BSA	19	0.61	38.6
	BMI	3	0.63	4.8
Proximal ascending aorta	Age	32	0.57	63.7
	BSA	13	0.67	24.2

* Additional variables that did not contribute independently to predictive models for aortic diameter at any level were systolic and diastolic blood pressure, stroke volume and height.
BMI = body mass index; BSA = body surface area.

than in older adults (r = 0.40 and 0.38, respectively, both p <0.0005).

Aortic root diameters were greater in men than women at all levels (p <0.001), but similar when indexed by body surface area (Table III). The sex-specific upper normal limits of 2-dimensional aortic root diameters are listed in Table IV. These partition values for absolute and indexed dimensions had high specificity (96 to 100%) at all levels in both men and women. Values are not presented for the proximal ascending aorta in view of the striking age dependence of this measurement.

Relation of root dimensions to anular size: In view of the apparent importance of supraaortic ridge enlargement in governing the severity of aortic root disease and its complications,[1-3] we determined the ratios of supraaortic ridge and sinuses of Valsalva to anular diameters. The ratio of sinus of Valsalva diameter to anular diameter (1.3 ± 0.1) was identical in children and adults and independent of gender, although there was a weak correlation between this ratio and age in adults (r = 0.38, p <0.0005). The ratio of supraaortic ridge to anular diameter was identical in adult men and women (1.1 ± 0.1) and somewhat smaller in children (1.0 ± 0.1); this ratio also was related to age among adults (r = 0.40, p <0.0005). Blood pressure and body mass index bore no independent relation to either ratio.

DISCUSSION

The present study provides systematic, detailed 2-dimensional echocardiographic measurements of the aortic root in a large population of normal children and adults, and clarifies the relative influences of gender, age, body size and hemodynamic factors on aortic root size. Although gender, blood pressure and stroke volume are significant correlates of aortic root dimensions, body size and age appear to be the primary independent determinants of aortic size in normal persons. Body size is the predominant determinant of aortic anular and sinus of Valsalva diameters, whereas age is the more important predictor of supraaortic ridge and ascending aortic dimensions. In contrast to our findings with regard to left ventricular mass,[17] obesity, as measured by body mass index, was only weakly related to aortic size.

The impact of age on aortic size, particularly of the supraaortic ridge and proximal ascending aorta, has been established in pathologic studies[18] and presumably reflects the development of cystic medial necrosis and fragmentation of elastin fibers as part of the aging process.[19-21] The progressive weakening with age of the relation between body size and aortic dimensions we have

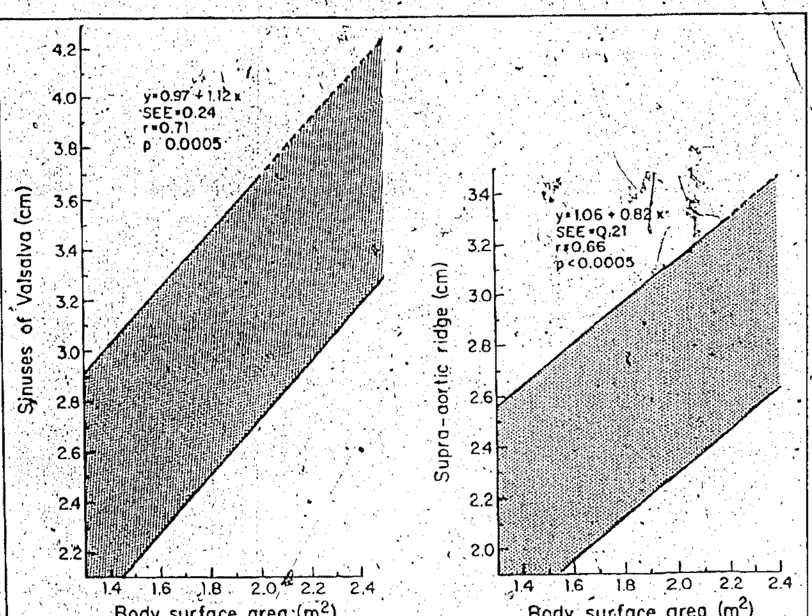

FIGURE 4. ***Left,*** **95% normal confidence limits for aortic root diameter at the sinuses of Valsalva in relation to body surface area in adults younger than 40 years of age.** ***Right,*** **95% normal confidence limits for aortic root diameter at the supraaortic ridge in relation to body surface area in adults under the age of 40 years.**

TABLE III Gender Differences in Aortic Root Dimensions in Adults

	Absolute Values (cm)			Indexed Values (cm/m²)		
	Men	p Value	Women	Men	p Value	Women
Anulus	2.6 ± 0.3	<0.001	2.3 ± 0.2	1.3 ± 0.1	NS	1.3 ± 0.1
Sinuses of Valsalva	3.4 ± 0.3	<0.001	3.0 ± 0.3	1.7 ± 0.2	NS	1.8 ± 0.2
Supraaortic ridge	2.9 ± 0.3	<0.001	2.6 ± 0.3	1.5 ± 0.2	NS	1.5 ± 0.2
Proximal ascending aorta	3.0 ± 0.4	<0.001	2.7 ± 0.4	1.5 ± 0.2	NS	1.6 ± 0.3

NS = not significant.

documented is currently unexplained, but it is attractive to speculate that in middle and older age body weight (and hence body surface area) may deviate progressively from that during the years when aortic size was programmed, and that subclinical degenerative processes altering aortic composition and distensibility may occur in some but not other persons. The lack of an independent impact of systolic or diastolic blood pressure within the normal range in the current study is consistent with previous reports showing no difference in aortic root size between hypertensive and normotensive adults of similar age.[1,20,21] Body surface area strongly influenced aortic root size at all levels, particularly in children, which was consistent with previous studies using M-mode echocardiography.[4,5,22]

The use of 2-dimensional rather than M-mode echocardiography to assess aortic root size and morphology offers clear advantages for both technical and clinical reasons. The 2-dimensional parasternal long-axis view allows full visualization of the entire aortic root throughout the cardiac cycle. M-mode aortic root measurements at the level where aortic valve opening is visualized predictably correlate best with 2-dimensional measurements at the sinuses of Valsalva, but are systematically lower than 2-dimensional measurements by a mean of 2 mm. This probably is due to the motion of the base of the heart toward the apex during left ventricular ejection followed by recoil superiorly during ventricular filling causing a cursor beam traversing the sinuses of Valsalva in mid-systole to pass closer to the aortic anulus by end-diastole. This cyclic shift between the sinuses of Valsalva and the aortic anulus results in understatement of aortic root size at end-diastole on independent M-mode tracings or M-mode tracings taken from 2-dimensional short-axis views. Thus, the normality of 2-dimensional aortic root measurements must be

TABLE IV Sex-Specific Criteria for Upper Normal Limits of Aortic Root Dimensions in Adults*

	Men		Women	
	Absolute (cm)	Indexed (cm/m²)	Absolute (cm)	Indexed (cm/m²)
Anulus (%)	3.1 (97)	1.6 (100)	2.6 (97)	1.6 (100)
Sinuses of Valsalva (%)	4.0 (99)	2.1 (99)	3.6 (96)	2.1 (97)
Supraaortic ridge (%)	3.6 (97)	1.9 (98)	3.2 (100)	1.9 (97)

* Specificity of each criterion among normal adults is given in parentheses.

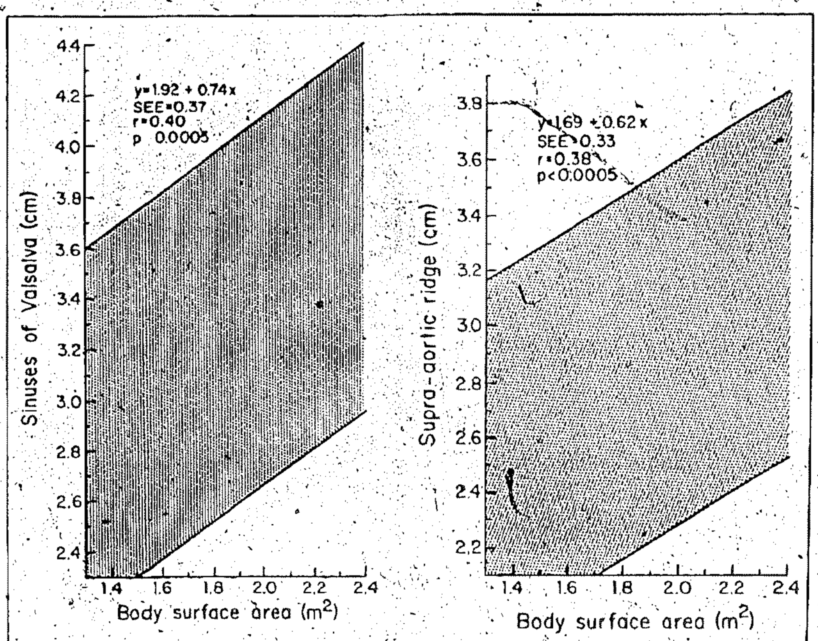

FIGURE 5. ***Left,*** **95% normal confidence limits for aortic root diameter at the sinuses of Valsalva in relation to body surface area in adults 40 years of age and older.** ***Right,*** **95% normal confidence limits for aortic root diameter at the supraaortic ridge in relation to body surface area in older adults.**

assessed using 2-dimensionally derived normal limits if false positive diagnoses of aortic root dilatation, as occurred in 40% of normal children and 19% of normal adults in the present study, are to be avoided.

The clinical importance of 2-dimensional aortic root measurements lies in the recently recognized adverse prognostic significance of dilatation extending above the sinuses of Valsalva to the supraaortic ridge. Patients without the Marfan syndrome but with this generalized aortic root dilatation as a cause of aortic regurgitation have more severe left ventricular dilatation, hypertrophy and dysfunction and are more likely to require aortic surgery than are patients with aortic regurgitation due to valvular disease or localized aortic root dilatation.[1] A similar increased likelihood of aortic complications has been noted in Marfan patients with generalized aortic root dilatation.[3] Guiney et al[2] found faster clinical progression in patients with aortic regurgitation due to noninflammatory aortic root disease than in those with rheumatic valvular disease. These observations likely reflect the importance of aortic diameter at the supraaortic ridge, the point of commissural insertion, in determining the extent of disruption of leaflet coaptation and hence the likelihood and severity of aortic regurgitation. Evaluation of the ratio of supraaortic ridge to anular diameter in patients with aortic root or valve disease may allow more precise identification of patients at greatest risk for complications than provided by simple classification of aortic root dilatation as generalized or localized to the sinuses of Valsalva. It is also possible that enlargement of the supraaortic ridge may contribute to the increased frequency of aortic regurgitation in elderly patients[23] by distorting valve geometry.

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