Aortic root dynamism, geometry, and function after the remodeling operation: Clinical relevance

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ABSTRACT

Objectives: Valve-conserving operations for aneurysms of the ascending aorta and root offer many advantages, and their use is steadily increasing. Optimizing the results of these operations depends on providing the best conditions for normal function and durability of the new root.

Methods: Multimodality imaging including 2-dimensional echocardiography, multislice computed tomography, and cardiovascular magnetic resonance combined with image processing and computational fluid dynamics were used to define geometry, dynamism and aortic root function, before and after the remodeling operation. This was compared with 4 age-matched controls.

Results: The size and shape of the ascending aorta, aortic root, and its component parts showed considerable changes postoperatively, with preservation of dynamism. The postoperative size of the aortic annulus was reduced without the use of external bands or foreign material. Importantly, the elliptical shape of the annulus was maintained and changed during the cardiac cycle (Δ ellipticity index was 15% and 28% in patients 1 and 2, respectively). The “cyclic” area of the annulus changed in size (Δ area: 11.3% in patient 1 and 13.1% in patient 2). Functional analysis showed preserved reservoir function of the aortic root, and computational fluid dynamics demonstrated normalized pattern of flow in the ascending aorta, sinuses of Valsalva, and distal aorta.

Conclusions: The remodeling operation results in near-normal geometry of the aortic root while maintaining dynamism of the aortic root and its components. This could have very important functional implications; the influence of these effects on both early- and long-term outcomes needs to be studied further. (*J Thorac Cardiovasc Surg* 2018;156:951-62)

Overall shape of aortic root and ascending aorta before and after the remodeling operation.

Central Message

The remodeling operation results in near-normal geometry of the aortic root while maintaining dynamism of the aortic root and its components with important functional implications.

Perspective

Multimodality imaging including 2D echo, MSCT, and CMR combined with image processing and CFD were used to define geometry, dynamism, and aortic root function before and after the remodeling operation. Size and shape of the aortic root showed considerable changes postoperatively, with preservation of dynamism. Postoperative size of the aortic annulus was reduced.

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The use of valve-conserving operations for the treatment of aneurysms of the ascending aorta and root is increasing worldwide.¹⁻⁴ This is due to the known complications of currently available mechanical and tissue valves⁵⁻⁸ and the fact that the living aortic root and valve perform extremely

sophisticated functions^{9,10} that translate into clinically important end points such as survival and quality of life.^{9,11-13} This stimulated the development of the Yacoub remodeling operation in 1982,¹⁴⁻¹⁶ followed 10 years later by the David reimplantation technique.¹⁷ The remodeling

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Abbreviations and Acronyms

3D	= 3-dimensional
CFD	= computational fluid dynamics
CMR	= cardiovascular magnetic resonance
ROA	= regurgitant orifice area
STJ	= sinotubular junction
WSS	= wall shear stress

Scanning this QR code will take you to the supplemental tables and video for this article.

technique aims at preserving dynamism of the aortic root.¹⁸⁻²⁰ This has been documented in humans²¹ as well as in ex vivo models.^{22,23} The aortic root with its complex structure is responsible for maintaining optimal coronary flow, left ventricular function, and cardiac output under a wide range of hemodynamic conditions²⁴ while ensuring durability by optimizing mechanical stress on valve components. We here define the geometry, dynamism, and function of the aortic root using extensive multimodality imaging and imaging processing and discuss the clinical implications of these findings.

PATIENTS AND METHODS

Patients

Six individuals, 2 with ascending aortic aneurysm and 4 age-matched controls (2 for each patient) were studied (Table E1). Both patients underwent the Yacoub procedure²⁵ with the new Uni-Graft W SINUS prosthesis (Braun, Melsungen, Germany).^{26,27} The investigations were performed at intervals of 3 months and 1 month after operation for patients 1 and 2, respectively. The normal control subjects were selected from an ongoing study, assessing healthy individuals, following informed consent. The study was approved by the Research Ethical Committee of the Aswan Heart Centre.

Yacoub Procedure With a Sinus-Shaped Graft

This is based on the previously described Yacoub remodeling operation.²⁵ In short, after cardiopulmonary bypass is established with arterial return to the aortic arch, the aorta is transected above the aneurysm, and antegrade cold blood cardioplegia used for myocardial protection. Three mattress sutures are then placed at the top of each commissure. The aneurysmal aortic sinuses are then excised to a level 2 mm above the crown-shaped annulus. The 3 commissural sutures are then pulled cephalad to reshape the aortic root from a flask shape to a shape approximating the normal trilobed aortic root, with each sinus having a longer height than width. This “reshaping” results in reducing the size of the previously “splayed out” ventriculoarterial junction (Figure 1, A). The distance between each of the 3 stretched sutures is measured and used to guide the choice of the sinus graft. The chosen sinus graft should have a diameter equal to the average distance between the stretched commissural sutures and importantly approximate the diameter of the “idealized” 3-dimensional (3D) model from the patient-specific imaging data (Figure 1, B). The chosen sinus graft is tailored by excising 3 thin triangular segments between the bulges of the sinuses (Figure 1, C). The height and width of these triangles is based on the measurements made for each specific commissural height between the different cusps.

FIGURE 1. A, Yacoub Procedure Technique and the sizing of the aortic root based on Figure in Yacoub²⁵ (right) and comparing pre- and post-operative overall shape (left). B, An overview of the image-based morphology analysis of the aortic root, ascending aorta and arch in patient 1. C, Per-operative photographs from patient 1 showing the aortic aneurysm (left) and starting the tailoring of the sinus graft (right). Trans-esophageal echocardiography showing correction of the aortic regurgitation with preservation of the aortic sinuses, and diminution in the size of the aortic annulus (D) patient 1, (E) patient 2. STJ, Sinotubular junction.

FIGURE 2. A, Identifying annulus position in 3D images (left); max bulge points, shape of the 3 bulges and leaflets (right) and (B), top left: pre- and post-operative aortic valve 3-dimensional (3D) segmentation over the cardiac cycle, active aortic orifice area is measured in mm² through the cardiac cycle. Top right: a map of cusp coaptation following Hamdan and colleagues;³⁴ red for <1 mm, green for <2 mm, and blue for <3 mm and illustrating cusp geometric parameters. Bottom: 3D-segmented cusps were realigned to better visualize changes in curvature and the interleaflet triangles. The appearance of the smaller surface of the leaflets postoperatively is due to the fact that the curvature of the cusps has been changed considerably. LCL, Left coronary leaflet; NCL, noncoronary leaflet; RCL, right coronary leaflet.

Patient 1

Matched Controls

Patient 2

FIGURE 3. Aortic root parameters and an example of changes in the tilt angle (angle between aortic root base and sinotubular junction [STJ]). RS, LS, and NS are the right, left, and noncoronary sinus annulus points projected to the STJ, respectively. Preoperative values 6.4°, postoperative 5.9°, normal value 5.5° (Berdaş and colleagues²⁸), matched controls 3.3° and 4.7°. LS, Left sinus; RS, right sinus; NS, noncoronary sinus.

The 3 commissural mattress sutures are fixed to the top of the grooves created in the Dacron tube. The mobile Dacron sinuses of the graft are then sutured starting from the “bottom” of the ventriculoarterial junction of each sinus and working up to the top of the commissure. After the completion of the lower suture line, the coaptation of the 3 cusps is determined by stretching each sinus to test for the height of the cusps²⁹ and making sure that there is no tendency to prolapse. If needed, the free border of one or more of the cusps can be plicated to prevent prolapse. The upper end of the Dacron graft is then trimmed to a length shorter than the excised aorta to ensure lifting of the displaced aortic annulus and preventing kinking of the reconstituted aorta, after completion of anastomosis of the adjusted upper end of the graft to the transected aorta.

As is customary in clinical practice, we here refer to the annulus as an imaginary circle/ellipse passing through the 3 points of the ventricular aortic junction. After aortic declamping, transesophageal echocardiography is used to measure annular diameter, sinus bulges, cusp height, and coaptation as well as presence of any residual aortic regurgitation (Figure 1, D and E).

Image Acquisition

Two-dimensional phase contrast cardiovascular magnetic resonance (CMR) images were used for through-plane velocity flow mapping at aortic valve level. For patients 1 and 2, 128-slice dual-source multislice computed tomography was acquired by with the Siemens SOMATOM Definition Flash (Siemens Healthcare, Tarrytown, NY).

Patient-Specific Aortic Root and Ascending Aorta Shape Analysis

The size and shape as well as flow in the different component parts of the aortic root and ascending aorta were measured and described for the patients treated using the sinus graft.

3D segmentation of anatomy. 3D whole heart acquisition using navigator sequences (Siemens, Healthcare, Erlangen, Germany) for the control cases and computed tomography angiography Digital Imaging and Communications in Medicine images pre- and postoperative for the 2 patients were imported into Mimics Research, version 18.0, and 3-matic (Materialise, Leuven, Belgium) for semiautomated 3D segmentation of the different components.

Overall shape and size of root and ascending aorta. The shape and size of the aortic root and ascending aorta were analyzed pre- and postoperatively at the annulus, the sinotubular junction (STJ), and at the level of the first branch of the ascending aorta and were compared with published healthy root dimensions.^{30–33} In addition, the length of each segment along its center line was determined.

The position, geometry, and dimensions of the annulus were identified in multiple planes at the 3D-reconstructed model (Figure 2, C). As the shape of the annulus is best described as an ellipse, the major and minor diameters (D_{maj} , D_{min}) of the ellipse were measured to identify the ellipticity index ($e = D_{maj}/D_{min}$).³⁴

The aortic root height was measured using centers of the plane at STJ level and at the root base. The center of the aortic root was set as the midpoint between these 2 endpoints. The tilt angle was defined using the method described by Berdaş and colleagues²² (Figure 3).

For detailed aortic root and sinus morphology analysis, the segmented aortic root was separated from the ascending aorta at the STJ. In-house developed MATLAB codes were used to capture dynamic behavior of the aortic root at 10 phases (for the patients). The method used is similar to that described by Bax and colleagues.^{35,36}

Identification of aortic root components. The 3D-reconstructed models of the aortic root were used for a comprehensive analysis of the aortic root components. The definition of cusp parameters and dimensions was based on those described by the groups of Schäfers, Kim, Levine, and Thubrikar.^{31,37–39}

Aortic sinus characteristics. The 3 sinuses were separated and measured. The pre- and postoperative sinus surface areas and sinus volumes, sinus width (chord length, direct distance between the commissures defining each sinus), the sinus height, and a fitted radius to measure the change of curve shape for each sinus were measured (Figure 2, A). Final measurements included the sinus bulge lengths from the aortic root center to the maximal bulge points and the distances between each pair of bulge points. The maximal bulge points are the furthest points on each sinus from the aortic root center.

Cusp geometry and coaptation. The length of the free and fixed edge, cusp height, cusp surface area, and the curvature were measured (Figure 2, B). Coaptation length and height were measured³⁸

(Figure 2, B). The regurgitant orifice area (ROA) was defined by the 3 free cusp edges.

Interleaflet triangle heights and widths. The dimensions (width and height) of the subcommissural triangles were measured at end-diastole to mimic the state of the heart during surgery (relaxed aorta).

Computational fluid dynamics (CFD). Blood flow velocities, wall shear stress (WSS), and pressure through the aortic root and ascending aorta were computed with CFX 17.0 software (Ansys, Inc, Canonsburg, Pa), with methods previously described by Torii and colleagues⁴⁰; time-resolved phase-contrast magnetic resonance images of 2-dimensional

Patient 1

Patient 2

FIGURE 4. Size of the aortic root and ascending aorta along the aortic center line from annulus to end of ascending aorta (*top*: patient 1; *bottom*: patient 2). The preoperative aortic values are shown in *red* and postoperative in *gray*. The diastolic cross-sectional areas of the annulus are shown. AscAo, Ascending aorta; STJ, sinotubular junction.

through-plane flow velocity at mid-sinus level⁴¹ and outflow boundary conditions were used. A shear stress transport turbulence model was added for capturing near wall flow behavior; a rigid wall model was used.⁴² Flow

through the head vessels was also retrieved from CMR flow images. Measurements were compared with results in previously reported CFD⁴³ and CMR 4-dimensional flow studies.^{44,45}

FIGURE 5. Dynamic changes of the annulus area, shape (and ellipticity index e) at different phases of the cardiac cycle, and flow rate at aortic valve level over the cardiac cycle.

RESULTS

Overall Size and Shape of Ascending Aorta and Root

The size of the aortic root and ascending aorta, from the annulus to the first head vessel, compared with the age-matched controls is shown in Figure 1, B, and Figure 4. The average and standard deviation of the lengths measured at 10 phases of the cardiac cycle were recorded. The preoperative length of the ascending aorta was reduced in patient 1 from 95 ± 4.4 mm to 41 ± 2.7 mm and in patient 2 from 94 ± 6.7 mm to 49 ± 3 mm postoperatively. The size and shape of the ascending aorta at different levels are shown in Figure 4.

Aortic Root Morphology

Overall shape. After repair, the shape of the aortic root changed from a splayed-out compressed flask-shaped structure to a normalized tube with 3 distinct sinuses assuming near-normal shape (Figure 1, A, and Figure 2, A). The tilt angle was measured (Figure 3).

Annulus shape and geometry. The annulus area in patient 1 was measured as 591 ± 39 mm² preoperatively and 576 ± 74 mm² postoperatively; in patient 2, the values were 1038 ± 21 mm² and 973 ± 46 mm² (Figure 5). The reduction of annular size in patient 2 was less than in patient 1 due to the neglected long-standing aortic regurgitation in

this case, which led to progressive annular dilation as well as cusp retraction.

Postoperatively, the percentage increase of the cross-sectional area over the cardiac cycle, calculated as $(A_{\max} - A_{\min}) * 100 / A_{\max}$, lies within the normal range in both patients (11.3% in patient 1 and 13.1% in patient 2; published normal range $11.2 \pm 5.4\%$ ³⁴). The elliptical nature of the aortic annulus, which is increased during diastole, has functional implications in reducing the stress on the cusps by reducing the area during diastole. The ellipticity index e and the dynamic changes of the annulus were identified (Figure 5).

Characteristics of the cusps and sinuses.

Sinus morphology and sinus curves dimensions. The results for the different components are listed in Tables E2 and E3. Changes in the surface area and volume of each sinus pre- and postoperatively are plotted over the cardiac cycle in Figure 6.

Cusp size and shape. The segmented cusps with its fixed and free edges are shown in Figure 2, B. The parameters cusp surface area, curvature, coaptation height and length, and ROA are shown in Table E4.

Interleaflet triangles width and height. Postoperatively, the N-L cusp nadirs for patient 1 were brought closer (base width reduced from 45 to 24 mm) (Table E3). The base of N-R was increased from 22 to 32 mm and R-L from

Patient 1

Patient 2

FIGURE 6. Sinus surface area and volume over the cardiac cycle for patient 1 (top) and patient 2 (bottom). SA, Surface area; LCS, left coronary sinus; RCS, right coronary sinus; NCS, noncoronary sinus.

25 to 33 mm. For patient 2, the preoperative base of the R-L and N-L triangle was maintained the same, whereas the N-R cusp nadirs have been brought closer (from 49 to 34 mm). The triangle heights are also listed in Table E2.

Flow Modeling With CFD

Assessment of the presence and degree of aortic regurgitation and aortic flow. The degree of aortic regurgitation was measured at the aortic valve level (Figure 7). The regurgitant volume decreased from 11.2 mL (13.17% of the stroke volume) to 0.48 mL (0.62%) in patient 1 and from 29.5 mL (34%) to 8.53 mL (5.56%) in patient 2. Postoperative aortic insufficiency in patient 2 was due to long-standing aortic regurgitation, which resulted in a degree of retraction in aortic cusps. This can only be remedied by cusp extension, which in our experience does not give durable results because of the lack of appropriate material. The matched controls to patient 1 had regurgitant volumes of 0.31 mL (0.53%) and 0.14 mL (0.17%); as for those of patient 2, 0.11 mL (0.17%) and 3.46 mL (5.6%). The computed blood flow distribution was visualized by the use of velocity streamlines (Figure 8, A). The velocity value ranges in the ascending and descending aorta for the postoperative simulations were compared with the controls, which were validated against published data (quantitative and qualitatively).⁴³⁻⁴⁵ Areas of large circulating flows are present in the aneurysmal sections of the aorta resulting in flow retardation and backflow in the descending aorta. Moreover, vortical regions are of large diameter and low velocities.

Flow pattern in the sinuses. The peak velocity in the coronary sinuses for both patients regained values of 0.25 to 0.3 m/s as it is for the controls and as previously described in Bellhouse and colleagues,⁴⁶ where a peak sinus flow value of 0.3 m/s (and less in the diastolic phase) is

indicating normal valve function. The rotating flow due to the sinus vortices is shown in Figure 8, B.

Reservoir function of the aortic root. Postoperatively, forward diastolic flow was observed, indicating an intact diastolic function of the aortic root (Figure 7).⁴⁷

WSS distribution on the arterial wall. Preoperatively, the WSS distribution for both patients showed elevated values compared with the normal controls and thick vortex rings at the anterior wall corresponding to elevated WSS due to flow impingement (Figure 9). Patient 1 had values reaching 15 Pa versus a maximum of 5 Pa computed for the normal cases; patient 2 reached a maximum of 7.5 Pa. Postoperatively, WSS values were in the normal range.

DISCUSSION

This study documents the influence of the remodeling operation on dynamism, geometry, and function of the component parts of the aortic root and ascending aorta and discusses the clinical relevance of these findings.

Significance of Dynamism for Aortic Root Function

One of the defining features of the Yacoub remodeling operation is preservation of the dynamic behavior of the aortic root, defined as the capacity of the different components of the root to change their shape and/or size during different phases of the cardiac cycle.¹⁸ This is demonstrated by the instantaneous changes in the size and shape of the aortic annulus (Figures 4 and 5).

Dynamism can have a direct influence on valve opening and closing characteristics.^{21,48,49} and degree of strain on the aortic cusps.²⁸ In addition, aortic root dynamism can have important implications for coronary flow,⁵⁰ as well as aortic reservoir function,^{51,52} which can affect long-term survival and quality of life. Each of the component parts of the aortic root contribute to the overall sophisticated functions of the valve mechanism. The clinical significance

FIGURE 7. Pre- and post op total flow rate (ml/s) at aortic valve level compared to normal controls, calculated by MRI 2D flow (A) patient 1, (B) patient 2.

FIGURE 8. Pre- and postoperative velocity streamlines for patients 1 and 2 (at peak systole, *left*, and late systole, *right*).

of dynamism and geometry is discussed in the accompanying video ([Video 1](#)).

The Aortic Annulus or Ventriculoarterial Junction

Although its name implies a circular structure, the annulus is crown shaped and constitutes the exit orifice from the ventricle and the entry to the aortic root and thus occupies a strategic, potentially controlling position. The annulus function depends on its dynamic shape, which changes from oval during diastole to circular during systole^{34,35} ([Figure 5](#)). This dynamism reduces the resistance to ventricular emptying during systole and lowers the strain on the cusps during diastole by reducing the orifice area (assuming an elliptical shape) without changing the length of the perimeter. Following the Yacoub operation using the sinus graft, our 2 patients showed more normal dynamism ([Figure 5](#) and [Tables E2-E4](#)). In addition, the size of the annulus was reduced without using the surrounding prosthetic belts. The reduction of the size of the annulus was achieved by remodeling the splayed-out annulus by lifting the commissure and suturing to the neosinuses of the graft. The reduction of the size of the annulus was documented by both the transesophageal echocardiography ([Figure 1, D](#)) and multislice computed tomography images ([Figure 2, C](#)). The durability of this type of repair should be enhanced by the correction of aortic regurgitation with reduction in the stretching effect of the ejected blood during systole and the regurgitating blood during diastole. This

was documented by measuring the instantaneous flow across the aortic annulus throughout the cardiac cycle and by quantifying the ROA ([Table E4](#) and [Figure 5](#)).

The Aortic Cusps

The aortic cusps have a complex 3D geometry similar to a suspension bridge,^{36,53} with a hinge, body, coapting surfaces, and anisotropic mechanical properties.⁵⁴ The current study has shown large changes in the shape, surface area, curvature, extent of coaptation, and length of attached border after the remodeling operation. One of the most noticeable effects was the change in the shape of the cusps from an oblong, relatively flat malcoapting configuration to a triangular coapting cup-shaped configuration ([Figure 2, B](#) and [C](#)) and changes in the dimensions of each cusp that were more pronounced in the noncoronary cusp. Both the length and extent of coaptation increased after the operation, with the disappearance of the regurgitant orifice in patient 1 and diminution in patient 2. Levine and colleagues⁵⁵ reported an increase in cusp area in patients with aortic aneurysm that was not always sufficient to prevent aortic regurgitation. These changes in cusp area are analogous to those observed in functional mitral regurgitation. The factors involved in stimulating the increase in cusp surface to match valve orifice are poorly understood.³⁸

The influence of the increased curvature on reducing the stress on the cusp was first pointed out by Lim and colleagues using CFD⁵⁶ and confirmed by Berdajs and

FIGURE 9. Preoperative vortex coherent structures at late systole (A) in patient 1 and (B) in patient 2. *Red sections* on the anterior wall show areas of elevated WSS > 5 Pa. Postoperative WSS ranging from 0 to 5 Pa in (C) patient 1 and (D) in patient 2 compared with controls.

colleagues.²⁸ The appropriate free edge of the cusp is related to the size of the aortic root.³⁹ This has the important function of maintaining the cusp shape and height as well as enhancing coaptation with the other cusps. Abnormal lengthening of the free border results in prolapse of the cusp with resulting regurgitation. When present, this can be corrected by plicating the central part of the free border

with a 7/0 stitch, which has the effect of preventing prolapse of the cusp (Figure 1, D).²⁹

The Aortic Sinuses and STJ

The remodeling operation reduced the width, height, surface area, and volume of each sinus, (Figure 6, Tables E2 and E3). In addition, it normalized the configuration of the root from of flask shape to a normalized trilobed structure. Dynamism of the aortic sinuses as indicated by dynamic changes in both dimension and volume was preserved; all values were reduced when compared with normal.^{34,38} Dynamism of the root has important implications for coronary flow⁵⁷ and reservoir function of the aorta.

Study Limitations

The main limitation of this study is the small number of patients studied; however, the inclusion of age- and sex-matched controls and the extensive detailed methods of analysis provide new information and insights regarding several important aspects of valve-sparing operations. For further evaluation of the effect of the findings reported in this study on long-term results, follow-up studies of a larger cohort of patients need to be performed.

Aortic Root Geometry, Dynamism and Function after the Remodelling Operation, Clinical Relevance

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VIDEO 1. Value of aortic root dynamism, its relevance, and importance of the study. Video available at: [https://www.jtcvs.org/article/S0022-5223\(18\)30980-2/fulltext](https://www.jtcvs.org/article/S0022-5223(18)30980-2/fulltext).

CONCLUSIONS

The remodeling operation appears to retain aortic root dynamism and restore near-normal geometry and flow characteristics, which could translate into important clinical endpoints such as quality of life and survival. Preoperative multimodality imaging can help in formulating the strategy for the surgical procedure. Further studies are required to determine the effect of dynamism and geometry on long-term results on a large number of patients.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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Key Words: aortic root dynamism, aortic root replacement, ascending root aneurysm, computational fluid dynamics, re-modeling, valve-sparing, Yacoub operation

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TABLE E1. Patients and age-matched controls

Patient	Sex	Age, y	BSA	Age-matched controls		
				Sex	Age, y	BSA
1	Female	21	1.8	Females	23/24	1.7/1.6
2	Female	37	1.8	Females	33/33	1.7/1.8

BSA, Body surface area.

TABLE E2. Sinus and subvalvular measurements

Sinus measurements							Subvalvular measurements				
Sinus curves, mm							Intracommissural triangles, mm				
Com-com length		Sinus radius		Sinus height, mm			Triangle height		Triangle base		
Pre	Post	Pre	Post	Pre	Post		Pre	Post	Pre	Post	
Patient 1											
NCS	27	24	15	12	24	24	N-R	15	14	22	32
LCS	31	24	16	12	25	26	L-R	15	14	25	33
RCS	31	24	17	12	24	26	N-L	17	14	45	24
Patient 2											
NCS	37	24	19	12	21	20	N-R	15	14	49	34
LCS	33	24	17	12	24	25	L-R	16	15	33	33
RCS	38	24	20	13	24	27	N-L	13	15	31	31

Com-com, Inter-commissural distance; NCS, noncoronary sinus; N-R, non-coronary to right coronary sinus distance; LCS, left coronary sinus; L-R, left coronary to right coronary sinus distance; RCS, right coronary sinus; N-L, non-coronary to left coronary sinus distance.

TABLE E3. Sinus bulge dimensions

	Patient 1				Patient 2				Controls (AHC)			
	Pre		Post		Pre		Post		M-P1		M-P2	
	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Dia	Dia	Dia	Dia
Bulge-center line, mm*												
LCS	28	0.7	21	0.7	27	1.5	21	0.6	17	16	15	20
RCS	33	1.4	25	1	27	2	23	0.5	14	15	16	17
NCS	25	1.2	22	0.7	26	1	24	0.6	15	16	15	12
Bulge-bulge, mm*												
L-R	57	1.4	40	0.8	49	1.9	38	0.4	28	28	29	28
N-L	38	2.1	38	0.6	37	2.3	38	0.8	29	26	25	27
N-R	52	2.3	40	0.3	48	2.1	40	0.3	23	26	25	27

AHC, Aswan Heart Centre; *M-P1*, control matched to patient 1; *M-P2*, control matched to patient 2; Avg, average; SD, standard deviation; Dia, diameter; LCS, left coronary sinus; RCS, right coronary sinus; NCS, noncoronary sinus; L-R, left coronary to right coronary sinus distance; N-L, non-coronary to left coronary sinus distance; N-R, non-coronary to right coronary sinus distance.

TABLE E4. Cusp measurements

	Surface area, mm ²		Geometric height, mm		Cusp depth-to-chord ratio		Free edge length, mm		Fixed edge length, mm		Coaptation, mm				ROA, mm ²	
											Height		Width			
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Patient 1																
NCC	386	300	17	15	0.19	0.31	32	26	41	37	N-R	3	3	13	12	
LCC	447	327	20	18	0.27	0.26	34	30	47	43	L-R	4	3	14	5	34
RCC	347	320	16	18	0.16	0.19	35	29	42	38	N-L	5	4	12	11	
Patient 2																
NCC	546	463	19	20	0.22	0.59	40	34	54	46	N-R	4	7	6	18	
LCC	565	402	23	18	0.27	0.24	39	33	55	48	L-R	4	6	5	19	76
RCC	600	486	18	18	0.13	0.24	46	33	48	45	N-L	3	7	8	13	23

ROA, Regurgitant orifice area; NCC, noncoronary cusp; N-R, non-coronary to right coronary sinus distance; LCC, left coronary cusp; L-R, left coronary to right coronary sinus distance; RCC, right coronary cusp; N-L, non-coronary to left coronary sinus distance.