

Valve Opening and Closing Dynamics after Different Aortic Valve-Sparing Operations

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Background and aim of the study: Aortic valve resuspension for ascending aortic aneurysm repair is associated with removal of the sinus of Valsalva. This may cause changes in leaflet motion and thus impact on long-term durability. The opening and closing characteristics of the aortic valve leaflets after reimplantation were studied using a published technique and a modification to create a 'neosinus', and the results compared to those of an age-matched control group.

Methods: Between September 1995 and March 2002, 25 patients underwent normal aortic root reconstruction (group A), while in a further 21 patients the modified neosinus technique was used (group B). In both groups, the native valve was preserved and suspended inside a tubular prosthesis, with reimplantation of the coronary arteries. Transthoracic and transesophageal studies of aortic valve dynamics were performed intraoperatively, before hospital discharge, and at one year after surgery in all patients; the data were compared with those from a separate group of 25 matched control individuals (group C).

Results: The valve opening velocity was 61.3 ± 20.1 , 46.3 ± 8 and 29.2 ± 9.8 cm/s in groups A, B and C, respectively (group A versus B, $p = 0.003$; A versus C,

$p < 0.0001$; B versus C, $p < 0.0001$). Closing velocity was increased to 57.5 ± 23 and 43.8 ± 7 cm/s in groups A and B, compared to 23.6 ± 7 cm/s in group C (A versus B, $p = 0.012$; A versus C, $p < 0.0001$; B versus C, $p = 0.0002$). In seven group A patients, the leaflets touched the prosthetic wall during systole. Slow systolic closing displacement (SCD) amounted to 7.3 ± 6 % of maximal opening in group A and 12.6 ± 5 % in group B ($p = 0.05$), compared to 21.1 ± 8.3 % in group C (group A versus group C, $p < 0.0001$; B versus C, $p = 0.002$).

Conclusion: Reimplantation of the natural aortic valve in a prosthetic graft causes abnormally high opening and closing speeds, with possibly increased stress. The study results showed lower valve opening and closure dynamics after the creation of a sinus bulge compared to the conventional reimplantation technique. However, mid-term clinical observations showed favorable valve competence for both types of repair. Further long-term follow up is necessary to prove whether more physiological leaflet dynamics lead to improved durability.

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In patients with ascending aortic aneurysm involving the sinus of Valsalva and aortic incompetence, the standard surgical therapy is implantation of a valved conduit. In order to preserve the patient's structurally unchanged valve, two valve-sparing procedures have been developed (1-3). However, the geometry and function of the complex unit of valve cusps and sinuses of Valsalva are altered due to the inelastic graft wall. In the David I procedure, the sinuses are completely

removed and replaced with a straight tube of vascular prosthesis. Various dynamic factors cause the cusps slowly to approximate during late systole, allowing the valve to close completely without any leaking closing volume and with low closing speed (4). Angulation and dynamic stresses may thus be increased after valve reimplantation, and this leads to accelerated valve degeneration or abrasion at the wall of the prosthesis (5-7).

In an attempt to minimize the potential problems of leaflet damage, the present authors have recently developed a modified technique of aortic root reconstruction in which the Dacron graft was remodeled by shaping a 'neosinus'. The opening and closing dynamics were then investigated after valve-sparing correc-

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tion of ascending aortic aneurysms using the technique described by David, and compared to a modification with the creation of a 'neosinus'; both techniques were subsequently compared with an age-matched control group. The valve dynamics was also studied in an age-matched control group in patients with normal valve function.

Clinical material and methods

Patients

Between September 1995 and March 2002, 46 patients (32 males, 14 females) with aortic root aneurysm and aortic insufficiency underwent replacement of the ascending aorta and reconstruction of the aortic root with preservation of the native aortic valve. The underlying diagnosis was chronic aneurysm in 36 patients, and acute aortic dissection (Stanford type A) in 10. The mean age of the patients was 57.5 ± 15.6 years (range: 10 to 78 years). All patients underwent preoperative echocardiography, which graded the aortic regurgitation (AR) from 0 (none or trivial) to 4 (severe). The mean grade of AR was 3.2. In four patients the AR was additionally caused by a secondary leaflet prolapse. Three patients had Marfan's syndrome. The David I technique (group A; $n = 25$) was performed during the initial period; subsequently, the modified 'neosinus' technique (group B; $n = 21$) was

used. The inclusion criteria for both groups were identical and consisted of the absence of gross organic changes in the valve cusps, regardless of the aneurysm size, the duration of aortic insufficiency, ventricular function, or age.

The control group (group C) consisted of 25 patients (matched for age and gender), with coronary artery disease in whom no abnormalities of the aortic valve, aortic root or left ventricle were detected by medical history, standard clinical examination and echocardiography. The clinical profiles of the patients are summarized in Table I. Echocardiography data were gathered from preoperative transthoracic and intraoperative transesophageal examinations, and mainly from transthoracic examinations at discharge ($n = 44$) and at one-year follow up ($n = 28$).

Echocardiographic data acquisition and measurement

Adequate function of the aortic valve was ascertained intraoperatively with transesophageal echocardiography (TEE) after weaning from cardiopulmonary bypass. All patients underwent Doppler transthoracic echocardiography (TTE) in the supine position, both before discharge from hospital and again 12 months later. Investigations were performed using a Vingmed System Five ultrasound fitted with a 3.5-MHz transthoracic and, exceptionally, a 5-MHz trans-

Table I: Patient demographics and perioperative data.

Parameter	Group A (n = 25)	Group B (n = 21)	Group C (n = 25)	p-value
Age (years)*	60.4 ± 15.1	53.7 ± 15.8	61.2 ± 15.1	NS
Gender ratio (M:F)	19:6	12:9	23:7	NS
BSA (m ²)*	1.89 ± 0.14	1.88 ± 0.15	1.92 ± 0.14	NS
Aneurysm of the ascending aorta	20 (80)	14 (66)		
Leaflet prolapse (n)	4 (16)	2 (9.5)	-	
Marfan syndrome (n)	3 (12)	2 (9.5)	-	
Additional aneurysm of the aortic arch (n)	2 (8)	2 (9.5)	-	
Dissection of the ascending aorta (n)	3 (12)	6 (28.5)	-	
PVD (n)	6 (23)	4 (19)	-	
IDDM (n)	3 (12)	2 (9.5)	-	
COPD (n)	4 (16)	3 (14.2)	-	
Acute lung edema (n)	2 (8)	2 (9.5)	-	
NYHA class (preoperative)*	3.4 ± 0.5	3.3 ± 0.4		NS
Ejection fraction (%)*	53.5 ± 10.1	57.7 ± 7.6	58.2 ± 10.9	NS
LVESD (mm)*	49.4 ± 3.5	48.8 ± 2.8	-	NS
Aortic regurgitation (grade)*	3.3 ± 0.4	3.1 ± 0.3	-	NS

*Values are mean \pm SD.

Values in parentheses are percentages.

BSA: body surface area; COPD: Chronic obstructive pulmonary disease; IDDM: Insulin-dependent diabetes mellitus; LVESD: Left ventricular end-systolic diameter; NS: Not significant; PVD: Peripheral vascular disease.

esophageal transducer (General Electric Medical Systems, Horten, Norway). All data except those for cusp dynamics were acquired at discharge and at follow up. Dynamic data were studied in the study of best quality for patients after surgery, mainly with intraoperative TEE (33 of 39 patients).

Tracings were recorded on a strip chart using a paper speed of 100 mm/s, and magnified. The purpose of these recordings was to analyze any possible intermittent systolic contact of an aortic cusp with the aortic wall, as well monitoring the speed and dynamics of cusp opening and closing movements (for definitions, see Fig. 1). Only views with the leaflet coaptation at the midline of the aortic root and a symmetrical appearance of the valve motion were analyzed. All measurements were averaged from three cardiac cycles, and performed by only two investigators.

The leaflet opening and closing characteristics were measured as follows: leaflet movement of the aortic valve was evaluated using M-mode echocardiography. The data obtained were transferred to an external computer (Power Macintosh G4 800 MHz; Palo Alto, CA, USA) and digitally analyzed (Echo Pac Software, Vingmed System Five; General Electric Medical Systems). Slow closing displacement (SCD) of the leaflets was calculated using the formula:

$SCD = (D_1 - D_2)/D_1 \times 100$, where D_1 is the maximal leaflet displacement, and D_2 is the leaflet displacement before rapid valve closing (Fig. 1).

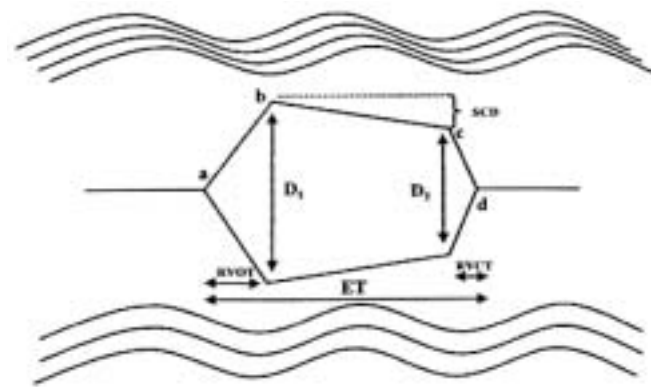


Figure 1: Schematic drawing of measured aortic valve opening and closing characteristics of three distinct phases: a-b, rapid valve opening; b-c, slow systolic closure; and c-d, rapid valve closing movement. D_1 : Maximal leaflet displacement; D_2 : Leaflet displacement before rapid valve closing; ET: Ejection time; RVCT: Rapid valve closing time; RVOT: Rapid valve opening time; SCD: Slow closing displacement. (From De Paulis R, et al., *Ann Thorac Surg* 2001;72:487. Reproduced with permission of Elsevier Publishers; © 2001 Society of Thoracic Surgeons).

Table II: Perioperative data.

Parameter	Group A (n = 25)	Group B (n = 21)	p-value
Operating time (min)*	324 ± 76	289 ± 45	0.09
CPB time (min)*	206 ± 44	182 ± 30	0.05
Cross-clamp time (min)	150 ± 22	135 ± 22	0.04
Operative techniques			
Reconstruction of leaflet prolapse (n)	4 (16)	2 (9.5)	
Minimally invasive technique (n)	1 (4)	-	
Partial aortic arch replacement (n)	5 (20)	7 (33)	
Concomitant procedures			
CABG (n)	5 (20)	5 (23.8)	
Closure of ASD (n)	1 (3)	1 (4.7)	
Mitral valve repair (n)	1 (3)	-	
Complications			
Death (n)	1 (3)	-	
Re-exploration for bleeding (n)	2 (8)	2 (9.5)	
Stroke (n)	2 (8)	-	
MI and low output syndrome (n)	2 (8)	-	
Sternal infection (n)	1 (4)	-	
Postoperative hospital stay (days)	16 ± 12.7	12.6 ± 6.2	0.32

*Values are mean ± SD.

Values in parentheses are percentages.

ASD: Atrial septal defect; CABG: Coronary artery bypass grafting; CPB: Cardiopulmonary bypass; MI: Myocardial infarction.

Operative technique

The chest was opened using a median sternotomy. Cardiopulmonary bypass was established and the core temperature was lowered to 32°C or to 18°C for circulatory arrest in patients with associated arch disease or dissections, respectively. The decision to preserve the native aortic valve was made intraoperatively after inspection of the valve leaflets. With increasing experience, obvious prolapse of one or two leaflets did not exclude patients from the procedure. The operative data are listed in Table II.

The sinuses of Valsalva were excised, leaving approximately 4-5 mm of aortic wall adjacent to the insertion line of the leaflets. In six patients, cusp prolapse was reconstructed using triangular resection of the excess cusp tissue and continuous 5-0 suture (Cardionyl™; Pèters Lab., Bobigny-Cedex, France).

Graft sizing changed with experience and after personal communication with Dr. T. David. Initially, the formula used was: [(leaflet height × 1.5) + 2 mm], but this was subsequently changed to: [(leaflet height × 2) + 2 mm]. Finally, in patients with a normal and non-dilated annulus the graft was matched to the annular

diameter, adding the aortic wall thickness. In cases where the creation of a 'neosinus' was planned, an additional 5 mm was added for excess diameter.

The graft was slightly beveled to account for the ventricular muscle extension into the commissure between the right and left coronary sinus (3). Transmural mattress sutures were placed just below the leaflet insertion to the aortic wall. These sutures were then passed through the graft, and tied. The valve was resuspended with pledgeted Prolene sutures above the commissures, and a running mattress suture was placed along the aortic wall remnant.

Three neosinuses were shaped by plicating the base of the graft with three sutures, taking 5-mm bites apart in height and circumference (n = 21). This reduced the diameter of the base, provided a more physiological triangular shape, and created a sinus bulge by height reduction at the line of the commissures (Fig. 2a and b). By suturing this modified prosthesis to the aortic root, the neosinuses were reshaped in a more physiological manner, thus compensating for the relative elongation of the cusp edges observed after chronic aneurysmal dilatation.

The coronary ostia were reimplemented into the graft. If necessary, partial or total arch replacement was performed during hypothermic circulatory arrest, with retrograde cerebral perfusion or low-flow antegrade cerebral perfusion. In these cases a second segment of vascular graft was used and later anastomosed to the root reconstruction graft.

Statistical analysis

An analysis of variance was used to compare continuous data among the three groups. Non-parametric data were compared using the chi-square test. A multiple-way analysis of variance for repeated measures was used to compare preoperative and postoperative ventricular diameter and volume. Post-hoc comparisons were made using the Scheffè F test (ANOVA). All data were expressed as mean ± SD. All statistical analyses were performed with StatView (version 5.0) for Windows software (SAS Institute, Inc., Cary, NC, USA).

Results

One perioperative death (2.2%) occurred due to cardiac failure (myocardial infarction and low-output syndrome). Postoperative complications included four re-explorations for bleeding (8.7%), one additional myocardial infarction with low-output syndrome, two strokes (4.3%) with permanent neurological deficit, and one sternal infection (Table II).

Twenty-eight of the operative survivors (n = 45) were followed for between 4 and 18 months (mean 11



Figure 2: Creation of the 'neosinus' by plicating the base of the graft with figure-of-eight sutures.

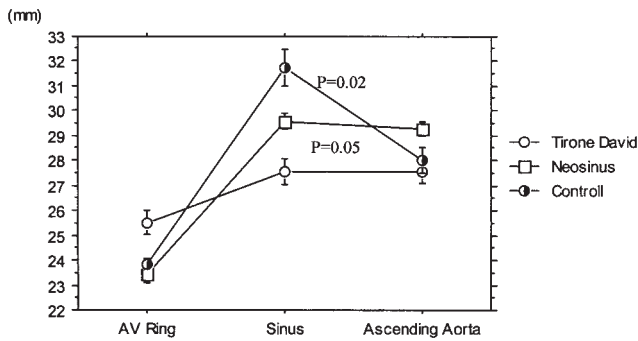


Figure 3: Diameters of the aortoventricular (AV) junction, sinus of Valsalva and ascending aorta in all groups. months). The late mortality was 8.8%. There were three sudden deaths and one non-cardiovascular death (bronchial cancer). During the follow up period there were no thromboembolic events or strokes; one group B patient required early reoperation due to rupture of the right coronary leaflet, and received a mechanical valve with further uneventful recovery. Another (group A) patient developed severe aortic insufficiency due to perforation of the left coronary leaflet four years after surgery, but this was reconstructed. One patient with Marfan's syndrome developed mitral endocarditis at nine months postoperatively. At one year after surgery, 25 of the patients followed up were in NYHA functional class I, two were in class II, and one patient was in class III.

Echocardiography

Postoperatively, complete competence of the AV was observed in 35 patients. Six patients had trivial AR (grade I), four had mild AR (grade II), and one had moderate AR (grade III). The mean transvalvular gradient was 3.4 ± 2.1 mmHg. Twenty-eight patients underwent TTE at one year follow up. There was a significant reduction in left ventricular end-systolic diameter (LVESD) during the postoperative follow up in both groups (postoperative versus one-year follow up

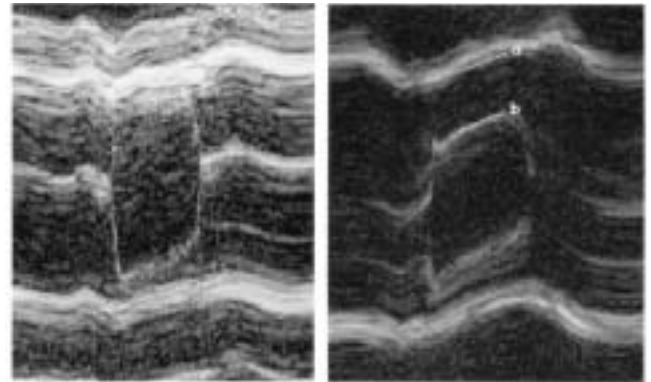


Figure 4: Transesophageal M-mode picture of the aortic root in patients with conventional reimplantation technique David I (group A, left), and in patients with the new neosinus technique (group B, right). a-b indicates the difference in the distance to the prosthetic wall.

LVESD, $p < 0.0001$). The systolic gradients were negligible, and valve competence was stable during the follow up (Table III).

Classic reimplantation (group A) led to an increased opening velocity of 61.3 ± 20 cm/s compared to normal controls 29.2 ± 9.8 cm/s (group A versus C, $p < 0.0001$). After the creation of a neosinus (group B), the opening speed was more physiological (46.3 ± 8.0 cm/s) (Table IV). In group A, the aortic valve also closed at a higher velocity (57.5 ± 22.7 cm/s) than in the control group (23.6 ± 6.8 cm/s), and showed shorter opening (A, 22 ± 6 ms versus C, 46 ± 10 ms; $p < 0.0001$) and closing times (A, 23 ± 10 ms versus C, 47 ± 14 ms; $p < 0.0001$). The minimum distance between the cusps and the prosthetic wall (Table IV) was largest (11.6 mm) in group C, and least in group A (3.7 mm). Neosinus creation shifted leaflet motion towards more physiological values (Table IV). In seven patients of group A, the cusps of the resuspended valve touched the graft during systolic opening, but this was not observed in any of the group B patients.

Table III: Comparison of postoperative and one-year follow up echocardiographic data.

Echocardiographic data	Postoperative*		1-year follow up*		p-value (A vs. B)	
	Group A (n = 23)	Group B (n = 21)	Group A (n = 15)	Group B (n = 13)	Postop.	1 year
AVA (cm ²)	2.3 ± 0.34	2.81 ± 0.4	2.20 ± 0.2	2.69 ± 0.4	<0.001	0.002
Pmax (mmHg)	9.8 ± 4.0	6.3 ± 3.7	10.1 ± 3.2	7.2 ± 3.6	0.01	0.08
Pmean (mmHg)	4.2 ± 2.1	2.7 ± 1.9	4.1 ± 1.5	3.0 ± 1.7	0.03	0.07
AR (grade)	0.45 ± 0.5	0.15 ± 0.4	0.3 ± 0.6	0.33 ± 0.5	0.06	0.91
LVESD (mm)	47.8 ± 4.6	46.7 ± 3.5	44.6 ± 3.7	43.8 ± 5.2	0.39	0.64
EF (%)	56.4 ± 10.1	60.8 ± 5.1	60.4 ± 6.6	64.1 ± 4.0	0.08	0.08

*Values are mean \pm SD.

AR: Aortic regurgitation; AVA: Aortic valve area; EF: Ejection fraction; LVESD: Left ventricular end-systolic diameter.

Table IV: Analysis for leaflet opening and closure times in M-mode technique.

Parameter	Group A* (n = 20)	Group B* (n = 19)	Group C* (n = 25)	A vs. B	A vs. C	B vs. C
VOT (ms)	22 ± 6	31 ± 4	46 ± 10	0.003	<0.0001	<0.0001
VOV (cm/s)	61.3 ± 20.1	46.3 ± 8	29.2 ± 9.8	0.005	<0.0001	
0.001						
VCT (ms)	23 ± 10	32 ± 6	47 ± 14	0.03	<0.0001	<0.0001
VCV (cm/s)	57.5 ± 22.7	43.8 ± 7.0	23.6 ± 6.8	0.012	<0.0001	0.0002
SCD (%)	7.3 ± 5.9	12.6 ± 4.9	21.1 ± 8.3	0.05	<0.0001	0.002
Distance (mm) ⁺	3.7 ± 2.1	6.8 ± 2.0	11.6 ± 1.5	<0.0001	<0.0001	<0.0001
Systolic contact (n)	7	0	0	-	-	-

*Values are mean ± SD.

⁺Leaflet to wall.

SCD: Systolic closing displacement; VCT: Valve closing time; VCV: Valve closing velocity; VOT: Valve opening time; VOV: Valve opening velocity.

The fraction of total closing displacement observed during the slow closing movement (Table IV) was less in group A (only 7.3% from maximal opening) than in groups B (12.6%) and C (21.1%).

The diameters of the sinus of Valsalva region were significantly different, being 27.5 ± 2.3 mm in group A, 29.5 ± 1.3 mm in group B, and 31.7 ± 4.1 mm in group C (A versus B, $p = 0.05$; B versus C, $p = 0.02$ (Figs. 3 and 4).

Discussion

The currently available techniques of valve-sparing aortic root reconstruction lead to a change in aortic root anatomy and dynamic function (8-13). In the David procedure, a Dacron tube graft is placed over the entire aortic root structure (1). This technique maintains valve competence by downsizing the sinotubular junction and sinuses, allowing the aortic cusps to coapt centrally. The disadvantage of this technique is that the cusps may touch and abrade against the Dacron tube graft when the valve opens. In addition, there are no sinuses of Valsalva and no systolic elastic expansion of the aortic root - a fact that results in significantly abnormal stress exerted on the cusps during opening and closing (5,6).

Cochran et al. (7) proposed a modification of tube graft reimplantation to produce pseudosinuses. In their technique, the slightly scalloped tube graft was sewn in a subannular position. This does not create a tear-shaped, natural sinus, but keeps the Dacron away from the leaflets. The technique has been shown experimentally to result in significantly less stress and strain on the cusps compared with the approaches of Yacoub or David (2,7,14-16).

Van Son et al. (17) described another technical modification, in which the aortic root is reconstructed with

preservation of the native AV and sinuses. Follow up is necessary to evaluate the long-term results. Grande-Allen et al. demonstrated, by using finite element modeling, that the valve-sparing with sinus space formation resulted in close to normal cusp stress load (6), while De Paulis and colleagues developed a specially shaped Dacron graft to re-establish a sinus bulge creating a new physiological widening of the aortic root with near-normal cusp dynamics measured by M-mode echocardiography (18,19).

In the present study, the dynamics of valve opening and closing after valve-sparing operations using the technique described as David I and a modified 'neosinus' technique were analyzed, and compared with a matched cohort of patients. The 'neousinus' technique was developed primarily to avoid cusp abrasion, and to accommodate the cusp edge elongation in chronic aneurysms, as the conventional technique may overcorrect the valve. This neousinus technique has the potential to improve valve durability by reducing cusp stress (4,20-23). Initially, the sinuses were bigger and more round-shaped; this was confirmed mainly by the larger valve opening area beyond the leaflet for group B (Table III). Second, as a consequence of the better shape and function of the sinuses, slow closing displacement of the cusps was significantly more evident and the motion more similar to normal, as in group A patients. The modified neousinus technique resulted in a better valve opening area and slightly lower gradients. By obtaining a more physiological valve motion, the stress on the leaflets may be decreased. Furthermore, in seven classic David patients, the cusps touched during valve opening - a phenomenon that was not observed in any of the neousinus cases. The present findings on cusp dynamics were consistent with the observations of Leyh et al. (5), who reported a more physiological valve motion for the remodeling

than for the reimplantation type of repair. Stress reduction by sinus formation was also calculated using finite element analyses (6).

Clinically, the present patients were well after both reimplantation types of repair. Ventricular function was improved, exercise tolerance was good in most cases, and only one valve-related late event was identified, this being caused by a secondary valve incompetence after repair for acute type A dissection. None of the patients suffered a thromboembolic event or an anticoagulation-related hemorrhage.

At present, it is too soon to determine the long-term fate of the native AV after the modified neosinus technique compared with the classic David operation, but good long-term function is anticipated - at least in those instances in which perfect valve geometry was achieved and either trivial or no aortic incompetence was apparent within the first two postoperative years. The mid-term results for the classic technique showed a very moderate rate of late failure, indicating that stresses are still within the strength of the leaflet tissue (19).

The neosinus technique is associated with reduced valve opening and closure velocities with the potential to minimize the stress of the cusps. This technique avoids leaflet contact with the Dacron prosthesis, thus providing additional evidence for leaflet abrasion. Although the mid-term results are encouraging, a longer follow up is necessary in order to evaluate the potential clinical benefits.

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