European Journal of Cardio-Thoracic Surgery 59 (2021) 1087–1094
doi:10.1093/ejcts/ezaa445 Advance Access publication 7 December 2020

ORIGINAL ARTICLE

Cite this article as: Petersen J, Lenz A, Adam G, Reichenspurner H, Bannas P, Girdauskas E. Changes in transvalvular flow patterns after aortic valve repair: comparison of symmetric versus asymmetric aortic valve geometry. Eur J Cardiothorac Surg 2021;59:1087–94.

Changes in transvalvular flow patterns after aortic valve repair: comparison of symmetric versus asymmetric aortic valve geometry

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Received 13 July 2020; received in revised form 28 October 2020; accepted 10 November 2020

Key question

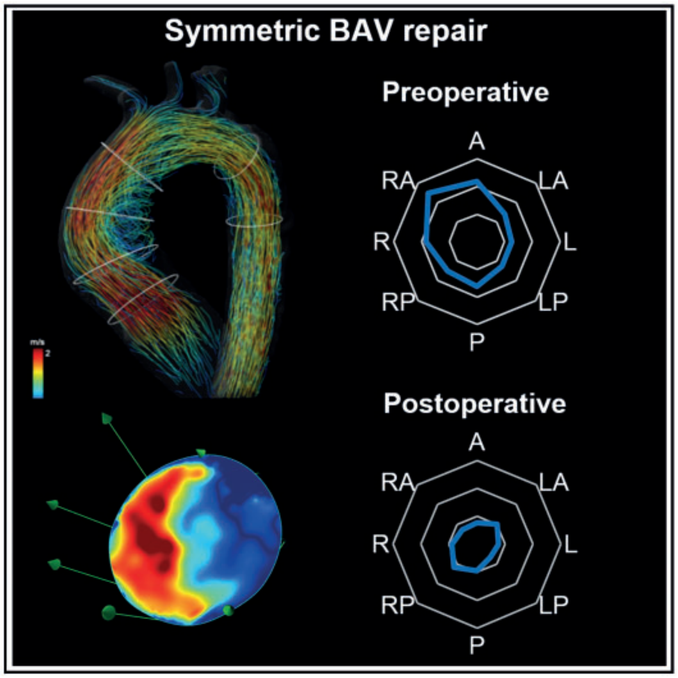
What are the haemodynamic changes after different bicuspid aortic valve (BAV) repair techniques (symmetric *vs* asymmetric BAV repair)?

Key finding(s)

Symmetric BAV repair results in reduced flow eccentricity, wall shear stress, and flow helicity.

Take-home message

Symmetric BAV repair results in more physiological flow patterns as compared to asymmetric repair; it should be aimed for in every BAV repair.



Abstract

OBJECTIVES: The aim of this study was to compare the effect of asymmetric versus symmetric bicuspid aortic valve (BAV) repair on transvalvular flow patterns and aortic wall shear stress (WSS).

METHODS: Four-dimensional flow magnetic resonance imaging was prospectively and consecutively performed in patients with congenital aortic valve (AV) disease before and after AV repair. The following MRI-based parameters were assessed: (i) flow eccentricity index, (ii) backward flow across the AV, (iii) grading of vortical and helical flow, and (iv) WSS (N/m^2) in the proximal aorta. MRI-derived flow parameters were compared between patients who underwent 'asymmetric BAV repair' (n = 13) and 'symmetric BAV repair' (n = 7).

Presented at the 32nd Annual Meeting of the European Association for Cardio-Thoracic Surgery, Milan, Italy, 18–20 October 2018.

CONVENTIONAL VALVE OPERATIONS

RESULTS: A total of 20 patients (39 ± 12 years, 80% male), who underwent BAV repair, were included. In the asymmetric BAV repair group, circumferential WSS reduction was found at the level of the aortic arch ($P = 0.015$). In the symmetric BAV repair group, postoperative circumferential WSS was significantly reduced compared to baseline at all levels of the proximal aorta (all $P < 0.05$). Postoperative circumferential WSS was significantly higher in the asymmetric versus symmetric BAV repair group at the level of the sinotubular junction (0.45 ± 0.15 vs 0.30 ± 0.09 N/m^2; $P = 0.028$), ascending aorta (0.59 ± 0.19 vs 0.44 ± 0.08 N/m^2; $P = 0.021$) and aortic arch (0.59 ± 0.25 vs 0.40 ± 0.08 N/m^2; $P = 0.017$). Segmental WSS analysis showed significantly higher postoperative WSS after asymmetric versus symmetric BAV repair, especially in the anterior aortic segment ($P = 0.004$).

CONCLUSIONS: Symmetric BAV repair results in more physiological flow patterns and significantly reduces WSS, as compared to asymmetric BAV repair. From a haemodynamic point of view, symmetric AV geometry should be attempted in every congenital AV repair.

Keywords: 4D flow MRI • Wall shear stress • Bicuspid aortic valve • Aortic valve repair

ABBREVIATIONS

AAo	Ascending aorta
AV	Aortic valve
BAV	Bicuspid aortic valve
4D flow MRI	Four-dimensional flow magnetic resonance imaging
PTFE	Polytetrafluoroethylene
TAV	Tricuspid aortic valve
UAV	Unicuspid aortic valve
WSS	Wall shear stress

INTRODUCTION

Bicuspid aortic valve (BAV) disease is the most common congenital valve disease with an estimated prevalence of 1–2% [1]. BAV is associated with an accelerated aortic valve (AV) deterioration due to the progressive cusp degeneration [2]. Therefore, BAV is the most common cause of aortic stenosis in patients presenting with AV disease in their fifth and sixth decades of life [3]. Aortic regurgitation (AR) in BAV necessitates AV surgery even earlier, in the fourth and fifth decades of life [4]. Unicuspid aortic valve (UAV) disease is associated with an even earlier AV degeneration and requires surgery often in the second and third decades of life [5].

Four-dimensional flow magnetic resonance imaging (4D flow MRI) has been developed to improve the understanding and visualization of complex haemodynamic flow patterns in several cardiovascular diseases [6]. Previous BAV studies documented an elevated wall shear stress (WSS) in the proximal aorta as compared to tricuspid aortic valve (TAV) controls [7, 8]. Furthermore, an extensive flow helicity [9] and increased flow eccentricity [10] was found in BAV patients, as compared to their TAV counterparts.

Recently, AV repair evolved as an alternative to AV replacement in non-elderly adults with severe aortic regurgitation. Correction of cusp pathology and AV annulus dilatation are 2 major components of successful BAV repair [11]. Recent studies have demonstrated that 4D flow MRI is a valuable tool to assess haemodynamic changes after AV repair [12, 13]. However, the impact of different AV repair strategies on transvalvular flow has not been analysed yet. Hence, the aim of our study was to compare the effect of asymmetric versus symmetric BAV repair on transvalvular flow patterns and aortic WSS.

METHODS

Patients

A total of 20 patients with UAV or BAV disease, who underwent AV repair between April 2017 and February 2019, were prospectively included. The study protocol was approved by our local ethics committee (registration number: PV5876), and written informed consent was obtained from each patient. We excluded all patients, who were not suitable for AV repair (e.g. in case of extensive cusp calcifications or large ruptured paracommissural fenestrations), in case of contraindications for MRI as well as patients <18 years of age.

We subdivided our study cohort according to intraoperative AV repair strategy: symmetric AV repair (commissural angulation ≥160°) was achieved in 7 patients ('symmetric BAV repair group'). The remaining 13 patients had an asymmetric BAV repair (commissural angulation <160°) ('asymmetric BAV repair group').

Aortic valve repair surgery

All patients underwent AV repair using a partial-upper sternotomy approach. In isolated AV repair, partial-upper sternotomy was performed in the 3rd intercostal space and in case of aortic root procedure, in the 4th intercostal space. After systemic heparinization, arterial cannulation of the distal ascending aorta (AAo) or the proximal aortic arch (in case of aortic root procedure and/or replacement of AAo) was performed. Venous cannulation was achieved percutaneously through the vena femoralis in Seldinger technique under echocardiographic guidance. After the initiation of cardiopulmonary bypass, mild-to-moderate hypothermia of 32–34°C was induced. After clamping of the aorta, horizontal aortotomy was done at the level of the sinotubular junction and a single shot of crystalloid cardioplegia (CUSTODIOL®) was administered in both coronary ostia. Commissural stay sutures were used for an adequate exposure. Thorough cusp assessment, measurement of geometric/effective cusp height and AV annulus diameter were performed to tailor AV repair strategy. Generally, we aimed to achieve an effective cusp height of ≥8 mm and an annular diameter of ≤25 mm after every AV repair.

In the 'asymmetric BAV repair group', all 13 patients had a Sievers type I, left-right fusion [14]. AV annular dilatation was present in all patients and was addressed by an internal ($n = 11$) or external ($n = 2$) polytetrafluoroethylene (PTFE) suture annuloplasty [15], using 23–25-mm Hegar dilator. Central cusp plication

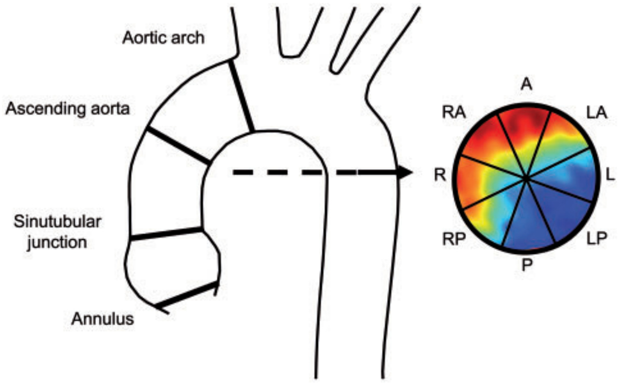


Figure 1: Measurement of wall shear stress at 4 different levels in the thoracic aorta (aortic valve, sinotubular junction, ascending aorta, aortic arch). Segmental wall shear stress was determined at 8 standardized local anatomic orientations of the vessel wall for segmental wall shear stress analysis. A: anterior; L: left; LA: left anterior; LP: left posterior; P: posterior; RP: right posterior; R: right; RA: right anterior.

was performed to achieve an effective cusp height of 8–10 mm. In 1 patient, a severely restrictive raphe required a triangular resection and an implantation of a limited CardioCell® bovine pericardial patch. In all 13 patients, an asymmetrical type B BAV repair with the commissural angulation of 140–159° [16] was achieved.

In the 'symmetric BAV repair group', 4 of the 7 patients underwent UAV bicuspidalization according to Schäfers' technique [17]. Severe calcification of the anterior part of UAV was present in all 4 patients. Calcified and restrictive raphe tissue was partially resected and a neo-commissure was created using a CardioCell® bovine pericardial patch in a 180° angle to the normal posterior commissure. Symmetric bicuspid configuration in terms of type A symmetrical repair [16] with an effective height of 10 mm was achieved in all 4 cases. Two of the 7 patients in the symmetric BAV repair group had a simultaneous aortic root aneurysm of 50–53 mm diameter. Valve-sparing root replacement, using a remodelling technique, was performed with a 26- or 28-mm Dacron prosthesis. In both cases, AV annulus diameter was reduced to 23 or 25 mm using an external PTFE suture annuloplasty [15]. The prolapse of fused R/l cusp was corrected by means of interrupted 6–0 Prolene plication sutures. During the remodelling procedure, a symmetric BAV configuration with a commissural angle of 180° was recreated [16]. One remaining patient in the symmetrical BAV repair group presented with a Sievers type 0 BAV [14] and prolapse of both cusps and severe AV annulus dilatation of 34 mm. The AV annulus was reduced to 25 mm using PTFE suture annuloplasty [15] and the cusp prolapse was corrected by central plication sutures of both cusps.

Four-dimensional flow magnetic resonance imaging

All patients underwent non-contrast 4D flow MRI of the thoracic aorta on a 3 T system (Ingenia, Philips, Netherlands) with a 32-channel body-phased array coil before and after AV repair [12]. Respiratory-gated and cardiac-triggered 4D flow MRI data were acquired over the entire cardiac cycle with full volumetric coverage of the thoracic aorta. Scan parameters included: velocity encoding 200 cm/s, temporal resolution 24–38 ms, spatial resolution 2.5 × 2.5 × 2.5 mm^3, field of view (280–330) × (280–330) × (50–66) mm^3, flip angle = 8°. Parallel imaging (k-t BLAST) with an acceleration factor of 4 was used. Scan time for each acquisition was ranged from 10 to 15 min.

Four-dimensional flow magnetic resonance imaging data analysis

4D flow MRI data were corrected for Maxwell terms, eddy currents and phase aliasing according to latest recommendations [18]. All data sets were automatically reconstructed to 24-time frames per cardiac cycle and used to render phase-contrast MRI angiograms in a 3D visualization software (GTFlow Version 3.2, GyroTools LLC, Switzerland). Analysis planes were placed at 4 defined anatomic landmarks in the thoracic aorta at the level of the AV, the sinotubular junction, the mid- AAo and the aortic arch proximal to the brachiocephalic trunc [12] (Fig. 1).

We focused on the following MRI-based measurements in both patient groups:

1. Flow eccentricity, which quantitatively describes outflow asymmetry, was automatically quantified by exporting defined analyses planes into MATLAB (The MathWorks, USA). Flow eccentricity was defined as the distance from the vessel centreline to the centre of the upper 15% of peak systolic forward flow normalized to the vessel diameter [8, 10, 12].
2. Forward flow volume and backward flow volume were quantified at the AV level and the regurgitant fraction (%) was calculated [12].
3. Helical and vorticial flow patterns in the AAo were semiquantitatively evaluated according to a 3-point scale: 0 (none), 1 (<360°) and 2 (>360°). Helical flow pattern was defined as a regional spiral movement along the blood flow direction, while a vorticial flow was described as a regional circular movement deviating from the physiological flow direction by >90° [12, 19].
4. WSS was derived from each analysis plane at peak systole. Values for peak systolic WSS were averaged over the 5 cardiac time frames centred on peak systole to reduce measurement noise [20, 21]. Averaged circumferential WSS was assessed for each plane as well as segmental WSS at 8 standardized local anatomic orientations of the vessel wall: anterior (A), left anterior (LA), left (L), left posterior (LP), posterior (P), right posterior (RP), right (R) and right anterior (RA) (Fig. 1) [7–9, 12].

Statistical analysis

Categorical variables (e.g. helices and vortices) are expressed as frequencies and percentages and were analysed using chi-square test or with few data (if the expected value was <5) the exact test according to Fischer was used. Continuous variables are presented as mean ± standard deviation. Data before and after surgery were compared by a two-sided paired *t*-test if normally distributed and by Wilcoxon matched-pairs signed-rank test if non-normally distributed. Analysis between asymmetric and symmetric BAV repair patients was done with an independent sample *t*-test. All reported *P*-values are two-sided and *P*-values of 0.05 or less were considered statistically significant. Adjustment of multiple testing was not performed. All statistical analyses were accomplished using Excel 16.21 (Microsoft, USA), GraphPad Prism 7 (GraphPad Software, USA) and IBM SPSS 23 software (IBM Corp., New York, USA).

CONVENTIONAL VALVE OPERATIONS

Table 1: Preoperative characteristics of patients with asymmetric versus symmetric bicuspid aortic valve repair

Patient characteristics	Asymmetric BAV repair (*n* = 13)	Symmetric BAV repair (*n* = 7)	*P*-value
Age (years), mean ± SD	39.7 ± 10.9	36.7 ± 14.1	0.60
Gender, male, *n* (%)	11 (84.6)	5 (71.4)	0.48
Arterial hypertension, *n* (%)	6 (46.2)	4 (57.1)	0.63
BMI (kg/m^2), mean ± SD	25.5 ± 3.6	24.1 ± 3.2	0.43
STS score, mean ± SD	0.65 ± 0.28	0.73 ± 0.65	0.58
Predominant aortic regurgitation, *n* (%)	13 (100)	5 (71.4)	**0.042**
Mean AV gradient (mmHg), mean ± SD	7.0 ± 2.2	25.6 ± 17.7	**0.032**

AV: aortic valve; BAV: bicuspid aortic valve; BMI: body mass index; STS- Score: The Society of Thoracic Surgeons- Score.

Table 2: Perioperative data of patients with asymmetric versus symmetric bicuspid aortic valve repair

Perioperative data	Asymmetric BAV repair (*n* = 13)	Symmetric BAV repair (*n* = 7)	*P*-value
Cardiopulmonary bypass time (min), mean ± SD	99 ± 23	124 ± 19	**0.023**
Cross-clamp time (min), mean ± SD	54 ± 15	84 ± 16	**0.001**
Duration of surgery (min), mean ± SD	197 ± 42	227 ± 20	0.10
Echocardiography at discharge, mean ± SD			
Max AV gradient (mmHg)	23.1 ± 10.9	19.6 ± 8.8	0.46
Mean AV gradient (mmHg)	12.2 ± 6.3	10.0 ± 4.2	0.43
ICU stay (days), mean ± SD	1.2 ± 0.3	1.6 ± 0.9	0.23
In-hospital stay (days), mean ± SD	6.0 ± 2.6	7.6 ± 4.3	0.31

AV: aortic valve; BAV: bicuspid aortic valve.

RESULTS

Perioperative data

The mean age at the time of surgery was comparable in both study groups (i.e. 39.7 ± 10.9 years in the asymmetric BAV repair group vs 36.7 ± 14.1 years in the symmetric BAV repair group; *P* = 0.60). Preoperative Society of Thoracic Surgeons score was low in both groups (0.65 ± 0.28 vs 0.73 ± 0.65, respectively, *P* = 0.58). In the asymmetric BAV repair group, all thirteen patients (100%) had a bicuspid type 1 morphology with predominant aortic regurgitation. Valve morphology was unicuspid in 4 patients (57%) and bicuspid in 3 patients (43%) in the symmetric BAV repair group (*n* = 7) with predominant aortic regurgitation in 5 patients. The other 2 symmetric BAV repair patients presented with a severe AV stenosis resulting in a significant higher mean AV pressure gradient compared to the asymmetric BAV repair group (25.6 ± 17.7 vs 7.0 ± 2.2; *P* = 0.032). Three patients (2 symmetric and 1 asymmetric BAV repair group) showed an enlargement of the AAo (41–45 mm) while one of such patients received a concomitant replacement of AAo. Measurement of the angle of the BAV in preoperative transoesophageal echocardiography showed significant differences between both groups (asymmetric BAV repair group: 135.5 ± 14.6 degree vs asymmetric BAV repair group: 172.3 ± 2.5 degree; *P* = 0.001). Remaining preoperative characteristics showed no significant differences between asymmetric versus symmetric BAV repair groups (Table 1).

Perioperative data are displayed in Table 2. Cardiopulmonary bypass time (99 ± 23 vs 124 ± 19 min; *P* = 0.023) and cross-clamp time (54 ± 15 vs 84 ± 16 min; *P* = 0.001) were significantly shorter in the asymmetric versus symmetric BAV repair group. Postoperative echocardiography at discharge showed no significant difference in transvalvular gradients in the asymmetric versus symmetric BAV repair group (i.e. 12.2 ± 6.3 vs 10.0 ± 4.2 mmHg; *P* = 0.43) and no relevant residual AR (i.e. AR grade >1) in both groups. Postoperative in-hospital stay showed no significant differences between both groups.

Transvalvular flow patterns

In the asymmetric BAV repair group, there were no significant changes in flow eccentricity from pre- to postoperative values at the level of the Sinotubular (STJ) (*P* = 0.27), AAo (*P* = 0.80) (Fig. 2a and b) and aortic arch (*P* = 0.44). In the symmetric BAV repair group, flow eccentricity was postoperatively significantly reduced at the level of AAo (0.38 ± 0.08 vs 0.25 ± 0.04; *P* = 0.003); (Fig. 2a and b). No significant changes were found at the level of the STJ (*P* = 0.12) and aortic arch (*P* = 0.99). Quantitative measurements of backward transvalvular flow showed no significant differences between study groups (Table 3).

Severity of preoperative helices did not differ significantly between asymmetric and symmetric BAV repair groups (*P* = 0.18). Postoperative helices were significantly reduced in the symmetric versus asymmetric BAV repair group (*P* = 0.046). Vortical flow showed no significant differences in both study groups (Table 4).

Circumferential wall shear stress analysis

In the asymmetric BAV repair group, postoperative circumferential WSS was significantly reduced as compared to preoperative values at the level of the aortic arch (0.59 ± 0.25 vs 0.79 ± 0.34 N/m^2; *P* = 0.015). In the symmetric BAV repair group, WSS was significantly reduced postoperatively in the AAo (0.44 ± 0.08 N/m^2 vs 0.83 ± 0.25 N/m^2; *P* = 0.003) and in the aortic arch (0.40 ± 0.08 N/m^2 vs 0.83 ± 0.39 N/m^2; *P* = 0.042) (Table 5).

Preoperative circumferential WSS was not significantly different in both study groups at all 3 aortic levels (all *P* > 0.05).

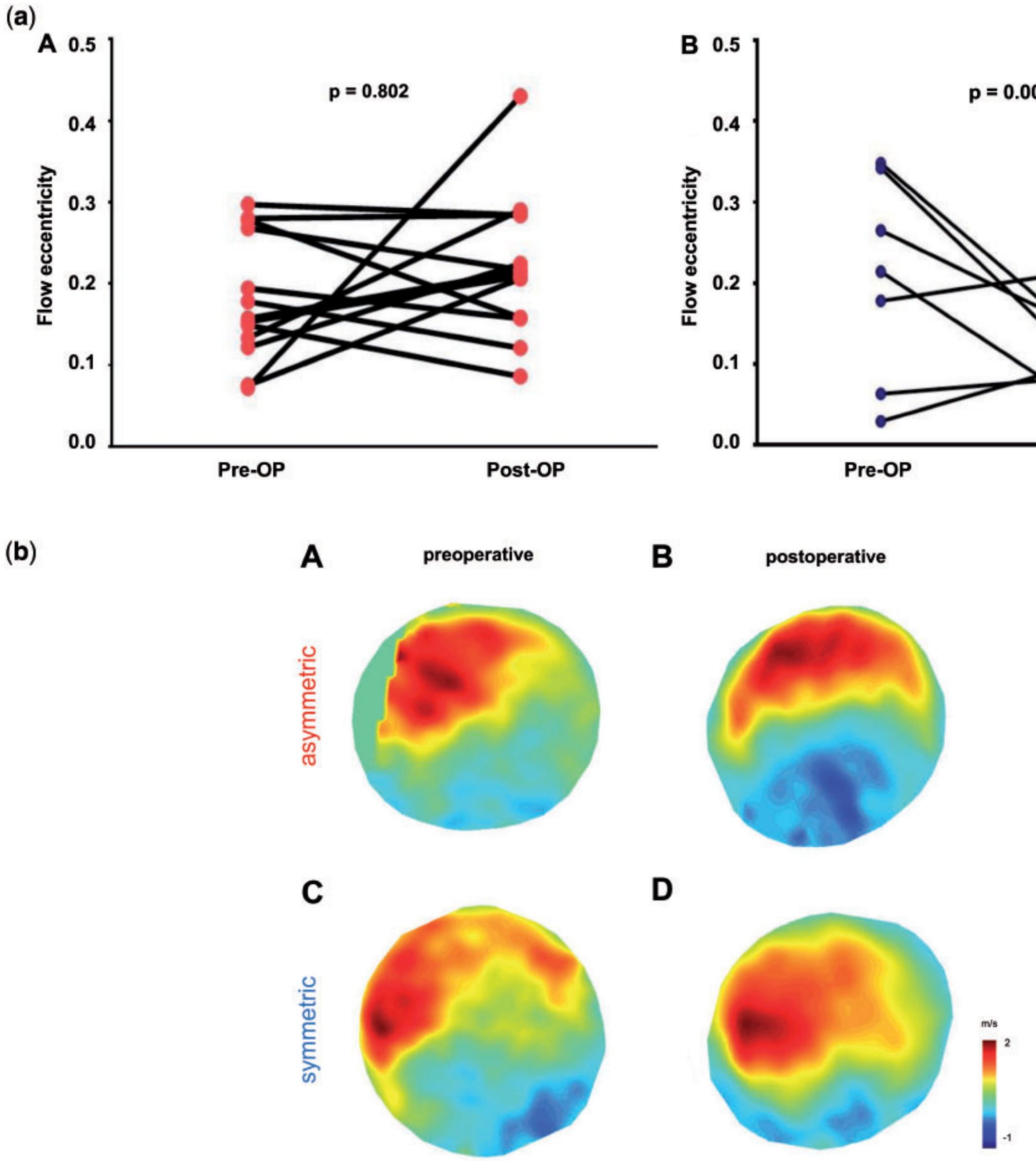


Figure 2: (**a**) Comparison of pre- and postoperative flow eccentricity in the ascending aorta in patients with asymmetric bicuspid aortic valve repair (**A**) and symmetric bicuspid aortic valve repair (**B**). (**b**) Heat map analysis showing differences in eccentric flow patterns of a patient before (**A**) and after (**B**) asymmetric bicuspid aortic valve repair and of a patient before (**C**) and after (**D**) symmetric bicuspid aortic valve surgery.

Postoperatively, WSS was significantly higher at all 3 aortic levels in the asymmetric versus symmetric BAV repair group (all $P < 0.05$) (Table 5).

Segmental wall shear stress analysis

Postoperative segmental WSS at the level of the STJ was significantly higher in 4 aortic segments in the asymmetric versus symmetric BAV repair group: anterior ($P = 0.004$), right-anterior ($P = 0.031$), right ($P = 0.016$) and right-posterior ($P = 0.048$) segments. Postoperative segmental WSS at the level of the AAo was significantly higher in the anterior segment (0.71 ± 0.30 vs 0.38 ± 0.18 N/m^2; $P = 0.019$) in the asymmetric versus symmetric BAV repair group (Fig. 3). At the level

Table 3: Comparison of pre- and postoperative forward and backward flow in patients with asymmetric versus symmetric bicuspid aortic valve repair

	Asymmetric BAV repair (*n* = 13)	Symmetric BAV repair (*n* = 7)	*P*-value
Forward flow (ml), mean ± SD			
Preoperative	149.5 ± 38.7	111.8 ± 71.1	0.22
Postoperative	94.6 ± 23.7	78.1 ± 35.9	0.27
Backward flow (ml), mean ± SD			
Preoperative	35.1 ± 26.3	25.2 ± 24.3	0.23
Postoperative	14.1 ± 10.6	9.1 ± 7.7	0.28

BAV: bicuspid aortic valve.

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of aortic arch, postoperative segmental WSS was significantly higher in the anterior segment in the asymmetric versus symmetric BAV repair group (0.70 ± 0.39 vs 0.29 ± 0.15 N/m^2; $P = 0.017$).

DISCUSSION

Our study demonstrates that symmetric BAV repair results in a more physiological transvalvular flow profile and consecutively reduced WSS as compared to asymmetric BAV repair.

Postoperative changes in four-dimensional flow magnetic resonance imaging *patterns*

Imaging data comparing preoperative versus postoperative haemodynamic flow profiles in AV surgery are limited. One previous study reported improved flow patterns after transcatheter aortic valve replacement for aortic stenosis, which resulted in less flow turbulence and more uniform WSS distribution [22]. Recently, we demonstrated that 4D flow MRI is a valuable tool to assess the haemodynamic impact of AV repair [12, 13]. Another study analysed transvalvular flow patterns after AV-sparing root surgery which, postoperatively, showed less eccentric flow patterns [23]. In our present study we were able to demonstrate that symmetric BAV repair results in a more physiological transvalvular flow profile than asymmetric BAV repair with a consecutively reduced eccentric flow and WSS.

Table 4: Comparison of pre- and postoperative helices and vortices in ascending aorta in patients with asymmetric versus symmetric bicuspid aortic valve repair

	Asymmetric BAV repair ($n = 13$) (%)	Symmetric BAV repair ($n = 7$) (%)	*P*-value
Helices in ascending aorta			
Preoperative			
Grade 0	0		
Grade 1	46.2	14.3	0.18
Grade 2	53.8	71.4	
Postoperative			
Grade 0	7.7	42.9	
Grade 1	92.3	42.9	**0.046**
Grade 2	0	14.2	
Vortices in ascending aorta			
Preoperative			
Grade 0	38.5	0	0.065
Grade 1	38.5		
Grade 2	23.0	62.5	
Postoperative			
Grade 0	69.2	28.6	0.13
Grade 1	30.8		
Grade 2	0	14.3	

BAV: bicuspid aortic valve.

Aortic valve repair in bicuspid aortic valve *disease and* four-dimensional flow magnetic resonance imaging *flow profiles*

BAV disease is associated with a life-long risk of AV and/or aortic interventions [24]. In need of AV surgery, AV replacement is most often performed, especially with mechanical valve prostheses in young BAV patients. Analysis of transvalvular flow patterns after AV replacement showed a higher amount of vortices in mechanical valve prostheses, while stented bioprostheses resulted in a more extensive flow helicity . Instead of physiological laminar flow, all valve prostheses (i.e. stentless/stented bioprostheses and mechanical prostheses) showed eccentric transvalvular flow directed towards the right anterior wall of the AAo [25]. The same also applies to the patients who undergo aortic root replacement with composite valve-conduit grafts [26]. In general, every type of AV replacement results in suboptimal and non-physiological transvalvular haemodynamics, which is quite different from healthy individuals who have laminar blood flow and symmetrical WSS [27].

Nowadays, specialized valve-repair centres aim to repair regurgitant BAV in non-elderly adults [28]. The primary aim of AV repair is to restore optimal AV geometry to achieve a durable repair. However, the most appropriate AV repair strategy in congenital AV disease is still under investigation. Surgical strategy may vary according to the BAV phenotype, while commissural orientation is an important factor for the choice of repair technique [16]. Type A symmetrical phenotype (160–180°) is corrected with central plication without changing the commissural orientation. An asymmetrical (140–159°) BAV is repaired by

Table 5: Circumferential wall shear stress (N/m^2) in patients with asymmetric versus symmetric bicuspid aortic valve repair

Circumferential wall shear stress (N/m^2)	Asymmetric BAV repair ($n = 13$)	Symmetric BAV repair ($n = 7$)	*P*-value (asymmetric versus symmetric)
Sinotubular junction, mean ± SD			
Preoperative	0.48 ± 0.23	0.40 ± 0.14	0.45
Postoperative	0.45 ± 0.15	0.30 ± 0.09	**0.028**
P-value (pre- versus postoperative)	0.714	0.237	
Ascending aorta, mean ± SD			
Preoperative	0.74 ± 0.24	0.83 ± 0.25	0.46
Postoperative	0.59 ± 0.19	0.44 ± 0.08	**0.021**
P-value (pre- versus postoperative)	0.083	**0.003**	
Aortic arch, mean ± SD			
Preoperative	0.79 ± 0.34	0.83 ± 0.39	0.46
Postoperative	0.59 ± 0.25	0.40 ± 0.08	**0.017**
P-value (pre- versus postoperative)	**0.015**	**0.042**	

BAV: bicuspid aortic valve.

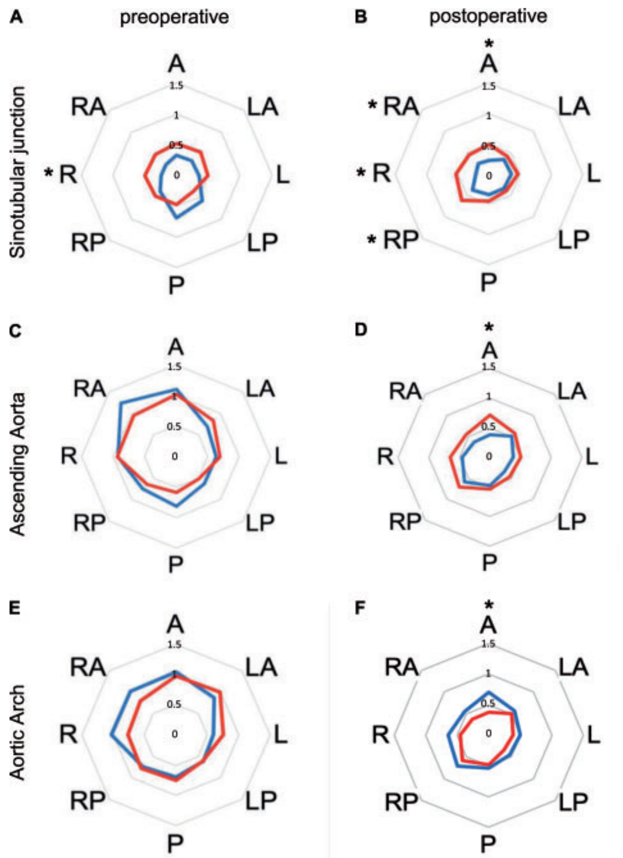

Figure 3: Spider charts of segmental peak systolic wall shear stress (N/m^2) before (**A**, **C**, **E**) and after (**B**, **D**, **F**) symmetric (blue spiders) and asymmetric (red spiders) bicuspid aortic valve repair at the level of the sinotubular junction (**A**, **B**), mid-ascending aorta (**C**, **D**) and distal aortic arch (**E**, **F**). Wall shear stress was assessed at 8 standardized local anatomic orientations of the vessel wall (A: anterior; LA: left anterior; L: left; LP: left posterior; P: posterior; RP: right posterior; R: right; RA: right anterior). Asterisks indicate segments with significant differences in wall shear stress between asymmetrical versus symmetrical bicuspid aortic valve repair group.

direct closure of the non-fused segment of the fused cusp and increasing the commissural orientation towards 180° by aortic root procedure or sinus plication. This repair technique maintains valve mobility while avoiding the use of patch material. The very asymmetrical (120–139°) BAV phenotype is treated best, similar to a tricuspid valve, by creating a new functional commissure at the level of fused cusp [16]. Several studies reported an asymmetrical BAV repair (i.e. < 160°) as an independent risk factor for repair failure [29]. Therefore, surgical techniques were developed towards a more symmetric approach to achieve a more appropriate commissure orientation [30]. However, there are no haemodynamic data to support this hypothesized clinical benefit of a more symmetric BAV configuration.

So far, only very few 4D flow MRI studies focused on the haemodynamic impact of AV repair surgery [12, 13]. Semaan *et al.* [23] were able to demonstrate a reduction of helical and eccentric flow after AV-sparing root surgery in BAV patients.

Previous studies had neither specifically addressed the haemodynamic differences between type 1 versus type 0 BAV patients nor analysed the haemodynamic impact of the BAV repair (i.e. symmetric versus asymmetric BAV repair). Therefore, the question which geometric BAV configuration produces the most favourable transvalvular flow pattern after AV repair is yet to be answered.

We specifically addressed this question by analysing 4D flow MRI transvalvular flow patterns. We found that symmetric BAV repair (type A, 160–180°) results in a significantly reduced helical flow, flow eccentricity and aortic WSS, as compared to asymmetric BAV repair (type B, 140–159°). Therefore, our data suggest that, in every congential AV repair, symmetric BAV repair with a commissural orientation towards 180° results in a more favourable haemodynamic configuration and should at least be attempted.

Limitations

Our study has several limitations. First, neither a healthy TAV control group nor a biological valve replacement control group was included for the comparison of transvalvular flow patterns after AV repair. However, the main goal of our study was to compare the haemodynamic effects of different BAV repair techniques. Furthermore, longer follow-up is needed to answer the question, whether beneficial haemodynamic profiles after symmetric BAV repair affect the BAV aortopathy progression and durability of BAV repair.

CONCLUSION

Symmetric BAV repair results in more physiological flow patterns and significantly reduces WSS, as compared to an asymmetric BAV repair. From a haemodynamic point of view, symmetric geometry should be attempted in every congenital AV repair.

Funding

No funding was received.

Conflict of interest: none declared.

Author contributions

Johannes Petersen: Data curation; Formal analysis; Methodology; Writing—original draft. **Alexander Lenz:** Data curation; Formal analysis; Writing—review & editing. **Gerhard Adam:** Supervision. **Hermann Reichenspurner:** Supervision. **Peter Bannas:** Methodology; Project administration; Validation; Writing—review & editing. **Evaldas Girdauskas:** Conceptualization; Project administration; Supervision; Validation; Writing—review & editing.

Reviewer information

European Journal of Cardio-Thoracic Surgery thanks Stefano Schena, David Schibilsky, Naomichi Uchida and the other, anonymous reviewer(s) for their contribution to the peer review process of this article.

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