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The Effect of Surgical and Transcatheter Aortic Valve Replacement on Mitral Annular Anatomy

Mathieu Vergnat, M.D.⁴, Melissa M. Levack, M.D.^{4,*}, Benjamin M. Jackson, M.D.¹, Joseph E. Bavaria, M.D.¹, Howard C. Herrmann, M.D.², Albert T. Cheung, M.D.³, Stuart J. Weiss, M.D., Ph.D.³, Joseph H. Gorman III, M.D.^{1,4}, and Robert C. Gorman, M.D.^{1,4}

¹Department of Surgery, University of Pennsylvania, Philadelphia, PA

²Department of Medicine, University of Pennsylvania, Philadelphia, PA

³Department of Anesthesia, University of Pennsylvania, Philadelphia, PA

⁴The Gorman Cardiovascular Research Group, University of Pennsylvania, Philadelphia, PA

Abstract

Background—The effect of aortic valve replacement on three-dimensional (3D) mitral annular geometry has not been well-described. Emerging transcatheter approaches for aortic valve replacement employ fundamentally different mechanical techniques for achieving fixation and seal of the prosthetic valve than standard surgical aortic valve replacement. This study compares the immediate impact of transcatheter aortic valve replacement (TAVR) and standard surgical aortic valve replacement (AVR) on mitral annular anatomy.

Methods—Real-time 3D echocardiography was performed in patients undergoing TAVR using the Edwards Sapien® valve (n=10) or AVR (n=10) for severe aortic stenosis. Mitral annular geometric indexes were measured using Tomtec EchoView to assess regional and global annular geometry.

Results—Mixed between-within ANOVA showed no differences between TAVR and AVR groups in any of the mitral annular geometric indices pre-operatively. However, post-operative analysis did demonstrate an effect of AVR on geometry. Patients undergoing open AVR had significant decrease in annular height, septolateral diameter, mitral valve transverse diameter and mitral annular area after valve replacement (P .006). Similar changes were not noted in the TAVR group.

Conclusions—TAVR preserves mitral annular geometry better than AVR. Thus, TAVR may be a more physiological approach to aortic replacement.

Keywords

Aortic Valve Replacement; Echocardiography; Mitral Valve; Modeling

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Address for correspondence: Robert C. Gorman, M.D., Gorman Cardiovascular Research Group, Glenolden Research Laboratory, 500 S. Ridgeway Avenue, Glenolden, PA 19036, Phone: 267-350-9614, FAX: 267-350-9627, gormanr@uphs.upenn.edu.

*Drs. Vergnat and Levack contributed equally to this work

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Introduction

Surgical aortic valve replacement (AVR) is the established therapy for symptomatic aortic stenosis; however, transcatheter aortic valve implantation (TAVR) has recently been shown to demonstrate acceptable early and intermediate outcomes in high risk patients with symptomatic severe aortic stenosis. [1–3] The effect of either technique for aortic valve replacement on mitral valve three-dimensional (3D) anatomy has not been described.

TAVR and AVR are anatomically and physiologically divergent procedures. Surgical AVR requires resection of the leaflet tissue with the valve anchored by sutures that draw aortic annular tissue *inwards* toward the valve prosthesis. In contrast, the TAVR device is placed without leaflet resection and imposes *outwardly* directed radial anchoring forces on adjacent structures to achieve fixation of the prosthetic valve. Given these differences in technique, we hypothesized that TAVR and AVR would have distinct immediate effects on mitral annular anatomy. In this study, using real-time three-dimensional echocardiography, we compared mitral annular geometry in patients undergoing TAVR and AVR.

Patient and Methods

Patients and Image Acquisition

Patients undergoing surgical treatment for severe or critical aortic stenosis were selected for inclusion in this study. Patients received a TAVR (N=10) (Sapien, Edwards Lifesciences, Irvine, CA) or standard open aortic valve replacement (N=10). TAVR valve sizing was determined by the discretion of the surgeon based on 2D echocardiographic annular diameter measurements at the time of surgery. For surgical AVR, selection of the valve type was done at the discretion of the surgeon at the time of cardiac surgery. Valve sizes were determined using conventional valve sizers.

All patients underwent intraoperative imaging of the mitral valve at the time of cardiac surgery, before and after aortic valve implantation. Real-time 3D transesophageal echocardiography data sets were acquired in addition to standard 2D echocardiographic exams, including color Doppler images of the mitral valve. Pre implantation imaging data sets were carried out in the operating room after induction of general anesthesia and before sternotomy. Post implantation imaging data sets were carried out after sternal closure and prior to leaving the operating room. Images were acquired through a mid-esophageal view with a Philips ie33 (Andover, MA, USA) ultrasound system equipped with a 2 to 7 MHz X7-2t TEE matrix transducer. For the rt-3DE data sets, electrocardiographically gated full-volume images were acquired over 4 cardiac cycles at a frame rate of 17–30 frames/s. For the 2D data sets, color Doppler images were used to determine the degree of MR.

This study was approved by the University of Pennsylvania Institutional Review Board.

Image Segmentation

Each full-volume data set was then exported to an Echo-View 5.4 (Tomtec Imaging Systems, Munich, Germany) software workstation for image analysis. The highest-quality data set was selected for each subject. Analysis was performed at midsystole. The plane of the mitral valve orifice was rotated into a short-axis view. The geometric center was then translated to the intersection of the 2 corresponding long-axis planes, which then corresponded to the intercommissural and septolateral axes of the mitral valve orifice. A rotational template consisting of 18 long-axis cross-sectional planes separated by 10 degree increments was superimposed on the 3D echocardiogram. Two annular points intersecting each of the 18 long-axis rotational planes were then identified by means of orthogonal visualization of each plane; the 2 points were marked interactively (Figure 1). The anterior

and posterior commissures were defined as annular points at the junction between the anterior and posterior leaflets. Once the annular geometry was established, annular planes were marked at fixed 1-mm intervals along the entire length of the intercommissural axis. Free-hand curves for each 2D annular plane were traced along atrial surface delineating the anterior and posterior leaflets as well as the coaptation zone. 600–1200-point data sets were created for each valve (Figure 1). The Cartesian coordinates of each assigned point were then exported to MatLab (The Mathworks, Inc, Natick, MA).

Mitral Annular Analysis

Eight MV geometric indices were defined for comparison between groups. (Table 1). Using custom MatLab algorithms and orthogonal distance regression, the least squares plane of the data point cloud for the annulus was aligned to the x-y plane. Under these geometric conditions, the annular height for each point (z_n) was plotted as a function of rotational position on the annulus. A number of anatomic landmarks were identified. The septum (S) was identified as the anterior horn of the annulus at the aortic valve. The lateral annulus (L) was identified as the middle of the posterior annulus circumference. The septolateral (SL) diameter was defined as the distance between these two points. With the annular model rotated such that the commissures were aligned along the y-axis, the maximum and minimum y-values of the annulus were identified as the anterolateral (AL) and posteromedial (PM) annular points. Annular height was defined as the $z_{\max} - z_{\min}$. Commissural width (CW) was defined as the 3D distance between the two commissures. Mitral annular area (MAA) was defined as the area enclosed by the 2D projection of a given annular data set onto its least squares plane. Mitral valve transverse diameter (MTD) was defined as the 3D distance separating the anterolateral annulus and the posteromedial annulus (Figure 2).

Statistical Analysis

Continuous variables are presented as mean $\pm$ standard deviation. Categorical variables are presented as percentages and compared using Chi-square or Fisher's Exact tests where appropriate. Mixed between-within ANOVA was used to compare the eight MV annular outcome variables among patients undergoing TAVR and AVR, before and after intervention. To minimize the likelihood of inflating type I error and to account for the eight dependent variables, $P = .006$ ($\approx .05 \div 8$) was taken to be statistically significant. If indicated, *post hoc* paired T-tests were performed between pre- and post-procedure groups and unpaired T-tests performed between TAVR and AVR groups. All statistical analysis was performed using SPSS software (SPSS Inc., Chicago, IL).

Results

Patient Characteristics

Baseline patient characteristics are presented in Table 2. Four patients in the TAVR cohort underwent transapical aortic valve implantation whereas six patients underwent transfemoral aortic valve implantation. Eight patients received a 23 mm Edwards-Sapien® valve and two received a 26 mm Edwards-Sapien® valve. All patients undergoing AVR received a bioprosthetic valve (CE Magna pericardial valve, N=7, Sorin MitroFlow, N=2 and St. Jude Trifecta, N=1). Of these, four patients received a 21 mm valve, three received a 23 mm valve and three received a 25 mm valve.

Comparison of Mitral Regurgitation

In the TAVR cohort, 50% of patients had mild MR, 40% had moderate MR, and 10% had severe MR prior to valve implantation. In comparison, 20% of patients in the AVR group

had no MR, 40% had mild MR, and 40% had moderate MR. The degree of MR remained unchanged for 50% of TAVR patients and improved in 50%. In the AVR group, 60% had unchanged MR whereas 40% had an improvement in MR (Figure 3).

Annular Geometry

Prior to aortic valve implantation, there were no differences in annular geometry between patients undergoing TAVR versus patients undergoing AVR based on between groups ANOVA (all P values NS), as summarized in Table 3.

Results of the within group ANOVA showed significant differences as a result of the operative effect for a variety of parameters, also summarized in Table 3. Post hoc analysis confirmed that patients undergoing surgical AVR had significant decreases in annular height, septolateral diameter, mitral valve transverse diameter and mitral annular area ($P = .006$), as depicted in Figures 4 and 5. For patients undergoing TAVR, there was no statistically significant change in annular geometry after valve placement.

Comment

Three-dimensional modeling of the mitral valve was used to evaluate eight discrete mitral annular geometric indices. These indices were compared between groups to evaluate for differences in baseline and post-procedure MV annular geometry between the TAVR and AVR cohorts. Interestingly, patients undergoing TAVR have preserved mitral annular geometry compared to patients undergoing standard AVR.

The Edwards SAPIEN heart valve consists of a bovine pericardial valve which is mounted on a stent and deployed by balloon expansion. The expandable device flattens the native aortic valve leaflets against the aortic wall and remains anchored in a sutureless fashion by virtue of the direct outward radial forces of the stent on the aortic valve annulus and leaflets. Given the bulk of the stent and relationship to the left ventricular outflow tract, we had hypothesized that distortions of the mitral annulus might occur with the Sapien device. Despite these concerns, the 3D geometry of the annulus remained unchanged after TAVR. In comparison, the patients undergoing AVR demonstrated significant deformation of the mitral annulus. The etiology of this deformation is likely the valve-anchoring sutures in the mitral-aortic continuity. The AVR group showed a decrease in annular height, narrowing in the anterior-posterior direction, and an overall reduction in size.

There was a trend towards an attenuation of relative saddle shape in patients undergoing AVR likely as result of the tethering effect of the sutures. Previous work has shown that the natural mitral annular saddle shape aids in reducing mitral annular strain [4–5], optimizing leaflet curvature profiles, reducing leaflet stress, [6] and improving leaflet coaptation. [7] Similarly, functionally impaired valves such as those in ischemic MR, have been shown to have severe alterations in 3D annular geometry with loss of the relative annular saddle shape. [8] Optimization of annular geometry and improving coaptation is, likely, important for promoting valve competence.

Functional MR (FMR) secondary to LV remodeling and elevated LV pressures in the setting of aortic stenosis has routinely been documented and frequently improves after AVR. [9–12] Nevertheless, despite previous attempts to characterize the long term durability of standard AVR in resolving concomitant FMR, a substantial degree of uncertainty still exists as to which patients warrant mitral valve interventions at the time AVR. Over the past decade, authors have sought to understand both the degree to which FMR improves after valve replacement and the clinical significance of residual MR. For example, Ruel and colleagues [13] described the natural history of patients undergoing surgical AVR with concomitant

FMR and found that postoperative FMR 2+ was occurred in 10.7% of patients with preoperative FMR 1 and in 31.6% of patients with preoperative FMR 2+. At 18 months after surgery, FMR 2+ increased to 36.5% with 1 preoperative CHF risk factor and to 55.6% with 2 preoperative CHF risk factors. As illustrated by this study, there is a higher degree of improvement in MR when patients have less preoperative MR. As such, it could be hypothesized that TAVR might provide a more durable option for improving FMR in the setting of AS since it preserves the natural annular saddle shape and geometric dimensions to a greater degree than AVR. Further studies will be needed to fully investigate the long-term functional impact of TAVR on the degree of MR; however, early reports on transcatheter interventions are beginning to show promising data. For example, Webb and colleagues reported on patients who received the Edwards-Sapien valve for AS. [14] 53% of patients in their study had moderate to severe MR at baseline and the median grade of MR decreased from 2 to 1 at discharge. Moreover, the percentage of patients with moderate to severe MR continuously decreased at 1, 6 and 12 month follow-up. They observed that there was a trend towards ongoing improvement in MR especially in patients with moderate to severe MR. Hekimian and colleagues reported similar results for patients having TAVR. [15] In the current study, MR was improved in 50% of patients undergoing TAVR and 40% of patients undergoing surgical AVR; however, the majority of patients had only mild to moderate MR. Although this work is limited by its small sample size and is not designed to specifically answer questions about the long term durability of TAVR, it does report a novel approach to looking at the functional consequences of aortic devices and may prove to be a more physiologic approach to aortic valve replacement, with respect to MV annular geometry.

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Figure 1. Mitral Valve Segmentation

Panel A- Rotational template used for segmentation of the mitral valve annulus. Annular points are placed every 10 degrees on the two-dimensional long axis view around the circumference of the annulus. Panel B- Segmentation of the anterior and posterior leaflets and coaptation is performed at 1 mm intervals along the length of the mitral valve.

Figure 2. Illustrative Example of Geometric Parameters

Mitral Annular modeling depicting the measured parameters used for analysis. Panel A and B demonstrate calculation of the annular height (AH) and septolateral diameter (SL). Panel C depicts the calculation for commissural width (CW) and mitral transverse diameter (MTD). Mid-AA = mid anterior annulus, Mid-PA=mid posterior annulus, PC=posterior commissure, AC=anterior commissure.

Figure 3. Comparison of Mitral Regurgitation

Percentage of patients with varying degrees of mitral regurgitation before repair for each group, and the corresponding changes in severity of mitral regurgitation after valve replacement for each group. No patients in either group experienced a worsening in the degree of mitral regurgitation.

Figure 4. Measured Geometric Indices Before and After Repair

Representation of the eight mitral annular geometric indices evaluated and the corresponding difference before and after aortic valve replacement. Geometric indices were similar between the TAVR and AVR groups before valve replacement, however, after intervention, patients who received a TAVR demonstrated relative preservation of annular geometry. Patients undergoing AVR demonstrated significant geometric deformation after valve replacement for a number of indices indicated by *. Error bars = standard deviation. A) Annular Height*; B) Commissural Width; C) Annular Height to Commissural Width Ratio; D) Mitral Valve Transverse Diameter*; E) Septolateral Diameter*; F) Commissural Width to Septolateral Diameter Ratio; G) Mitral Annular Area*; H) Annular Circumference.

Figure 5. Differences in Annular Height, Septolateral Diameter and Mitral Annular Area Relative to Initial Geometry

Panel A- Comparison of select geometric indices in TAVR vs. AVR. Patients undergoing AVR had significant decreases in annular height, septolateral diameter and mitral annular area relative to their initial geometry. Panel B- Plot of annular height along the annular circumference. Annular height is preserved in TAVR after aortic valve replacement but is notably decreased after standard aortic valve replacement. *denotes significance

Table 1

Eight Mitral Annular Outcomes Variables

Geometric Index	Abbreviation
Annular Height	AH
Commissural Width	CW
Annular Height to Commissural Width Ratio	AHCWR
Mitral Transverse Diameter	MTD
Septolateral Diameter	SL
Commissural Width to Septolateral Diameter Ratio	CWSLR
Mitral Annular Area	MAA
Annular Circumference	Circ

Table 2

Baseline Patient Characteristics

Characteristic	TAVI (N=10)	AVR (N=10)
Age-yr	83.6 ± 5.3	74.3 ± 7.9
Female sex - no./total no.(%)	5/10 (50)	5/10 (50)
Aortic Valve Area (cm ²)	0.5 ± 0.1	0.7 ± 0.1
Aortic Valve Mean Gradient (mmHg)	42.2 ± 20.6	42.4 ± 13.6
Ejection Fraction (%)	54.4 ± 17.4	57.2 ± 7.9
NYHA class- (%)		
II	-	4/10 (40)
III	7/10 (70)	6/10 (60)
IV	3/10 (30)	-
Mitral regurgitation- (%)		
None	-	2/10 (20)
Mild	5/10 (50)	4/10 (40)
Moderate	4/10 (40)	4/10 (40)
Severe	1/10 (10)	-

Table 3

Comparison of Mitral Annular Parameters Before and After Repair

Group	AH	CW	AHCWR	SL	MTD	MAA	CWSLR	TotalCirc
AVR preop	7.6 ± 1.6	31.4 ± 4.3	24.5 ± 5.5	32.3 ± 5.0	37.3 ± 5.0	962 ± 258	0.98 ± 0.12	115 ± 15
AVR postop	5.3 ± 1.2[†]	27.3 ± 6.3	20.8 ± 7.7	29.0 ± 4.7[†]	34.3 ± 5.7[†]	819 ± 267[†]	0.96 ± 0.22	106 ± 19[*]
Sapien preop	7.1 ± 1.4	30.3 ± 2.8	23.4 ± 3.7	31.0 ± 4.2	36.2 ± 3.7	892 ± 201	0.99 ± 0.14	111 ± 12
Sapien postop	6.9 ± 1.2[†]	29.9 ± 3.6	23.1 ± 3.0	30.5 ± 4.5	36.0 ± 3.8	869 ± 220	0.99 ± 0.14	109 ± 13
P Interaction	.001	NS	NS	NS	.006	.005	NS	NS
P within	<.0005	NS	NS	.001	.002	<.0005	NS	.009
P between	NS	NS	NS	NS	NS	NS	NS	NS

[†] Post hoc P .006 comparing within group (effect of operative status).

^{*} Post hoc P=.022 comparing within group (effect of operative status).

[‡] Post hoc (not sanctioned) P=.007 comparing post-operative Sapien patients to post-operative AVR patients.

(No P .006 comparing between groups; which operation undergone.)