Dynamic Indices of Mitral Valve Function Using Perioperative Three-Dimensional Transesophageal Echocardiography

Karsten Bartels, MD,* Robert H. Thiele, MD,*† Barbara Phillips-Bute, PhD,* Donald D. Glower, MD,‡ Madhav Swaminathan, MD, FASE,* Joseph Kisslo, MD, FASE,§ and G. Burkhard Mackensen, MD, FASE‖

Objective: **Perioperative transesophageal echocardiography is essential for decision-making for mitral valve surgery. While two-dimensional transesophageal echocardiography represents the standard of care, tracking of dynamic changes using three-dimensional imaging permits assessment of morphologic and functional characteristics of the mitral valve. The authors hypothesized that quantitative three-dimensional analysis would reveal distinct differences among diseased, repaired, and normal mitral valves.**

Design: **Case-control observational clinical study.**

Setting: **Tertiary care hospital.**

Participants: **Using novel mitral valve quantification software, the authors retrospectively analyzed 80 datasets of cardiac surgery patients who underwent intraoperative transesophageal echocardiographic imaging. Twenty patients with degenerative mitral regurgitation were evaluated before and after mitral valve repair. Twenty patients had functional mitral regurgitation, and 20 patients had no mitral valve disease.**

Measurements and Main Results: **Primary outcome measures of dynamic mitral valve function were: 1) three-dimensional annulus area, 2) annular displacement distance, 3) annular displacement velocity, and 4) annular area fraction. Other mitral annular tracking indices, in addition to intraobserver reliability and interobserver agreement, also were reported. Annulus area was enlarged in degenerative and functional mitral regurgitation. Annular displacement distance was decreased in functional mitral regurgitation and repaired valves. Annular displacement velocity was decreased in functional mitral regurgitation. Annular area fraction was decreased in functional mitral regurgitation and repaired valves. Intraobserver reliability and interobserver agreement were high for all 4 analyzed indices.**

Conclusions: **Normal, functional regurgitant, degenerative, and repaired mitral valves have distinctly different dynamic signatures of anatomy and function as reliably determined by perioperative echocardiographic tracking.**

KEY WORDS: echocardiography, ultrasound, mitral valve, perioperative, computer applications, 2D TEE, 3D TEE, dynamic indices

MORE THAN 2 MILLION people in the United States alone suffer from moderate-to-severe mitral regurgitation (MR).[1] Non-functional, organic (usually degenerative) MR is the most common reason for mitral valve (MV) surgery. In cases of functional (usually ischemic) MR, the decision on when and how to intervene remains controversial.[2] However, complex repairs, including surgical ventricular restoration, have proven to be promising for select patients.[3] MV repair is most often preferred over MV replacement; yet, 7% to 10% of all patients who undergo repair will require reoperation within 10 years.[4]

Two-dimensional transesophageal echocardiography (2D-TEE) is the standard modality for evaluating the MV during repair surgery.[5,6] Three-dimensional (3D) TEE has improved the description of complex MV anatomy, but quantitative analysis mostly has been limited to static, single-frame approaches.[7–12] Tracking of dynamic movement using 3D imaging permits novel assessment of morphologic and functional characteristics of the MV over time[13–16] that may prove useful in surgical decision-making in the future.

As a precursor to such study, this investigation was performed to test the feasibility for quantitatively comparing the dynamic MV characteristics obtained from intraoperative 3D-TEE examinations in 4 different groups. It was hypothesized that such quantitative descriptors of MV apparatus movement would be reflected in different dynamic profiles for each of the groups. The authors chose four primary outcome variables based on the following rationale: 3D annular area was chosen as an indicator of annular dilatation, a hallmark of MV disease. Annular area fraction, annular velocity, and annular displacement distance were chosen to allow a description of dynamic MV behavior. Ventricular dysfunction and altered annular motility were thought to likely impact these indices and thereby permit characterization of different dynamic profiles in the separate MV groups.

METHODS

A comprehensive intraoperative TEE examination is a routine component of care for every cardiac surgery patient at Duke University Medical Center.[17] This exam is performed after induction of general anesthesia and institution of mechanical ventilation and consists of a standard echocardiographic assessment with a real-time, 3D-capable TEE matrix transducer (X7-2t TEE, iE33 system; Philips Medical Systems, Andover, MA).

Ethical approval for this study and waiver of the need for informed consent were obtained from the Duke University Institutional Review Board. Digitally stored images of TEE examinations of patients who previously had undergone cardiac surgery were reviewed. Only studies

*From the *Department of Anesthesiology, Division of Cardiothoracic Anesthesiology and Critical Care Medicine, Duke University Medical Center, Durham, NC; †Department of Anesthesiology, University of Virginia School of Medicine, Charlottesville, VA; ‡Department of Surgery, Division of Cardiovascular and Thoracic Surgery; §Medicine, Division of Cardiology, Duke University Medical Center, Durham, NC; and ‖Department of Anesthesiology and Pain Medicine, Division of Cardiothoracic Anesthesiology, University of Washington, Seattle, WA.*

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Address reprint requests to G. Burkhard Mackensen, University of Washington, Department of Anesthesiology and Pain Medicine, Box 356540, Health Sciences Building BB1461, 1959 NE Pacific Street, Seattle, WA 98195. E-mail: gbmac@uw.edu

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with existing 3D images of the MV were evaluated. Twenty patients with degenerative mitral regurgitation were evaluated before and after MV repair. Twenty patients had functional mitral regurgitation (FMR), and 20 patients had no MV disease.

Procedures in the normal MV group included coronary artery bypass grafting (n = 18), aortic valve replacement (n = 2), and repair of anomalous pulmonary venous drainage (n = 1). The FMR group underwent coronary artery bypass grafting (n = 11), MVR (n = 9), tricuspid valve replacement (n = 2), aortic valve replacement (n = 1), ventricular assist device implantation (n = 5), and removal of an infected AICD (n = 1). Multiple procedures were possible.

For the repair of the degenerative MVs, rigid or semirigid annuloplasty rings were used: St. Jude Medical Séguin (n = 3), Carpentier-Edwards Classic 4400 (n = 12), Medtronic Future 638R (n = 5). Average ring size was 35.3 mm +/− 3.4mm. In addition to surgical ring annuloplasty, MV repair included the following techniques: GORE-TEX® repair of chordae tendineae (n = 11), edge-to-edge A1 to P1 stitch (n = 1), edge-to-edge A2 to P2 stitch (n = 13), edge-to-edge A3 to P3 stitch (n = 4), cleft closure (n = 4), and resection (n = 1).

The degree of MR was based on conventional TEE examination and graded according to American Society of Echocardiography guidelines.[18] MV pathology was classified by consensus of 2 independent board-certified echocardiographers. Inclusion criteria were: 1) a 3D data set of the MV obtained in the mid-esophageal 4-chamber view, 2) at least moderate MR for the unrepaired degenerative MR group, 3) at least moderate MR in the functional MR group, and 4) no more than trace MR in the normal MV group. Exclusion criteria were: 1) significant stitch artifact in full volume images obtained via gated acquisition that precluded proper identification of mitral annular landmarks and 2) fewer than 5 volumes (3D frames) between end-diastole and end-systole in order to ensure adequate temporal resolution.

Following induction of general anesthesia, endotracheal intubation, and commencement of mechanical ventilation, a real-time 3D-TEE matrix probe (iE33 system; Phillips Medical Systems, Andover, MA) was placed. Gated full-volume images for patients with regular rhythm, as well as real-time 3D-TEE acquisitions for patients with irregular heart rhythm, were obtained during apnea. Scan depth and sector density were adjusted to allow optimal visualization of the mitral annulus throughout the cardiac cycle. Commercially available 3D MV quantification software (4D MV assessment™ 2.0, Tomtec Imaging Systems, Unterschleissheim, Germany) was used to perform off-line analysis of the MV as previously described by Warraich et al.[19] Since the electrocardiographic data were lost upon export to the tracking software station, identification of end-diastole was based on MV closure, and end-systole was defined as the frame prior to aortic valve closure just preceding the opening of the MV. The mitral annulus was marked in the 2D mid-esophageal, 4-chamber view and the 2-chamber view in mid-systole. Furthermore, the aortic annulus, the commissural points, and the MV coaptation point were marked. In the case of MR, the coaptation line was adjusted as necessary. The software then automatically tracked the MV landmarks and areas during systole. The 3D annulus area was measured at mid-systole. Annular displacement distance, annular displacement velocity, and the annular area (A) fraction ($[A_{max} - A_{min}]/A_{max}$) were calculated throughout systole and reported as the maximum value measured. Distance and velocity were measured at the centroid of the MV annulus. To better illustrate measurements taken, Figure 1 depicts an MV at two different time points during systole. Measurements of 10 MV datasets were performed in triplicate by 2 independent echocardiographers in a blinded fashion. Interobserver variability was determined by comparing the results between both, while intraobserver variability was evaluated by measuring in triplicate.

Histograms were generated from the 3D and dynamic outcome variables, and the distribution of the data was assessed visually. For nonnormally distributed data, 95% confidence intervals were not reported. Global comparisons among the four groups then were made using the Kruskal-Wallis test followed by Dunn's test to correct for multiple comparisons. A chi-square test was used for binary variables (Graph Pad Prism, Version 6.01, GraphPad Software, Inc., La Jolla, CA).

Intraobserver reliability was assessed for each of the 2 observers on each of 4 primary measures (3D annulus area, annular displacement distance, annular displacement velocity, and annular area fraction). Agreement among the 3 observations was assessed with Kendall's coefficient of concordance. Next, a mean was calculated for the 3 individual values for each measure on each valve. Interobserver agreement was assessed with correlations and Bland-Altman plots (SAS statistical software, version 9.2, SAS Inc, Cary, NC). Significance for all statistical analyses was defined as $p < 0.05$.

RESULTS

Baseline preoperative characteristics of the studied patients are outlined in Table 1. Statistical significance is indicated for global comparisons. Patients with FMR had lower left ventricular (LV) ejection fraction and a lower degree of functional status. Analysis required approximately 1 minute for normal and FMR valves and up to 4 minutes for regurgitant valves

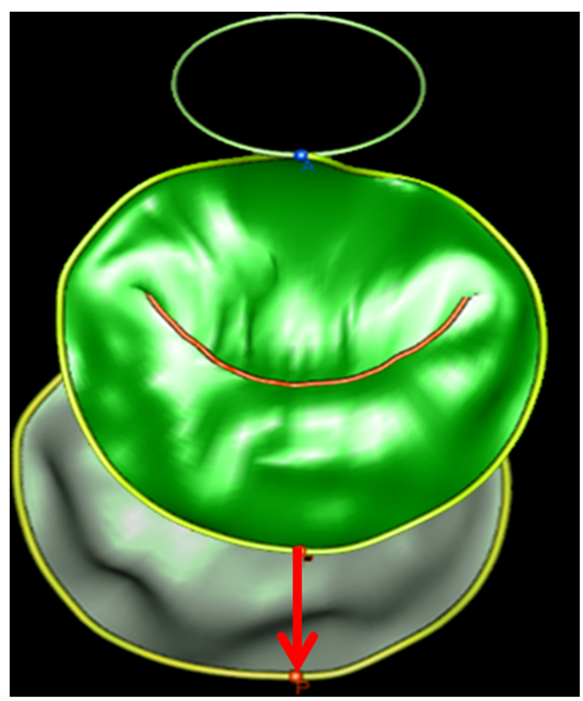

Fig 1. The schematic images depict a mitral valve at two different time points during systole. The 3D reconstructed annulus is tracked throughout its systolic motion, and the maximum annular displacement velocity and distance are recorded. Both distance and velocity are measured at the centroid of the MV annulus. The 3D annulus area was reported at mid-systole. To reflect that annular area changes in size throughout systole, annular area (A) fraction was calculated as follows: Subtraction of the minimum systolic area from the maximum systolic area followed by division by the maximum area: [Amax−Amin]/Amax.