Annular Height-to-Commissural Width Ratio of Annuloplasty Rings In Vivo

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Background—A “saddle-shaped” mitral annulus with an optimal ratio between annular height and commissural diameter may reduce leaflet and chordal stress and is purported to be conserved across mammalian species. Whether annuloplasty rings maintain this relationship is unknown.

Methods and Results—Twenty-three adult sheep underwent implantation of radiopaque markers on the left ventricle and mitral annulus. Eight animals underwent implantation of a Carpentier-Edwards Physio ring, 7 underwent a Medtronic Duran flexible ring, and 8 served as controls. Animals were studied with biplane videofluoroscopy 7 to 10 days postoperatively. Annular height and commissural width (CW) were determined from 3D marker coordinates, and annular height:CW ratio (AHCWR) was calculated. Annular height was similar in Control and Duran animals but significantly lower in the Physio group at end diastole (8.4±3.8, 6.7±2.3, and 3.4±0.6 mm, respectively, for Control, Duran, and Physio; ANOVA=0.005) and at end systole (14.5±6.2, 10.5±5.5, and 5.8±2.5 mm, respectively, for Control, Duran, and Physio; ANOVA=0.004). Both ring groups reduced CW significantly relative to Control. AHCWR did not differ between Control and Duran but was lower in Physio (23±11%, 24±7%, and 12±2% at end diastole and 42±17%, 37±17%, and 21±10% at end systole, respectively, for Control, Duran, and Physio, respectively; ANOVA <0.05 for both).

Conclusions—Mitrail annular height and AHCWR of the native valve were unchanged by a Duran ring, whereas the Physio ring led to a lower AHCWR. Theoretically, such a flexible annuloplasty ring may provide better leaflet stress distribution by maintaining normal AHCWR. (Circulation. 2005;112[suppl I]:I-423–I-428.)

Key Words: mitral valve • mitral valve repair • mitral regurgitation • cardiac surgery

The mitral annulus is a discontinuous fibromuscular ring1,2 with ill-defined anatomical structure and poorly understood physiology. Dynamic motion of the mitral annulus and its “sphincteric” facilitation of mitral valve closure have been described in detail by Tsakiris et al3 more than 3 decades ago but only recently has attention been focused on the 3D geometry of this complex structure. Early echocardiographic studies revealed the mitral annulus to be “saddle-shaped”4 with subsequent investigations confirming these findings.5–8 Computational analysis has shown that the 3D shape of the annulus may be important for proper stress distribution on the mitral leaflets,9 and the annular height:comissural width (CW) ratio (AHCWR), a surrogate for the saddle shape of the annulus, has been found to be conserved across species. This relationship is markedly altered by mitral insufficiency because of acute ischemia or cardiomyopathy.7,10 In vitro, a saddle-shaped annulus is associated with more balanced chordal stress distribution.11 Thus, the 3D geometry of the mitral annulus may play an important role in the proper function of the valve.

Ring annuloplasty is currently a standard component of most mitral valve reparative techniques,12 yet whether annuloplasty rings truly remodel the 3D shape of the annulus and optimize leaflet stress is unknown. Rigid planar prostheses would not be expected to do so, but flexible annular bands and rings designed specifically to reflect natural annular geometry, such as the Cosgrove band system and Carpentier-Edwards Physio ring (Edwards Lifesciences),13 may maintain normal annular shape. In this study, we investigated the in vivo AHCWR and 3D geometry of the ovine mitral annulus after implantation of the Duran flexible (Medtronic) or the Physio semirigid annuloplasty ring.

Methods

Surgical Preparation

This work is a new analysis of data derived from a previously reported experiment.14 Twenty-three adult sheep underwent minia-
Mitrail annular geometry was calculated as the distance in 3D space between the 2 commissural markers (#1 and #5), whereas the mitral annular plane was defined as the least-squares plane fitted to all 8 of the annular markers. To compute annular height, the orthogonal displacement of each annular marker from the annular plane was first obtained, and the distance between the 2 maximally displaced markers above and below this plane was used as the mitral annular height (Figure 2).

Statistical Analysis
All of the data are reported as mean ± 1 SD unless otherwise stated. Hemodynamic and marker-derived data from consecutive steady-state beats from each heart were time aligned at ED. Marker data were calculated over 20 frames before and after ED, thus allowing evaluation over a time period of 650 ms. Intergroup comparisons were made using 1-way ANOVA with post hoc Bonferroni’s correction where appropriate. Because of technical problems, end-systolic data from 1 Duran group animal was not suitable for analysis, because annular marker distance to the least-square annular plane showed erratic behavior near ES with large changes from below to above the annular plane within a few frames for all of the annular markers. We postulate that these unreliable measurements were possibly attributable to misidentification of annular markers or some other error in our automated marker tracking program, which we could not identify.

Results
Hemodynamics
Average sheep weight did not differ significantly between groups (65 ± 6, 68 ± 9, and 72 kg, respectively, for Control, Duran, and Physio; ANOVA = 0.07), cardiopulmonary bypass time (101 ± 10, 136 ± 15, and 133 ± 15 minutes, respectively, for Control, Duran, and Physio; ANOVA = 0.001), and aortic cross-clamp time (54 ± 5, 92 ± 9, and 93 ± 10 minutes, respectively, for Control, Duran, and Physio; ANOVA = 0.001) were longer in the ring groups. Table 1 summarizes mean steady-state hemodynamic variables of the 3 study groups. Hemodynamic parameters were very similar across the groups, but peak LV pressure was significantly higher in

Figure 1. Diagram of the mitral and aortic valves illustrating the 8 annular markers. ACOM indicates anterior commissure; PCOM, posterior commissure; AML, anterior mitral leaflet; PML, posterior mitral leaflet; AV, aortic valve.

Figure 2. Schematic representation of mitral annular height as calculated in the study. A least-squares plane was fitted to all 8 annular markers, thus defining the mitral annular (MA) plane, and annular height was determined at the distance between the 2 markers maximally displaced above and below this plane.
Control animals, and end-diastolic pressure was elevated in the Duran animals relative to the remaining 2 groups. More than 1/1000 mitral regurgitation was not observed in any animal.

Annular Geometry

Group mean data for CW, annular height, and AHCWR throughout the cardiac cycle for the 3 study groups is shown in Figure 3 with end-diastolic and end-systolic values summarized in Table 2. Annular height was significantly greater in the Control and Duran groups, but both ring annuloplasty rings substantially reduced CW. Consequently, AHCWR of the Duran group closely reflected that seen in Control, although annular height was somewhat lower. On the other hand, the reduced annular height in the Physio group led to a relatively low AHCWR, even with significant reduction of CW. These ring effects on AHCWR were consistent throughout the cardiac cycle. Of note, both annular height and AHCWR tended to increase from ED to ES in all of the groups reflecting the conformation change of annular geometry during ventricular systole.

As annular height in our study was by definition a surrogate for annular “planarity” or saddle shape, we next calculated the displacement of each annular marker from the least-squares annular plane throughout the cardiac cycle to obtain a more complete picture of annular geometry. Group mean data for each annular marker displacement from this plane throughout the cardiac cycle for each group are shown in Figure 4, with end-diastolic and end-systolic values summarized in Figure 5. Displacement of each annular marker

![Figure 3](image-url)  
Figure 3. Annular height (top), CW (middle), and AHCWR (bottom) for Control ■, Duran ●, and Physio ▲ animals throughout the cardiac cycle. A 650-ms time window centered at ED (t=0) is illustrated for all variables.

![Figure 4](image-url)  
Figure 4. Displacement of each annular marker from the least-squares annular plane throughout the cardiac cycle for Control (top), Duran (middle), and Physio (bottom) animals. A 650-ms time window centered at ED (t=0) is illustrated for all variables.
from the annular plane across the 3 groups followed a similar trend throughout the cardiac cycle, yet the absolute values were greater in the Duran and Control animals, reflecting a less-planar annulus. The increased saddle-shape of Control and Duran annuli is more clearly shown in Figure 5. At ED, the Physio ring reduced maximal marker displacement above the annular plane (marker #3, ie, annular “saddlehorn”), whereas the Duran ring maintained the native position of the annular saddlehorn. Furthermore, the Duran flexible ring imitated the native annular depression in the region of the posterior commissure (marker #5), which was not observed in the Physio group, both at ED and ES. Thus, in general, the Duran ring maintained the 3D shape of the native annulus more so than the Physio ring did.

**Discussion**

The complex 3D geometry of the mitral annulus may play an important physiological role in the proper and durable function of the valvular complex, as optimal annular shape possibly confers better valvular stress distribution. Although annuloplasty rings are widely used in clinical practice as a central component of mitral valve repair, their precise effects on normal annular shape have not been described. The current study revealed that the Duran flexible annuloplasty ring maintained the native valve annular height and AHCWR better than did a Physio semirigid ring, a semirigid prosthesis specifically designed to reflect the “saddle” configuration of the native annulus.

A detailed description of annular geometry was first provided by Levine et al, who reported the annulus to be saddle-shaped with elevation of septal and lateral annular segments and nadirs of the saddle near the commissures. These investigators found annular height to be $1.4 \pm 0.3$ cm in 15 healthy human volunteers, and this value closely reflects the $1.2 \pm 0.1$ cm annular height of normal subjects reported recently using 3D echocardiography, but it is somewhat greater than that described by Kaplan et al using similar methodology. Our values of annular height at ES and ED fall in the above range and corroborate a recent myocardial marker-based estimation of annular height as a deviation of midseptal annulus (annular saddlehorn) from the posterior annular plane. Analysis of the current data using such a definition of annular height (results not shown) revealed consistent results across the groups, although absolute values were smaller than those calculated based on the current definition of annular height. However, using sonomicrometry-based measurements in adults sheep, Gorman et al reported an annular height of $4.1 \pm 0.9$ mm at ED and $5.3 \pm 0.9$ mm at ES. This discrepancy may stem from the number of annular reference points used to define the annular least-squares plane (6 for sonomicrometry and 8 for myocardial markers) and positioning of only 1 reference point on the septal annulus in the Gorman et al study. In the current experiment, flexible ring annuloplasty better maintained the native annular height than the Physio ring, and, through its reduction of CW, permitted normalization of AHCWR throughout the cardiac cycle. The Physio annuloplasty ring reduced CW to a similar degree, but its low annular height significantly reduced AHCWR. Although the Control AHCWR observed in this study was higher than that reported by Salgo et al, it approached the 22% to 23% value calculated by Gorman et al in the normal human subjects studied by Kaplan et al. Preservation of normal AHCWR is thought to optimize leaflet stress, which may, in turn, lead to a more physiological and durable repair. In this regard, use of the Duran ring would be favored over the semirigid Physio ring. At this time, however, such extrapolation of these data is speculative as LV function, and energetics do not differ with either rigid or flexible rings, and no clear advantage to either ring type has been demonstrated in the clinical literature. Furthermore, both Duran and Physio rings have been found to restrict the motion of the posterior mitral leaflet and may, thus, alter anterior leaflet stress irrespective of their effect on annular geometry. It is noteworthy that annular height and AHCWR increased during systole in all 3 of the groups, thereby assuming a more favorable geometry during the time of maximum force application on the mitral leaflets by rising LV pressure. This pattern of systolic increase in annular height has been reported consistently. Thus, the 3D geometric changes of the mitral annulus during the cardiac cycle may serve to optimize leaflet stress during varying hemodynamic conditions.
Analysis of displacement of each annular marker from the least-squares plane permitted reconstruction of the 3D shape of the entire annulus, and, as others, we found it to approximate the shape of a saddle. The midseptal annular marker (annular saddlehorn) was uniformly found to be the highest point above the annular plane in all 3 of the groups, whereas the posterior commissure marker represented the nadir. The 3D geometry of the annulus in the current study, however, represented a more tilted saddle. A tilt toward the posterior commissure was observed resulting in a significant “dip” in this area of the annulus while the anterior commissure was simultaneously brought up to the level of the annular plane, as reported previously from our laboratory. It is unclear what structural or functional advantage this configuration may confer, if any, but prior studies have shown that annular segments near the posterior commissure represent the most dynamic portion of the annulus. It is, therefore, not surprising that the posterior commissure dip was greatly accentuated in Control animals during ventricular systole and substantially contributed to annular height increase during this portion of the cardiac cycle. This dynamic response was imitated by the Duran flexible ring but was blunted in the Physio group. It appears that the flexible ring not only conformed better to the native annular shape at ED but also permitted substantial systolic increase in annular height, although it has been shown previously to abolish normal annular perimeter and area change in sheep. Conversely, the Physio ring is too planar in its design, yet did allow some degree of annular height change during systole, most likely through its semirigid structure.

It is tempting to propose that annuloplasty ring design should follow native function, and, therefore, a more saddle-shaped prosthesis should be sought to better imitate nature. Such an annuloplasty ring may result in a more physiological repair conferring more normal stress distribution on the leaflets, which might translate into enhanced repair durability. The native mitral annulus, however, is not a homogenous structure, and its dynamic change in area, perimeter, 3D geometry, and translational movement during the cardiac cycle must all be considered in a more rational approach to ring design. Such a disease-guided approach has produced the Edwards IMR ETLogix annuloplasty ring, which addresses specific changes seen in the annulus subtending the postero-medial scallop of the posterior mitral valve leaflet. Better elucidation of mitral annular form and function will permit more “custom” annuloplasty ring development in the future.

Study Limitations
Several limitations of this study must be emphasized before extrapolating these observations to the clinical context. Myocardial marker studies require suturing miniature tantalum markers to the cardiac structures of interest, and the presence and collective mass of the markers may alter normal annular motion. The markers used in this study, however, were very light (4 to 8 mg) and would not be expected to affect the normal dynamics of the mitral annulus. Interspecies differences in annular anatomy may limit the clinical relevance of these data, but human and ovine annular dynamics are similar during the cardiac cycle. and measurements of annular height obtained in this study are consistent with clinical literature.

Acknowledgments
Supported by grants HL-29589 and HL-67025 from the National Heart, Lung and Blood Institute. Drs Timek and Lai are Carol and Leah McConnell Cardiovascular Surgical Research Fellows. Dr Timek is a recipient of the Thoracic Surgery Foundation Research Fellowship Award. Dr Timek was also supported by National Heart, Lung and Blood Institute Individual National Research Service Award grant IRNH-10452. Dr Lai was supported by a fellowship from the American Heart Association, Western States Affiliate. We appreciate the superb technical assistance provided by Mary K. Zasio, Carol W. Mead, and Maggie Brophy.

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Circulation. 2005;112:I-423-I-428
doi: 10.1161/CIRCULATIONAHA.104.525485
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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