Geometric Determinants of Functional Tricuspid Regurgitation
Insights From 3-Dimensional Echocardiography

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Background — Tricuspid regurgitation (TR) is an important predictor of morbidity and mortality in heart failure. We aimed to examine the 3D geometry of the tricuspid valve annulus (TVA) in patients with functional TR, comparing them with patients with normal tricuspid valve function and relating annular geometric changes to functional TR.

Methods and Results — TVA shape was examined by real-time 3D echocardiography in 75 patients: 35 with functional TR and 40 with normal tricuspid valve function (referent group). The 3D shape of the TVA was reconstructed from rotated 2D planes, and the annular plane was computed by least-squares fitting. Annular area and mediolateral, anteroposterior, and high (superior)-low (inferior) distances were calculated. TR was assessed by vena contracta width. The normal TVA has a bimodal pattern (high-low distance = 7.23 ± 1.05 mm). High points were located anteroposteriorly, and low points were located mediolaterally. With moderate or greater TR (vena contracta width = 5.80 ± 2.62 mm), the TVA became dilated (17.24 ± 4.75 versus 9.83 ± 2.18 cm², P < 0.0001, TR versus referent), more planar with decreased high-low distance (4.14 ± 1.05 mm), and more circular with decreased ratio of mediolateral/anteroposterior (1.11 ± 0.09 versus 1.32 ± 0.09, P < 0.0001, TR versus referent).

Conclusions — The normal TVA has a bimodal shape with distinct high points located anteroposteriorly and low points located mediolaterally. With functional TR, the annulus becomes larger, more planar, and circular. These changes in annular shape with TR have potentially important mechanistic and therapeutic implications for tricuspid valve repair.

Key Words: tricuspid annulus • echocardiography • regurgitation

Understanding the 3D shape of the mitral valve and annulus has been important in elucidating the pathophysiological mechanisms of functional mitral regurgitation, in designing physiologically suitable annular rings for mitral valve repair, and in understanding the spatial relationships of the mitral valve and annulus to properly diagnose mitral valve diseases such as mitral valve prolapse.1–4

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Tricuspid valve (TV) function plays an important role in a number of clinical disease states, including left-sided valve disease and heart failure, and the development of functional tricuspid regurgitation (TR) is directly associated with increased morbidity and mortality.5–10 This recognition has increased motivation to repair functional TR, especially at the time of concomitant surgery for left-sided disease. However, the incomplete efficacy of current approaches remains frustrating5,11,12 and suggests an incomplete understanding of the underlying mechanisms. Little is known about the normal 3D shape of the TV and annulus and changes that occur with functional TR. As in the case of mitral regurgitation, a better understanding of the pathophysiological mechanisms underlying functional TR could potentially suggest ways to improve therapy. The purpose of the present study was to examine the 3D geometry of the TV annulus (TVA) under normal circumstances and in patients with functional TR, relating the geometric changes in the tricuspid annulus between these 2 groups.

Methods

Patient Population

The study group consisted of consecutive patients referred for echocardiography with a diagnosis of clinical heart failure (right or left) by the referring physician and found to have at least moderate functional TR (normal tricuspid leaflet morphology). There were 2 control or referent subject groups in the present study. The first (referent 1) consisted of patients with normal TV function (morphologically normal tricuspid leaflets with no or trace tricuspid regurgitation) and without structural heart disease; the second referent...
group consisted of patients with normal TV function but who had either left ventricular (LV) dysfunction, mitral valve disease, or pulmonary hypertension. This second referent group (referent II) was included to provide an appropriate comparison to the study population, patients with functional TR, in whom coexistent LV dysfunction, mitral valve disease, or pulmonary hypertension is often present. Patients with an irregular rhythm such as atrial fibrillation, which can hinder accurate 3D reconstruction, or with inadequate echocardiographic images suitable for quantitative analysis were excluded.

2D Echocardiography

Two-dimensional echocardiograms were obtained with a Sonos 7500 machine with an S3 transducer (Philips Medical Systems, Bothell, Wash). LV end-diastolic dimension was obtained in the parasternal view at the base per American Society of Echocardiography guidelines.13 TR degree was assessed by vena contracta (VC) width and ratio of maximal TR jet area to the corresponding right atrial area averaged from parasternal and apical views.14–17 Right ventricular systolic pressure (RVSP) was estimated from the tricuspid regurgitant velocity with the modified Bernoulli equation: 4 \( \times (\text{velocity})^2 \) + 10 mm Hg for right atrial pressure.18,19 The use of 10 mm Hg for estimation of right atrial pressure provides a consistent estimation of RVSP across a broad spectrum of patients referred for echocardiography and compares favorably with hemodynamic measurements.18–20 Right ventricular (RV) function was assessed by fractional area change of RV area in the apical 4-chamber view.21–22 LV ejection fraction (LVEF) was calculated by biplane Simpson’s method. RV dysfunction was defined as fractional area change of RV area <45%.9 RV dilation was defined by a RV minor-axis diameter >43 mm at the base in the apical 4-chamber view.23 LV dysfunction was defined as LVEF <50%, and pulmonary hypertension was defined as an RVSP >50 mm Hg.20,24

3D Echocardiography

Full-volume real-time 3D datasets were obtained in the RV inflow, short-axis, and apical 4-chamber (focused on RV) views with a Sonos 7500 and x4 probe (Philips Medical Systems). Acquisition was performed with ECG gating and suspended respiration, typically over 6 to 7 cardiac cycles. Real-time 3D datasets were then transferred to a computer for offline analysis with customized software.1,3 The real-time 3D datasets contained primarily images of the TVA and accompanying portions of the RV and did not include Doppler assessment or images of other cardiac structures. This allowed for analysis of the 3D data blinded to the 2D echocardiogram and color Doppler data.

3D Tracing of the TV

Three-dimensional tricuspid annular geometry was defined in mid-systole by manual tracing. Midsystole was chosen as a consistent time point in the cardiac cycle at which TR is present. Midsystole was determined by counting the total systolic frames and choosing the midpoint systolic frame. Simultaneous visualization of 1 or more 2D planes from the 3D dataset was performed to facilitate tracing of the TVA (Figure 1A). The images were animated and oriented to optimize identification of the annular hinge points, which were then traced directly on the 3D display. The annulus was traced in rotated intersecting 2D planes of the annulus with roughly 2 to 3 mm between points (Figure 1B). A single point identifying the center of the aortic valve was also placed to define a consistent anatomic orientation for rotational alignment of the annulus. The position of the RV papillary muscles (when present) was also identified to define the vertical orientation reference for the annulus.

Analysis of Annular Geometry

The TVA was analyzed by first establishing a reference x-y plane as the least-squares plane fitted to the annular points (the point about which the square of their vertical deviations perpendicular to the plane is minimized).3 All traced points were represented by \( x, y, \) and \( z \) coordinates in a 3D Cartesian coordinate system, in which the \( x \) and \( y \) plane represents the transverse plane of the tricuspid annulus, and the \( z \) axis is the vertical dimension parallel to the ventricular apex-to-atrium axis. A continuous closed annular loop of connected line segments was defined and used to compute the geometric centroid of the annulus. The traced coordinates were subsequently translated to position this centroid at the origin of the coordinate system.

To quantify the 3D position of the annular points around the annular circumference, the \( x \) and \( y \) coordinates were converted into a rotational coordinate system.1 The height of the annulus above or below the plane of least-squares fit was then plotted as a function of angular position (Figure 2, bottom panels). TV annular area, the anatomic location of high (toward the right atrium) and low (toward the RV) points, and the medial-lateral (M-L) and anterior-to-posterior (A-P) distances (Figure 3) were measured from the 3D reconstructions of the annulus. The degree of nonplanarity was measured by the distance between high and low points (H-L). An elliptical saddle shape becomes stretched into a circle along the A-P distance, the height of the saddle (H-L distance) gets smaller (flattens). Thus, to assess degree of stretch or flattening of the tricuspid annulus, an annular stretch ratio was examined in which as the annulus “stretches” out, the A-P distance increases and the H-L distance decreases: A-P/H-L. The degree of circularity was computed as the ratio of M-L diameter to A-P diameter (M-L/A-P), with increased circularity as this ratio approaches 1.

Statistical Analysis

Data are presented as mean±SD. Means between 2 groups were compared by the Student \( t \) test. To assess differences among means of 2 or more groups (referent group I, referent group II, and functional TR group), a 1-way ANOVA was performed. Fisher exact test was used to compare categorical variables. Age, gender, TR, RVSP, RV diastolic area, RV systolic area, RV area change, LV dimension, and LVEF were entered into a stepwise multivariable analysis with Akaike’s information criteria to evaluate predictors of tricuspid annulus geometry (TV annular area, H-L distances, ratios of M-L/A-P and A-P/H-L, and study groups). Similarly, age, gender, TR, RVSP, RV diastolic area, RV systolic area, RV area change, LV dimension, LVEF, study groups, variable, annular area, A-P, M-L, and H-L distances, and ratios of M-L/A-P and A-P/H-L were entered in a stepwise multivariable analysis to determine predictors of TR (VC). One patient was excluded from multivariable analysis because of a missing data point. The curve in Figure 4 is based on a log

Figure 1. A, Five planar images from the 3D data-set are simultaneously displayed with angle orientation and translation of planes optimized for visualization of the annulus. RA indicates right atrium. B, Point-by-point tracing of the tricuspid annulus (yellow dots) with aortic valve (Ao; purple dot) for reference.
transformation of H-L distance. A regression line was fit to the data, and then the intercept was exponentiated and the regression coefficient placed in the exponent. Two observers traced the tricuspid annulus in a subset of patients (n = 11005; 6 from referent group I, and 6 from the study group). Intraclass correlation coefficients were calculated to assess interobserver agreement. Statistical analysis was performed with SPSS 13.0 (SPSS Inc, Chicago, Ill) and R (http://cran.r-project.org).25 A probability value <0.05 was considered statistically significant.

The authors had full access to the data and take full responsibility for its integrity. All authors have read and agree to the manuscript as written.

Results
An annular geometry in patients with normal TV function
Demographic and 2D echocardiographic features are shown in Table 1. Each referent group had 20 patients. There was no difference in age or gender between the 2 referent groups, nor was there any significant difference in degree of TR, RV dimension, or fractional RV area change between the 2 referent groups. As expected, referent group II had a significantly lower LVEF and higher RVSP than referent group I. Referent II patients included 13 patients (65%) with LV dysfunction and 14 (70%) with pulmonary hypertension.

In both referent groups, the tricuspid annulus was a nonplanar structure with a distinct bimodal or saddle-shaped pattern having 2 high points (oriented superiorly toward the right atrium) and 2 low points (oriented inferiorly toward the RV; Figure 2A). This bimodal pattern was consistently observed in all referent subjects. The high points were located at 0° (anterior orientation adjacent to aortic valve) and 180° (posterior orientation), with an average radial angle of 3° ± 13°.
and 175±12° from the aortic valve (Figure 2D). The 2 low points were observed at 92±15° and 279±14° (M-L orientation). The average distances between high and low points were 7.21±1.09 and 7.26±1.05 mm for referent groups I and II, respectively (P=NS; Table 2). Figure 3A demonstrates the anatomic location of the high and low points relative to the aorta. The average tricuspid annular area was 9.72±2.08 and 9.94±2.33 cm² for referent groups I and II, respectively (P=NS). The annulus was ellipsoid in shape, with the M-L orientation 14° (M-L orientation: 12° from the aortic valve (Figure 2D). The 2 low points were observed at 92±15° and 279±14° (M-L orientation). The average distances between high and low points were 7.21±1.09 and 7.26±1.05 mm for referent groups I and II, respectively (P=NS; Table 2). Figure 3A demonstrates the anatomic location of the high and low points relative to the aorta. The average tricuspid annular area was 9.72±2.08 and 9.94±2.33 cm² for referent groups I and II, respectively (P=NS). The annulus was ellipsoid in shape, with the M-L distance greater than the A-P distance. There was no significant difference in TV annular geometric parameters between the 2 referent groups (Table 2).

**Anunnular Geometry in Patients With Functional TR**

Thirty-five patients with moderate or greater functional TR had an average VC width of 5.80±2.62 mm and average recent ratio of maximal TR jet area to the corresponding right atrial area of 41.7±12.5% (Table 1). There was associated LV dysfunction in 74% (15/35) and pulmonary hypertension in 51% (18/35). There were no significant differences in age and gender between the functional TR and referent groups. There was no significant difference in LVEF between referent group II and the functional TR group (43±18% versus 48±23%, referent II versus functional TR; P=NS), although as expected, referent group I had a significantly higher LVEF than the functional TR group. The average RVSP in the functional TR group was not significantly different from that of referent group II (60.5±17.7 versus 55.7±21.9 mm Hg; P=NS). Patients with functional TR had a smaller RV area change and larger RV dimension than referent groups.

In patients with functional TR, the annular area was larger and the tricuspid annulus was flatter (H-L distance 4.14±1.05 versus 7.23±1.05 mm, functional TR versus referent groups, P<0.0001), which diminished the saddle shape. Compared with referent groups, patients with functional TR had greater percentage increases in the A-P distance (88%) than in the M-L distance (31%), consistent with greater dilation along the free-wall aspect of the annulus (Figure 3B). In addition, the annulus became more circular, with a decreased M-L to A-P ratio (1.11±0.09 versus 1.32±0.09, P<0.0001, functional TR versus referent groups). The annular “stretch ratio” (A-P/H-L) increased in the functional TR group compared with referent groups, consistent with a greater degree of “stretch” or flattening of the annulus along its A-P distance in the functional TR group (12.76±4.94 versus 3.60±0.63; functional TR versus referent groups; P<0.001).

There were 2 types of annular shapes noted with functional TR, which we termed “intermediate” and “advanced.” Both shapes were within the spectrum of becoming more planar relative to the referent groups. The intermediate shape had 1 distinct high point located anteriorly, with the posterior edge becoming flat relative to the anterior high point (Figure 2B). The advanced shape was more uniformly flat in both anterior and posterior locations (Figure 2C). The H-L distances of the tricuspid annulus are displayed for referent, intermediate, and advanced shapes in the corresponding bottom panels of Figures 2E and 2F. Both intermediate and advanced annular shapes were more dilated, planar, and circular relative to referent groups. The intermediate group had smaller annular area (14.47±2.42 versus 20.53±4.58 cm²; P<0.0001), A-P distance (45.52±3.81 versus 51.62±6.78 mm, P=0.004), M-L distance (39.49±4.80 versus 48.94±6.37 mm, P<0.0001), and A-P/H-L ratio (9.85±2.84 versus 16.21±

**TABLE 2. 3D Annular Parameters: Referent Groups and Functional TR Patients**

<table>
<thead>
<tr>
<th>Component</th>
<th>Referent I (n=20)</th>
<th>Referent II (n=20)</th>
<th>Functional TR (n=35)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, cm²</td>
<td>9.72±2.08</td>
<td>9.94±2.33</td>
<td>17.24±4.75</td>
<td>&lt;0.0001*†</td>
</tr>
<tr>
<td>ML distance, mm</td>
<td>34.00±5.04</td>
<td>33.41±3.99</td>
<td>43.81±7.27</td>
<td>&lt;0.0001*†</td>
</tr>
<tr>
<td>AP distance, mm</td>
<td>25.95±3.60</td>
<td>25.23±2.83</td>
<td>48.30±6.12</td>
<td>&lt;0.0001*†</td>
</tr>
<tr>
<td>M-UA-P ratio</td>
<td>1.31±0.09</td>
<td>1.33±0.08</td>
<td>1.11±0.09</td>
<td>&lt;0.0001*†</td>
</tr>
<tr>
<td>H-L distance, mm</td>
<td>7.21±1.09</td>
<td>7.26±1.05</td>
<td>4.14±1.05</td>
<td>&lt;0.0001*†</td>
</tr>
<tr>
<td>A-P/H-L ratio</td>
<td>3.66±0.62</td>
<td>3.55±0.65</td>
<td>12.76±4.94</td>
<td>&lt;0.0001*†</td>
</tr>
</tbody>
</table>

Values are mean±SD. *P<0.05, I vs TR; †P<0.05, II vs TR.
Embryologically, the TV has a septal leaflet and a mural or free-wall leaflet.26,27 Hence, embryologically, the TV is really bicuspid in original design, consistent with the 2 peaks observed in the present study. The present study findings also confirm those of Hiro et al.28 who examined tricuspid annular shape in sheep using sonomicrometry and also demonstrated a nonplanar geometry.

**Geometric Changes in Functional TR**

The changes in the tricuspid annulus with functional TR, namely, increased annular area, planarity, and circularity, have also been observed in the mitral annulus with functional mitral regurgitation.29–32 As the annulus becomes more circular with TR, there is greater enlargement of the anteroposterior distance than the mediolateral distance, which may result from dilation of the tricuspid annulus preferentially along its free-wall distance, much like the posterior mitral annulus.

Although we describe 2 annular shapes based on presentation of 1 saddle horn versus none, these shapes are likely a continuum, consistent with the continuously varying relationship between 3D annular height and tricuspid annular area (Figure 4). The presence of 1 high point in the anterior region of the annulus in the intermediate shape may be due to the relation of the anterior edge to the fibrous skeleton of the heart, possibly providing more resistance to flattening as the annulus dilates.

**Determinants of Functional TR**

We can suggest that the flattening of the TVA that occurs with TR can potentially alter the normal papillary muscle–to-leaflet and annulus relationship. With flattening of the annulus, the low points of the annulus may be stretched away from the papillary muscles, thereby increasing tethering. Persistent TR after ring annuloplasty has been correlated with leaflet tethering by Fukuda et al.12

The bimodal shape of the tricuspid annulus remained present in referent patients with similar RV pressure loads and LV dysfunction, which suggests that it is not RV pressure load or left-sided heart disease that influences the annular remodeling changes observed with functional TR. Presumably, therefore, it is RV dysfunction and dilation that affect these annular remodeling changes. The fact that we were unable to separate the effects of RV dysfunction and TR suggests that they are indeed linked, perhaps through the mechanism of annular shape. Possibly, the tricuspid annulus can be thought of as the “gear” that modulates the effects of RV remodeling on TV function.

**Clinical Implications: Therapy for Functional TR**

Function TR is increasingly recognized as a significant cause of morbidity and mortality, and accordingly, there has been a greater impetus to perform TV repair at the time of surgery for left-sided disease.7,12,33–35 Current treatment of functional TR consists of resizing the annulus with either ring or suture annuloplasty.7,11 Dreyfus et al.7 demonstrated that the decision to perform tricuspid annuloplasty based on tricuspid annular dilation rather than degree of TR at the time of surgery resulted in improved long-term outcome. Matsunaga and Duran36 have demonstrated preoperative tricuspid annular dilation to be associated with development of late postoperative TR after repair of ischemic mitral regurgitation.
Unfortunately, the success of TV repair is often uncertain, especially with suture repair techniques, and results in residual or progressive TR after TV anuloplasty.5,7,11,12 The present study offers mechanistic insights that can potentially be applied to improve repair for functional TR in both operative and newly emerging percutaneous approaches.37 In the present study, we demonstrated that changes in the 3D annular shape also predicted functional TR, not just annular area alone, and hence, achievement of a saddle shape may be an important therapeutic goal beyond that of annular reduction alone. Ideally, annular remodeling with tricuspid anuloplasty should take into account the geometric changes that occur with TR, namely, increased circularity and planarity, and restore the normal bimodal-elliptical shape of the tricuspid annulus to reduce leaflet tethering and leaflet stress.4 Nonplanar rings have been used and considered effective in the mitral position on the basis of annular nonplanarity,38 and comparable rings are being advocated for the tricuspid position. Tricuspid annular shape and position changes have been considered in improving the surgical repair of TV abnormalities.39–41 3D analysis of TV shape might also assist in guiding percutaneous TV repair, defining the 3D anatomy of the tricuspid annulus in individual patients with the aim of deploying an appropriate device to modify annular shape and reduce TR.

**Saddle Shape of Tricuspid Annulus: Implications for Diagnosing TV Prolapse**

The bimodal shape of the tricuspid annulus also has important clinical implications for the diagnosis of TV prolapse. TV prolapse has been estimated to occur in 21% to 50% of patients with mitral valve prolapse in prior studies using diagnostic criteria that incorporated both parasternal long-axis and 4-chamber views.42,43 However, as demonstrated by the present study, the mediolateral plane that is displayed in the 4-chamber view cuts the annulus along its low or inferior points, and hence, leaflets may appear to prolapse superiorly relative to the annular line in this view, when in fact they remain below the annular line in the anteroposterior plane. Ideally and most appropriately, prolapse should be demonstrated in an anteroposterior plane such as the RV inflow view, which intersects the leaflet along its most superior (toward the right atrium) points. The short-axis view at the level of the aorta could also be used to define prolapse of the septal leaflet when appropriately oriented in the anteroposterior axis and not intersecting the valve obliquely (between the longitudinal and the transverse planes).

**Study Limitations**

Annular points can be difficult to define, because the exact insertion of the basal attachment of the leaflets may be difficult to appreciate in a single frame. To overcome this, the software used in the present study allowed examination of the TV in motion to define the annulus as the hinge point at which the leaflets attached.

The main aim of the present study was to evaluate changes in annular shape with TR, and therefore, tethering relationships of the RV papillary muscles to the tricuspid annulus were not examined. Moreover, in some patients, right-sided papillary muscles can be difficult to visualize, because these papillary muscles are small and variable in their attachments to the RV.

The jet area/right atrial area method to quantify TR has limitations, because physiological conditions, machine settings, and eccentric jets can influence the size of the distal TR jet. In addition, the study group consisted of patients with moderate or greater TR who were referred with heart failure as a reason for echocardiography. Hence, our findings may not be generalizable to all patients with moderate or greater TR. Patients were not followed up serially over time, and thus, the differences in annular shape may not represent an actual transition.

**Conclusions**

The normal TVA is a bimodal nonplanar structure with distinct high points located anteroposteriorly and low points located mediolaterally. With development of functional TR, the annulus becomes larger, more planar, and circular. The changes in annular geometry that occur with functional TR have potentially important mechanistic and therapeutic implications for repair.

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**Disclosures**

None.

**References**


Functional tricuspid regurgitation (TR) is increasingly recognized as a significant cause of morbidity and progressive right ventricular overload, and accordingly, there has been a greater impetus to perform tricuspid valve repair at the time of surgery for left-sided disease. The success of tricuspid valve repair is often uncertain, especially with suture repair techniques, and results in residual or progressive TR after tricuspid valve annuloplasty. In this study, we demonstrate that the normal tricuspid valve annulus is saddle shaped, with the highest points located in an anteroposterior orientation and the lowest points located in a mediolateral orientation. With the development of functional TR, the tricuspid annulus became dilated, more planar, and circular. These changes in the 3D annular shape also predicted functional TR, not just the lowest points located in a mediolateral orientation. With the development of functional TR, the tricuspid annulus became dilated, more planar, and circular. These changes in the 3D annular shape also predicted functional TR, not just

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**CLINICAL PERSPECTIVE**

Functional tricuspid regurgitation (TR) is increasingly recognized as a significant cause of morbidity and progressive right ventricular overload, and accordingly, there has been a greater impetus to perform tricuspid valve repair at the time of surgery for left-sided disease. The success of tricuspid valve repair is often uncertain, especially with suture repair techniques, and results in residual or progressive TR after tricuspid valve annuloplasty. In this study, we demonstrate that the normal tricuspid valve annulus is saddle shaped, with the highest points located in an anteroposterior orientation and the lowest points located in a mediolateral orientation. With the development of functional TR, the tricuspid annulus became dilated, more planar, and circular. These changes in the 3D annular shape also predicted functional TR, not just

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