Three-Dimensional Geometry of the Tricuspid Annulus in Healthy Subjects and in Patients With Functional Tricuspid Regurgitation

A Real-Time, 3-Dimensional Echocardiographic Study

Shota Fukuda, MD; Giuseppe Saracino, MS; Yoshiki Matsumura, MD; Masao Daimon, MD, Hung Tran, RDCS; Neil L. Greenberg, PhD; Takeshi Hozumi, MD; Junichi Yoshikawa, MD; James D. Thomas, MD; Takahiro Shiota, MD

Background—Most rings currently used for tricuspid valve annuloplasty are formed in a single plane, whereas the actual tricuspid annulus (TA) may have a nonplanar or 3-dimensional (3D) structure. The purpose of this study was therefore to investigate the 3D geometry of the TA in healthy subjects and in patients with functional tricuspid regurgitation (TR).

Methods and Results—This study consisted of 15 healthy subjects and 16 patients with functional TR who had real-time 3D echocardiography. With our customized software, 8 points along the TA were determined with the rotated plane around the axis at 45° intervals. The TA was traced during a cardiac cycle. The distance between diagonals connecting 2 points was measured. The height was defined as the distance from the plane determined by least-squares regression analysis at all 8 points. Both the maximum (7.5 ± 2.1 versus 5.6 ± 1.0 cm²/m²) and minimum (5.7 ± 1.3 versus 3.9 ± 0.8 cm²/m²) TA areas in patients with TR were larger than those in healthy subjects (both P < 0.01). Healthy subjects had a nonplanar-shaped TA with homogeneous contraction. The posteroseptal portion was the lowest toward the apex from the right atrium, and the anteroseptal portion was the highest. In patients with functional TR, the TA was dilated in the septal to lateral direction, resulting in a more circular shape than in healthy subjects. A similar 3D pattern was observed in patients with TR, but it was more planar than that in healthy subjects.

Conclusions—Real-time 3D echocardiography showed a complicated 3D structure of the TA, which appeared to be different from the “saddle-shaped” mitral annulus, suggesting an annuloplasty for TR different from that for mitral regurgitation. (Circulation. 2006;114[suppl I]:I-492–I-498.)

Key Words: echocardiography • physiology • valves
dilated cardiomyopathy in 6, anterior myocardial infarction in 4, and hypertrophic cardiomyopathy in 3. Mild TR was observed in 4 patients (25%), moderate in 7 (44%) patients, and severe in 5 patients (31%). Patients with congenital heart disease, nonsinus rhythm, an evident intrinsic abnormality of the TV, and poor image quality of their echocardiograms were excluded.

Transesophageal 3D Echocardiography

Transesophageal RT3DE was performed with a Sonos 7500 live-3D echocardiography system (Philips Medical Systems, Andover, Mass) with a 2.5-MHz × 4 matrix array transducer. The 3D data set, including that for the entire TV, was acquired in 7 consecutive cardiac cycles during a breath-hold with ECG gating. Gain and compression controls as well as the time gain compensation settings were optimized for the quality of the 3D images. The frame rate was 16.8 ± 4.0 with an image depth of 15.3 ± 1.9 cm. All 3D data sets were digitally stored and analyzed off-line.

The 3D geometry of the TV was analyzed with our custom-made software for visualization and analysis of 3D echocardiographic data. To acquire the complex 3D geometry of the TA, the user pinpointed the location of 8 TA points throughout a cardiac cycle from 4 cross-sectional TA planes rotated at 45° about a fixed rotational axis (Figure 1). The rotational axis was defined as the vector orthogonal to the TA plane and passing through the center of the annulus (Figure 1A). The rotation between cross sections was counterclockwise, looking from the apex to the TA (Figure 1B and 1C). The initial cross-sectional plane was defined as the plane parallel to the rotational axis and passing through both the middle of the septum and the lateral wall. Our systematic method of manually marking the position of TA points standardized the process of capturing TA 3D geometry among all cases and enabled us not only to perform regional analysis of the TA geometry but also to compare its dynamic changes during cardiac cycles. To ensure accuracy of tracing, reconstruction of the TA annulus was superimposed on the original motion echocardiographic images. Once the tracing was completed, the motion of the reconstructed TA was examined throughout a cardiac cycle (Figure 2). Reconstructed 3D images of the TA in a healthy volunteer and in a patient with functional TR are shown in Figure 2A and 2B, respectively.

3D descriptors of the TA, such as TA area and the TA best-fit plane, were numerically derived from the acquired data as follows:

1. The TA best-fit plane was derived from a least-squares fit of a plane to the 3D TA points; (2) TA area was defined as the area enclosed in the projection of the 3D TA curve to the best-fit TA plane; TA was indexed to body surface area.

Let $N$ be the number of reconstructed TA points; $A_k$, with $k \in [0,N]$, and $A_1 = A_0$ be a 2D vector representing the projection of each reconstructed 3D TA point to the best-fit TA plane. The TA area was obtained by using the following formula:

$$\text{Area} = \frac{1}{2} \sum_{k=0}^{N} \det[A_{k-1} - A_1]$$

(3) At the time of maximum and minimum TA area, the distance $d$ between the diagonal connecting 2 points in each of 4 directions, as shown in Figure 3A, was derived from the equation $d = |PA_1 - PB_1|$. Contraction $c$, in each 4 directions, was then calculated as follows:

$$c = \frac{d_{\max} - d_{\min}}{d_{\max}} \times 100$$

and (4) the height of each TA point was defined as the distance between the TA point and the TA best-fit plane (Figure 3B) normalized by TA area.

Figure 1. RT3DE images made with our customized software, showing the process to trace the TA. A, The axis of rotation (red line) ideally passes through the center of the TA. In the cross-sectional plane passing through the middle of the septum, the lateral portion of the TA was manually marked (yellow point). B, The cross-sectional plane was rotated around the center of the axis (red line) at 45° intervals to mark the posterolateral portion of the TA (yellow point). C, The posterior portion of the TA was then marked (yellow point) in the cross-sectional plane rotated 90° from the original position. LA indicates left atrium; LV, left ventricle; and RA, right atrium.

Figure 2. Sample images, showing the 3D geometry of the TA in a healthy subject (A) and in a patient with functional TR (B). Composites of still frames were taken during a cardiac cycle starting from end systole. The dynamic motion of the TA was demonstrated by sequential still images. The TA showed unique 3D structures throughout a cardiac cycle in a healthy subject (A), but it was more planar in patients with TR (B).
In addition, right ventricular (RV) volume was measured by RT3DE, and then RV ejection function was calculated as (diastolic volume−systolic volume)/diastolic volume×100.\(^{15}\)

**Statistical Analysis**

Values are expressed as mean±SD. Comparison of echocardiographic parameters between healthy subjects and patients with TR was performed with an unpaired t test. Linear regression analysis was used for correlation of variables of interest. A 1-way ANOVA followed by post hoc testing with the Bonferroni test was used for comparison of healthy subjects and patients with mild TR, moderate TR, and severe TR with respect to TA area and percentage change in TA area and for comparison of the 4 directions in the TA. Differences were considered significant at \(P<0.05\).

Interobserver and intraobserver variabilities for measurements of TA area, distance, and height were obtained by analysis of 10 random 3D images by 2 independent blinded observers and by the same observer at 2 different times. The results were analyzed by both least-squares-fit linear regression analysis and the Bland-Altman method.\(^{16}\)

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**

**Dynamic Changes in TA Area**

In all healthy subjects, the TA increased from midsystole to early diastole, decreased during middiastole, and increased again in late diastole, showing a biphasic pattern with 2 peaks in early- and late-diastole (Figure 4A). In contrast, a early-diastolic peak was not observed in 12 (75%) patients with TR (Figure 4B). Both the maximum (7.5±2.1 versus 5.6±1.0 cm\(^2\)/m\(^2\); \(P=0.003\)) and minimum (5.7±1.3 versus 3.9±0.8 cm\(^2\)/m\(^2\); \(P<0.001\)) TA areas in patients with TR were larger than those in healthy subjects. The percent change in TA area in patients with TR was smaller than that in healthy subjects (22.4±8.7% versus 29.6±5.5%, \(P=0.01\)).

When the patients with TR were divided into 3 groups according to the severity of TR, there were significant differences in maximum (\(P=0.005\)) and minimum (\(P<0.001\)) TA area, the percent change in TA area (\(P=0.001\)) among healthy subjects, and in patients with mild, moderate, and severe TR, as shown in Table 1. Both maximum and minimum TA areas in patients with moderate and severe TR were larger than those in healthy subjects (all \(P<0.05\); Table 1). Minimum TA area in patients with severe TR was also larger than that in those with mild TR (\(P<0.05\)). In addition, patients with severe TR had a smaller percent change in TA area than did healthy subjects and in patients with mild and moderate TR (all \(P<0.05\)).

Diastolic (150.2±47.9 versus 72.9±17.5 mL) and systolic (100.7±46.7 versus 27.3±8.5 mL) RV volumes in patients with TR were larger than those in healthy subjects (both \(P<0.001\)). RV ejection fraction in patients with TR was lower than that in healthy subjects (34.4±12.9% versus 62.8±5.2%, \(P<0.001\)). In addition, RV volumes were significantly related to the corresponding TA area at diastole (\(r=0.75, P<0.001\)) and systole (\(r=0.81, P<0.001\)). RV ejection fraction was also correlated with the percent change in TA area (\(r=0.70, P<0.001\)).

**Horizontal Assessment of TA Shape and Motion**

The results of measuring the distance in the 4 diagonal directions and its contraction in healthy subjects and in patients with TR are shown in Table 2. There were significant differences in distance among the 4 directions in healthy subjects, whereas no differences were observed in patients.
with functional TR (Table 2). There was no statistically significant difference in contractility among the 4 directions both in healthy subjects and in patients with TR.

When the results for healthy subjects and patients with TR were compared, the septal to lateral and posteroseptal to anterolateral distances in patients with TR were greater than those in healthy subjects at the time of maximum TA area. All 4 diagonal directions significantly differed at the time of minimum TA area. Contraction in the septal to lateral and anteroseptal to posterolateral directions in patients with TR was lower than those in healthy subjects.

**Vertical Geometry of the TA**

The localized heights of each of the 8 points are summarized in Figure 5. In healthy subjects, posteroseptal and anterolateral segments of the TA were close to the RV apex, and the lowest point from right atrium was the posteroseptal segment where the coronary sinus started (Figure 5A). In contrast, anteroseptal and posterolateral segments were close to the right atrium, and the highest point of the TA was in the anteroseptal segment, which was close to the RV outflow tract and aortic valve. In patients with TR, a geometric pattern similar to that of healthy subjects was observed, but the more severe the TR, the more planar the TV annulus (Figure 5).

**Observer Variability**

Correlations for interobserver and intraobserver variability of echocardiographic measurements were $r=0.92$ and $r=0.88$ for TA area, $r=0.82$ and $r=0.84$ for distance, and $r=0.71$ and $r=0.76$ for height, respectively. From the Bland-Altman method, interobserver and intraobserver variabilities were $0.33 \text{ cm}^2$ and $0.35 \text{ cm}^2$ for TA area, $1.1 \text{ mm}$ and $1.1 \text{ mm}$ for distance, and $0.50 \text{ mm}$ and $0.41 \text{ mm}$ for height, respectively.

**Discussion**

RT3DE combined with our custom software was useful for assessing the unique 3D geometry of the TA in healthy subjects and in patients with functional TR.

Functional TR is a common complication in patients with left-sided valve disease and ventricular dysfunction. TV annuloplasty is now a standard surgical procedure for the treatment of functional TR. Most surgeons consider the use of an annuloplasty ring an essential part of basic repair techniques for obtaining good results. However, the rings currently being used for TV annuloplasty were originally released for the mitral valve, and moreover, most rings are formed in a single plane with variation, whereas the actual TA may have a nonplanar, or 3D, structure. There is therefore a need for a better understanding of the 3D geometry of the TA, especially in the normal heart.

Although there have been many studies of the saddle-shaped mitral annulus, these issues have not been fully studied for the TA. In a previous study with a small number of subjects ($n=2$), 3DE with a reconstruction method was used to measure the 3D structure of the normal TA. A recent experimental study used sonomicrometry in an ovine model with opening of the pericardium. These studies were, however, limited because of the small number of subjects, nonphysiological conditions, and the differences in species. We therefore used the recently released RT3DE with our custom software, which could offer the potential for the

---

**TABLE 1. TA Area and % Change of TA Area in Healthy Subjects and in Patients With Mild, Moderate, and Severe TR**

<table>
<thead>
<tr>
<th></th>
<th>Healthy Subjects (n = 15)</th>
<th>Mild TR (n = 4)</th>
<th>Moderate TR (n = 7)</th>
<th>Severe TR (n = 5)</th>
<th>Overall P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum TA area (cm²/m²)</td>
<td>5.6 ± 1.0</td>
<td>6.1 ± 1.9</td>
<td>8.3 ± 2.6*</td>
<td>7.5 ± 0.5*</td>
<td>0.005</td>
</tr>
<tr>
<td>Minimum TA area (cm²/m²)</td>
<td>3.9 ± 0.8</td>
<td>4.4 ± 1.1</td>
<td>6.0 ± 1.3*</td>
<td>6.4 ± 0.6*#</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Percent change of TA area (%)</td>
<td>29.6 ± 5.5</td>
<td>27.1 ± 4.1</td>
<td>25.4 ± 8.8</td>
<td>14.6 ± 6.2**</td>
<td>0.001</td>
</tr>
</tbody>
</table>

TA indicates tricuspid annulus; TR, tricuspid regurgitation.

* $P < 0.05$ vs healthy subjects; # $P < 0.05$ vs mild TR; ** $P < 0.05$ vs the other 3 groups.

---

**TABLE 2. Results of Dimension in 4 Directions and Its Contraction**

<table>
<thead>
<tr>
<th></th>
<th>S-L</th>
<th>PS-AL</th>
<th>A-P</th>
<th>AS-PL</th>
<th>Overall P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum (mm)</td>
<td>34.2 ± 3.7</td>
<td>36.8 ± 4.2</td>
<td>38.9 ± 5.3*</td>
<td>37.9 ± 4.4*</td>
<td>0.03</td>
</tr>
<tr>
<td>Minimum (mm)</td>
<td>28.2 ± 3.7</td>
<td>31.0 ± 4.7*</td>
<td>32.9 ± 3.5*</td>
<td>31.7 ± 2.7*</td>
<td>0.007</td>
</tr>
<tr>
<td>Contraction (%)</td>
<td>17.2 ± 8.8</td>
<td>15.4 ± 10.4</td>
<td>14.7 ± 7.3</td>
<td>15.6 ± 6.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Patients with TR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum (mm)</td>
<td>42.4 ± 5.3#</td>
<td>44.1 ± 5.9#</td>
<td>43.0 ± 6.4</td>
<td>40.5 ± 6.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Minimum (mm)</td>
<td>38.1 ± 6.3#</td>
<td>38.2 ± 4.9#</td>
<td>37.6 ± 4.1#</td>
<td>36.7 ± 6.4#</td>
<td>0.7</td>
</tr>
<tr>
<td>Contraction (%)</td>
<td>10.3 ± 6.4#</td>
<td>13.0 ± 8.6</td>
<td>11.9 ± 8.3</td>
<td>8.9 ± 9.8#</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A-P indicates anterio to posterior; AS-PL, antero-septum to postero-lateral; PS-AL, postero-septum to antero-lateral; S-L, sepal to lateral; TR, tricuspid regurgitation.

* $P < 0.05$ vs SL direction; # $P < 0.05$ vs healthy in corresponding parameter.
physiological assessment of the 3D geometry of the TA in humans.

We demonstrated that healthy subjects had a nonplanar-shaped TA with homogeneous contraction. In patients with functional TR, the annulus was dilated in the septal to lateral and posteroseptal to anterolateral directions, thereby resulting in a more circular TA shape. Contraction of the TA was then asymmetrically decreased. More interestingly, the nonplanar and non–single-plane structure of the TA was observed both in healthy subjects and in patients with TR. A similar geometric pattern was observed between them, but the more severe the TR, the more planar the TV annulus (Figure 5). The highest point of the TA was in the anteroseptal segment, which was close to the RV outflow tract and the aortic valve. The lowest point toward the RV apex from the right atrium is the posteroseptal segment, where the coronary sinus started. The geometry of the TA thus may be complicated and appears to be different from the saddle shaped mitral annulus, suggesting an annuloplasty in TR different from that in mitral regurgitation. We show in Figure 6 the physiological and optimal ring shape for TV annuloplasty, which was based on the results of healthy subjects at the time of measurement of the minimum TA area in this study.

Single-plane rings are used for mitral valve repair, although the saddle shape of the mitral annulus is well known. There is considerable controversy concerning the choice of annuloplasty rings that have different shapes and flexibility and are made of different materials. David et al demonstrated that patients with a flexible annuloplasty ring had better left ventricular systolic function than those with a rigid annuloplasty ring 2 to 3 months after mitral valve reconstruction for chronic mitral regurgitation secondary to degenerative disease of the mitral valve. Salgo et al indicated the importance of saddle-shaped geometry to reduce leaflet stress in numerical simulation of the mitral valve. Timek et al also concluded that a flexible annuloplasty ring might provide better leaflet stress distribution by maintaining the saddle shape of the annulus. Therefore, to reduce leaflet stress as well as to preserve ventricular function after the surgical procedure, physiological rings may be more advantageous than nonphysiological rings for not only the mitral valve but also the tricuspid valve.

Study Limitations
There were several limitations in this study. First, the study population was relatively small. Further study with a much
larger population should be done to confirm the result of this study. Second, variation in the etiology underlying left-sided heart disease might affect the results in patients with functional TR. Third, the etiology of functional TR is thought to be annular dilatation and tethering of the leaflets due to ventricular dilatation and dysfunction.\(^2\)\(^{29}\) We previously showed that annuloplasty, performed to reduce the annulus size, might not be enough to eliminate TR in patients with severe tethering of the leaflets.\(^7\) In fact, residual TR after TV annuloplasty, varying from 10% to 20%, has been reported.\(^4\)\(^–\)\(^7\) Therefore, the use of partial or closed annuloplasty rings with a 3D/physiological structure would be recommended for TR patients with mild or moderate tethering of the leaflets. From a theoretical standpoint, the use of a more physiological annuloplasty ring may potentially contribute to improve atrioventricular dynamics. Further study will be needed to clarify the importance of this contribution and its benefits in terms of clinical outcomes.

Finally, although the 3DE system using in the present study provided higher image quality with a high resolution than the previous 3D ultrasound system, 7 alternate cardiac cycles were needed to acquire the 3DE data set. Stable conditions were therefore necessary over this period to obtain a clear 3D data set.

**Conclusions**

RT3DE with our custom software revealed a complicated 3D structure of the TA, which appears to be different from the saddle-shaped mitral annulus, suggesting different surgical techniques to treat TR versus those for mitral regurgitation.

**Disclosures**

None.

**References**


Three-Dimensional Geometry of the Tricuspid Annulus in Healthy Subjects and in Patients With Functional Tricuspid Regurgitation: A Real-Time, 3-Dimensional Echocardiographic Study
Shota Fukuda, Giuseppe Saracino, Yoshiki Matsumura, Masao Daimon, Hung Tran, Neil L. Greenberg, Takeshi Hozumi, Junichi Yoshikawa, James D. Thomas and Takahiro Shiota

Circulation. 2006;114:I-492-I-498
doi: 10.1161/CIRCULATIONAHA.105.000257
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2006 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/114/1_suppl/I-492

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/