Non-Circular Shape of Right Ventricular Outflow Tract
A Real-Time 3-Dimensional Transesophageal Echocardiography Study

Masaki Izumo, MD; Maiko Shiota, MD; Takeji Saitoh, MD; Eiji Kuwahara, MD; Yoko Fukuoka, MD, PhD; Swaminatha V. Gurudevan, MD; Kirsten Tolstrup, MD; Robert J. Siegel, MD; Takahiro Shiota, MD

Background—The shape of right ventricular outflow tract (RVOT) has been assumed to be circular. The aim of this study was to assess RVOT morphology using 3-dimensional transesophageal echocardiography (3D TEE).

Methods and Results—This prospective study included 114 patients who underwent 3D TEE. Two-dimensional (2D) TEE measured maximum and minimum RVOT diameters (RVOTD max and min) during a cardiac cycle. 3D TEE determined RVOT area (RVOTA) max and min, RVOT fractional area change, and RVOT shape index (RVOTSI; vertical/horizontal RVOTD). Cardiac output (CO) was calculated using 2D TEE, 3D TEE, and a Swan-Ganz catheter in 23 patients. RVOTSI was 0.84±0.21 (max) and 0.82±0.20 (min). Only 17 patients (14.9%) had circular RVOT (RVOTSI: 0.95–1.05); 82 patients (71.9%) were categorized into group 1 and 32 patients (28.1%) into group 2. 2D TEE, compared with 3D TEE, underestimated RVOTA and CO (both P<0.001). CO with 3D TEE had better agreement with CO with a catheter than CO with 2D TEE (r=0.83 and 0.53, respectively).

Conclusions—3D TEE revealed that RVOT geometry was not generally circular but oval with 2 different types. Because of the detailed morphological information of RVOT, 3D TEE could provide more accurate assessment of CO than 2D TEE. (Circ Cardiovasc Imaging. 2012;5:621-627.)

Key Words: right ventricular outflow tract ◼ 3-dimensional echocardiography

Recently introduced 3D transesophageal echocardiography (3D TEE) provides more accurate geometrical information of RV.20 The aims of this study were (1) to assess RVOT morphology and function using 3D TEE and (2) to compare CO calculated invasively with CO calculated noninvasively.

Clinical Perspective on p 627

Methods

Study Population
A total of 122 patients with clinically indicated TEE were prospectively enrolled between April 2010 and March 2011. Patients without sinus rhythm during procedure (n=4, 3.3%) and with poor quality images (n=4, 3.3%) were excluded from this study; finally, 114 patients were enrolled. This study was approved by the institutional review board of Cedars-Sinai Medical Center.

2D TEE and 3D TEE
TEE was performed using iE33 ultrasound imaging system (Philips Medical Systems, Andover, MA) equipped with a fully sampled matrix array TEE transducer which can display both 2D and live 3D images. All patients underwent 2D and 3D TEE in the left lateral decubitus position on the same day. The maximum (max) and minimum (min) 2D RVOT diameters (2D RVOTD) were examined from the short axis view.
obtained at the midesophageal level with 30° to 90° during a cardiac cycle (Figure 1). Max and min RVOT area (RVOTA) were calculated assuming that RVOT was circular. The RVOT velocity time integral (cm) was also obtained by placing a 1- to 2-mm pulsed wave Doppler sample volume in the proximal RVOT just within the pulmonary valve obtained at the midesophageal level with 30° to 90°.

Zoomed 3D TEE images of the entire RV were then acquired in 4 cardiac cycles (frame rate: 14±5 frames/s, range 6–29 frames/s). To avoid stitch artifacts, the images were acquired during a brief suspension of breathing, and special care was taken to stabilize the probe during data acquisition. All 3D TEE data were digitally stored for offline analysis (QLAB cardiac 3DQ, Philips Medical Systems, Andover, MA). Using multiplanar reconstruction of the 3D TEE volume set, RVOT vertical and horizontal diameters (max and min) and RVOTA were measured during a cardiac cycle with movement of 2D plane in the 3D space at the level of pulmonary valve annulus (Figure 2). The angle between the basal interventricular septum and the axis of the aortic root (septoaortic angle) was also measured at max RVOTA (Figure 3). The following equations were used for calculating SV based on the recommendation of the American Society of Echocardiography: 

\[ SV = \text{the cross sectional area} \times \text{velocity time integral} \]

\[ \text{cross sectional area} = \frac{\pi}{4} \times (\text{2D RVOTD})^2 \]

\[ \text{cross sectional area} = \frac{\pi}{4} \times \text{vertical diameter} \times \text{horizontal diameter} \]

The RVOT velocity time integral (cm) was also obtained by placing a 1- to 2-mm pulsed wave Doppler sample volume in the proximal RVOT from the short axis view obtained at the midesophageal level with 30° to 90°; and CO was derived as: 

\[ CO = SV \times \text{heart rate} \]

2D Transthoracic Echocardiography

All patients underwent complete 2D echocardiographic and Doppler examinations. Left ventricular end-diastolic volume (EDV) and end-systolic volume (ESV) were measured according to the Simpson’s biplane method. Left ventricular ejection fraction was calculated by the following formula: 

\[ (\text{EDV}-\text{ESV})/\text{EDV} \times 100 \]

RV fractional area change was analyzed by tracing the RV end-diastolic area (RVAd) and end-systolic area (RVAS) in the apical 4-chamber view using formula: 

\[ (\text{RVAd}-\text{RVAS})/\text{RVAd} \times 100 \]

With continuous-wave Doppler, the maximum peak tricuspid regurgitant velocity recorded from any view was used to determine pulmonary artery systolic pressure with the simplified Bernoulli’s equation (pulmonary artery systolic pressure=4* [peak velocity]^2+mean right atrial pressure). Mean right atrial pressure was estimated according to the most recent guideline recommended by the American Society of Echocardiography.

Cardiac Catheterization

Standard right heart catheterization was performed in 26 patients using a Swan-Ganz catheter with jugular or femoral venous access within 2 weeks before or after TEE (mean 4,5±2.2 days, valvular heart disease; 13 patients, atrial septal defect; 7 patients, ventricular septal defect; 3 patients, paroxysmal atrial fibrillation; 3 patients). 3 patients (11.5%, valvular heart disease; 2 patients, ventricular septal defect; 1 patient) with significant tricuspid regurgitation were no symptoms.

Figure 1. Right ventricular outflow tract (RVOT), measurement obtained at the midesophageal level with 30° to 90° by 2-dimensional transthoracic echocardiography.

Figure 2. An example of 3-dimensional (3D) transesophageal echocardiography (TEE) image for the assessment of right ventricular outflow tract (RVOT). The 3D dataset was manually cropped using the plane perpendicular to the RVOT at the pulmonary valve.
excluded in this study. CO was determined by thermodilution (mean of 3 consecutive measurements without variation >10%).

Statistical Analysis
Data for COs calculated with 2D TEE, 3D TEE, and a catheter were presented as medians with interquartile range (IQR). The other variables were expressed as mean±SD. An unpaired \( t \) test was performed to compare continuous variables between group 1 and group 2. A paired \( t \) test was used to compare 2D and 3D RVOTA. Mann–Whitney \( U \) -test was used to compare CO derived by 2D and 3D TEE. Differences were considered significant if \( P<0.05 \). Linear regression analysis was used for correlation of variables of interest. Bland–Altman plots were used to evaluate differences in CO by 2D TEE, 3D TEE, and catheter. Statistical analyses were performed using SPSS 18.0 (SPSS, Inc, Chicago, IL).

Results
Baseline Characteristics and Echocardiographic Findings
Baseline characteristics are summarized in Table 1. Table 2 shows echocardiographic findings. 2D TEE, compared with 3D TEE, underestimated RVOTA max and min (5.2±1.9 versus 6.5±1.9 cm\(^2\), 2.8±1.5 versus 3.5±1.5 cm\(^2\), respectively, both \( P<0.001 \); Figure 4). Vertical RVOTD max and min were better correlated with 2D RVOTD max and min than horizontal RVOTD max and min (Figure 5).

Comparisons in Echocardiographic Findings
Based on RVOT shape, all patients were classified into group 1 (RVOT shape index \( \leq 1 \), \( n=82 \)) or group 2 (RVOT shape index >1, \( n=32 \); Figure 3). As for the shape of RVOT,

Table 1. Baseline Characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>64.2±16.0</td>
</tr>
<tr>
<td>Male/female, %</td>
<td>78 (68.4)/36 (31.6)</td>
</tr>
<tr>
<td>Paroxysmal Af, %</td>
<td>36 (31.6)</td>
</tr>
<tr>
<td>Valvular heart disease, %</td>
<td>43 (37.3)</td>
</tr>
<tr>
<td>Mitral regurgitation, %</td>
<td>30 (26.3)</td>
</tr>
<tr>
<td>Mitral stenosis, %</td>
<td>2 (1.8)</td>
</tr>
<tr>
<td>Aortic regurgitation, %</td>
<td>2 (1.8)</td>
</tr>
<tr>
<td>Aortic stenosis, %</td>
<td>9 (7.9)</td>
</tr>
<tr>
<td>Congenital heart disease, %</td>
<td>10 (8.8)</td>
</tr>
<tr>
<td>ASD (%)</td>
<td>8 (7.0)</td>
</tr>
<tr>
<td>VSD (%)</td>
<td>2 (1.9)</td>
</tr>
<tr>
<td>Positive blood culture (%)</td>
<td>25 (21.9)</td>
</tr>
</tbody>
</table>

Table 2. Clinical and Echocardiographic Findings

<table>
<thead>
<tr>
<th>Parameters</th>
<th>All (n=114)</th>
<th>Group 1 (n=83)</th>
<th>Group 2 (n=31)</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>64.2±16.0</td>
<td>62.9±16.9</td>
<td>67.4±14.5</td>
<td>0.151</td>
</tr>
<tr>
<td>Female, %</td>
<td>31.6</td>
<td>28.9</td>
<td>38.7</td>
<td>0.758</td>
</tr>
<tr>
<td>LVEDVI, mL/m(^3)</td>
<td>50.7±17.7</td>
<td>50.6±18.9</td>
<td>50.2±13.7</td>
<td>0.945</td>
</tr>
<tr>
<td>LVESVI, mL/m(^3)</td>
<td>22.7±11.6</td>
<td>22.5±10.6</td>
<td>22.8±13.6</td>
<td>0.930</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>57.9±10.7</td>
<td>56.0±12.0</td>
<td>55.9±17.3</td>
<td>0.990</td>
</tr>
<tr>
<td>RVAd, cm(^2)</td>
<td>20.8±6.1</td>
<td>20.6±6.5</td>
<td>21.4±5.5</td>
<td>0.654</td>
</tr>
<tr>
<td>RVAs, cm(^2)</td>
<td>12.3±4.8</td>
<td>12.3±5.2</td>
<td>12.3±3.7</td>
<td>0.986</td>
</tr>
<tr>
<td>RVFAC, %</td>
<td>41.9±10.6</td>
<td>41.5±11.1</td>
<td>43.0±10.2</td>
<td>0.652</td>
</tr>
<tr>
<td>PASP, mm Hg</td>
<td>40.8±14.5</td>
<td>40.7±14.2</td>
<td>39.9±16.0</td>
<td>0.866</td>
</tr>
<tr>
<td>2D RVOTD max, mm</td>
<td>25.5±4.6</td>
<td>24.7±4.4</td>
<td>27.2±4.6</td>
<td>0.007</td>
</tr>
<tr>
<td>2D RVOTD min, mm</td>
<td>18.2±5.0</td>
<td>17.5±4.5</td>
<td>20.1±5.7</td>
<td>0.028</td>
</tr>
<tr>
<td>2D RVOTA max, cm(^2)</td>
<td>5.2±1.9</td>
<td>4.9±1.8</td>
<td>6.0±2.0</td>
<td>0.015</td>
</tr>
<tr>
<td>2D RVOTA min, cm(^2)</td>
<td>2.8±1.5</td>
<td>2.5±1.3</td>
<td>3.4±1.9</td>
<td>0.029</td>
</tr>
<tr>
<td>3D RVOTA max, cm(^2)</td>
<td>6.5±1.9</td>
<td>6.5±1.9</td>
<td>6.4±2.2</td>
<td>0.733</td>
</tr>
<tr>
<td>3D RVOTA min, cm(^2)</td>
<td>3.5±1.0</td>
<td>3.8±1.4</td>
<td>3.8±1.5</td>
<td>0.917</td>
</tr>
<tr>
<td>RVOT shape index at max</td>
<td>0.84±0.21</td>
<td>0.74±0.13</td>
<td>1.1±0.13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RVOT shape index at min</td>
<td>0.82±0.20</td>
<td>0.75±0.14</td>
<td>1.1±0.13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Septoaortic angle,°</td>
<td>121.3±9.0</td>
<td>124.9±7.7</td>
<td>113.1±5.5</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

LVEDVI indicates Left ventricular end diastolic volume index; LVESVI, left ventricular end systolic volume index; LVEF, left ventricular ejection fraction; RVAd, right ventricular diastolic area; RVAs, right ventricular systolic area; 2D, 2-dimensional; RVOTD, right ventricular outflow tract diameter; 3D, 3-dimensional; RVOTA, right ventricular outflow tract area; RVFAC, right ventricular fractional area change; PASP, pulmonary artery systolic pressure; max, maximum; and min, minimum.

P value; group 1 vs group 2.
circular RVOT (RVOT shape index: 0.95–1.05) was found only in 17 patients (14.9%). No differences in LVEDVI, LVESVI, left ventricular ejection fraction, RVal, RVala, RV fractional area change, and pulmonary artery systolic pressure were found between the 2 groups (Table 2). Only septo-aortic angle was significantly greater in group 1 than group 2 (124.9±7.7 versus 113.1±5.8°, P<0.001). Although 3D RVOTA max and min did not differ between the 2 groups, group 1 had smaller 2D RVOTD (max: 24.7±4.4 versus 27.2±4.6 mm, P =0.007, min: 17.5±1.3 versus 20.1±2.0 cm², P=0.015, min: 2.5±1.3 versus 3.4±1.9 cm², P=0.029) than group 2. The differences in RVOTA max and min between 3D TEE and 2D TEE were significantly greater in group 1 than group 2 (max: 1.4±1.2 versus 0.13±1.2 cm², min: 1.1±1.2 versus 0.08±1.2 cm², both P<0.001).

Evaluation of CO
2D TEE (median, 4.1 L/min; IQR 2.9 to 5.07 L/min), compared with 3D TEE (median, 4.4 L/min; IQR 3.4 to 5.4 L/min), underestimated CO (P=0.019; Figure 6). No significant differences in CO were found between 2D TEE and 3D TEE in group 2 (median, 4.4 L/min; IQR 3.7 to 5.1 L/min versus 3.9 L/min; 3.6 to 4.7 L/min, P=0.119). However, CO determined by 3D TEE was significantly greater than that by 2D TEE in group 1 (median 4.4 L/min; IQR 2.9 to 7.7 L/min versus 4.1 L/min; 2.5 to 6.4 L/min, P=0.008). CO determined by 3D TEE had better agreement with CO determined by a catheter (median, 4.2 L/min; IQR 3.3 to 4.9 L/min) than 2D TEE (r=0.82 and 0.57, respectively, Figure 7). The mean difference in CO between 3D TEE and catheter (0.08 L/min; 95% limits of agreement 0.70 L/min; −0.54 L/min) was significantly smaller than that between 2D TEE and catheter (−0.32 L/min; 95% limits of agreement 0.64 L/min; −1.28 L/min, P<0.001; Figure 8).

Reproducibility
The intraobserver variabilities as assessed by intraclass correlation were 0.95 (95% CI, 0.81–0.99) for 2D RVOTD max, 0.94 (95% CI, 0.77–0.98) for 2D RVOTD min, 0.91 (95% CI, 0.71–0.94) for 3D RVOTA max, and 0.92 (95% CI, 0.77–0.96) for 3D RVOTA min. The interobserver variabilities on these measurements were 0.93 (95% CI, 0.79–0.96), 0.92 (95% CI, 0.76–0.95), 0.89 (95% CI, 0.39–0.94), and 0.90 (95% CI, 0.80–0.91), respectively. The Bland–Altman method showed that interobserver and intraobserver variabilities were 0.35±0.90 and 0.26±0.32 cm² for 3D RVOTA, 0.17±0.23 and 0.19±0.24 cm² for 3D RVOTA min, respectively.

Discussion
The assessment of RVOT is of clinical importance for measuring right-sided SV, Qp/Qs, and regurgitant fraction. Understanding RVOT morphology and function dictates clinical management of such issues as pulmonary stenosis,23,24
Conventional 2D echocardiography is one of the modalities for assessing RVOT; however, it often provides less than satisfactory results.\textsuperscript{13-16} Anwar et al\textsuperscript{20} reported that 3D transthoracic echocardiography depicted an oval-shaped RVOT, helped the RVOT assessment, and added more details to 2D echocardiography. However, RVOT was not visualized in 48\% patients of their study patients and 3D transthoracic echocardiography could not provide the quantitative assessment because of its limited image quality. Furthermore, there was no comparison between CO by the use of 3D-derived RVOT area and catheter data. To our knowledge, the present study is the first report to demonstrate the following findings: (1) RVOT geometry was not generally circular but oval with 2 different types; (2) 2D TEE, compared with 3D TEE, underestimated both RVOTA max and min; (3) CO determined by 3D TEE had better agreement with CO by a catheter than 2D TEE, and (4) CO determined by 2D TEE, compared with 3D TEE, underestimated CO in patients with horizontally long RVOT shapes.

**RVOT Morphology**

Of our study patients, only 14.9\% patients had a circular RVOT and the remaining 85.1\% patients had oval RVOT with wide range (RVOTOSI, 0.50–1.48). A (3D–2D) RVOTA max and min were significantly greater in group 1 than group 2, which is due to the similarity between 2D TEE-derived diameters and the vertical diameters in elliptically shaped RVOT. Over 70\% of the study patients were classified into horizontally long RVOT (group 1). Therefore, the evaluation of RVOT with 3D geometry analysis must be taken into consideration. There were 2 different types of RVOT in our study: horizontal (group 1) and vertical (group 2) RVOT shapes. We could not find any differences in ventricular volumes and right ventricular pressure overload between the 2 groups. However, the angle between basal interventricular septum and the axis of the aortic root (septoaortic angle) was significantly smaller in group 2 than group 1 (Table 2, Figure 3). The more acute this angle becomes, the more vertical the RVOT shape is. Swinnie et al\textsuperscript{26} reported that this angle becomes more acute with advancing age. In our study as well, this angle significantly correlated with age ($r=−0.66$, $P<0.001$), and age in group 2 tended to be higher than that in group 1.

**Calculation for CO**

The window for measuring RVOT size has not been standardized, and oblique imaging of RVOT may affect the results.\textsuperscript{12} 3D TEE techniques have provided unique anatomic views of RVOT structures and improved the definition of spatial relationship in complex anatomicies. In the present study, CO determined by 3D TEE had better agreement with CO determined by a catheter than CO by 2D TEE. When compared with 3D TEE, 2D TEE underestimated RVOTA, which can lead to underestimation of CO. As our Figure 6 shows, detailed geometric evaluation of RVOT using 3D TEE revealed that 2D TEE, compared with 3D TEE, underestimated CO in patients with horizontally long RVOT shapes (group 1).

**Clinical Implication**

Recently, transcatheter aortic valve implantation has extended our ability to treat patients with severe symptomatic aortic stenosis.\textsuperscript{27-29} The incidence of more than mild paravalvular regurgitation after transcatheter aortic valve implantation varies between 7\% and 20\%,\textsuperscript{27,28} which is associated with increased mortality.\textsuperscript{30} Prosthesis/patient mismatch between annular diameter and device size may be one of the reasons for paravalvular regurgitation.\textsuperscript{11} The exact evaluation of the geometry of oval-shaped left ventricular outflow tract has important potential clinical implications on transcatheter aortic valve implantation.\textsuperscript{31} Recently, pulmonary valve replacement using an Edwards SAPIEN transcatheter heart valve, which is usually employed in transcatheter aortic valve implantation, has been reported.\textsuperscript{32} Understanding RVOT morphology may help us in the selection of therapeutic strategy for percutaneous pulmonary valve implantation. Khambadkone et al\textsuperscript{33} also reported device-related adverse events, such as dislodgement.
and embolization of the valve stent during percutaneous pulmonary valve implantation or follow-up, because of unfavorable shape, size, and elastic properties of RVOT. Accordingly, the precise assessment of RVOT shapes by 3D echocardiography may contribute to the improvement in treatment outcomes.

Study Limitation

We acknowledge that lower 3D TEE frame rate may cause underestimation of RVOTA; however, this study showed 2D TEE underestimated both RVOTA max and min compared with 3D TEE (frame rate: 14±5 frames/s). Assessment of RVOT using echocardiography is often difficult because of its poor insonation angle, although, earlier studies have demonstrated the usefulness of calculation of CO from RVOT flow using TEE.33,34 Only 1 plane for RVOTD was assessed by 2D assessment especially in the presence of low CO and tricuspid regurgitation.35 In our study, therefore, we excluded significant tricuspid regurgitation, and the mean CO determined by catheter was 4.5 L/min.

Conclusions

3D TEE revealed that RVOT geometry was not generally circular but oval with 2 different types. 3D TEE provided the detailed morphological information of RVOT, which allowed more accurate assessment of CO than 2D TEE.

Acknowledgments

We would like to thank Dr. and Mrs. Paul I. Terasaki for their kind support and encouragement.

Disclosures

Drs Siegel and Shiota are members of the Philips Medical Systems’ speaker bureau.

References


**CLINICAL PERSPECTIVE**

The assessment of right ventricular outflow tract (RVOT) is of clinical importance for measuring right-sided stroke volume, Qp/Qs, and regurgitant fraction. Conventional 2-dimensional (2D) echocardiography is one of the modalities for assessing the RVOT; however, we often find a discrepancy between noninvasive and invasive assessment. Recently, pulmonary valve replacement using a transcatheter device has been reported. Therefore, an understanding of RVOT morphology and function may be important in the clinical management of various cardiopulmonary diseases. Nevertheless, RVOT geometry and function have not been fully evaluated. In this study, 3-dimensional transesophageal echocardiography (3D TEE) revealed that RVOT geometry was not generally circular but oval with 2 different types. 3D TEE provided detailed morphological information about the RVOT, which allowed more accurate assessment of cardiac output than 2D TEE. In addition, the angle between the basal interventricular septum and the axis of the aortic root (septoaortic angle) was shown to be a determinant of RVOT shape; the more acute this angle becomes, the more vertical the RVOT shape is. As earlier studies have reported, aging strongly affects RVOT shape and the angle becomes more acute with aging. As a future direction, we propose that the precise assessment of RVOT shape using 3D TEE may contribute to improved catheter-based treatment outcomes.
Non-Circular Shape of Right Ventricular Outflow Tract: A Real-Time 3-Dimensional Transesophageal Echocardiography Study
Masaki Izumo, Maiko Shiota, Takeji Saitoh, Eiji Kuwahara, Yoko Fukuoka, Swaminatha V. Gurudevan, Kirsten Tolstrup, Robert J. Siegel and Takahiro Shiota

*Circ Cardiovasc Imaging*. 2012;5:621-627; originally published online August 13, 2012; doi: 10.1161/CIRCIMAGING.112.974287
*Circulation: Cardiovascular Imaging* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2012 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-9651. Online ISSN: 1942-0080

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circimaging.ahajournals.org/content/5/5/621

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in *Circulation: Cardiovascular Imaging* 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: Cardiovascular Imaging* is online at:
http://circimaging.ahajournals.org//subscriptions/