Quantitative Assessment of Severity of Ventricular Septal Defect by Three-Dimensional Reconstruction of Color Doppler–Imaged Vena Contracta and Flow Convergence Region

Masahiro Ishii, MD; Kanoko Hashino, MD; Genjyu Eto, MD; Takahiro Tsutsumi, MD; Wakako Himeno, MD; Yoko Sugahara, MD; Hiromi Muta, MD; Jun Furui, MD; Teiji Akagi, MD; Yuhei Ito, MD; Hirohisa Kato, MD

Background—The aim of the present study was to investigate the feasibility and potential value of the computer-controlled, 3D, echocardiographic reconstruction of the color Doppler–imaged vena contracta (CDVC) and the flow convergence (FC) region as a means of accurately and quantitatively estimating the severity of a ventricular septal defect (VSD).

Methods and Results—We performed a 3D reconstruction of the CDVC and the FC region in 19 patients with an isolated VSD using an ultrasound system interfaced with a Tomtec computer. The variable asymmetric geometry of the CDVC and the FC region could be 3D-visualized in all patients. The 3D-measured areas of CDVC correlated well with volumetric measurements of the severity of VSD (r=0.97, P<0.001). Regression analysis between the shunt flow rate (calculated from the product of the area of CDVC and the continuous Doppler–derived velocity time integral) and the corresponding reference results (calculated by cardiac catheterization) demonstrated a close correlation (r=0.95, P<0.001). There was also a good correlation between shunt flow rates calculated using the conventional 2D, 1-axis measurement of the FC isovelocity surface area with the hemispheric assumption (r=0.95, P<0.001); shunt flow rates calculated using 3D, 3-axis measurements of the FC region (r=0.97, P<0.01); and reference results by cardiac catheterization. However, the 2D method substantially underestimated the actual shunt flow rate.

Conclusions—The 3D reconstruction of the CDVC and the FC region may aid in quantifying the severity of VSD.

Key Words: defects • imaging • blood flow • echocardiography

In the clinical management of patients with ventricular septal defects (VSDs), quantitative assessment of the severity of the VSD is of major importance.1–3 Laminar acceleration flow phenomena for flows toward the cardiac defect (ie, flow convergence [FC] phenomena), detected reproducibly by color Doppler flow-mapping methods, have been studied clinically and experimentally.4–8 More recently, in vitro and in vivo studies have suggested that the width of color Doppler–imaged vena contracta (CDVC) measurements (the smallest flow diameter in any part of the flow acceleration field) accurately reflect regurgitant flow.9–13 As of yet, there has been no widely accepted, noninvasive method capable of reliably quantifying the shunt flow rate in patients with VSDs, partly because the evaluation of intracardiac flow events using 2D imaging systems may not be robust enough to characterize these spatially complex, often asymmetric events.10,12,14 Recent developments in ultrasound and computer technology have made dynamic, 3D reconstruction of the flow jets from conventional 2D images possible.15–19 Visualization of flows in 3 dimensions could allow for a better qualitative and quantitative assessment of the severity of VSDs. The aim of our study was to investigate the feasibility and potential value of computer-controlled, 3D, echocardiographic reconstructions of the CDVC and the FC region as a means of accurately and quantitatively estimating the severity of VSDs.

Methods

Study Population
We prospectively studied 19 patients with a median age of 3.9±3.2 years (range, 3 months to 11 years) who had an isolated VSD, as determined by clinical examination and 2D echocardiography. Diagnosis included perimembranous outlet VSDs in 10 patients, doubly committed subarterial VSDs in 7 patients, and inlet VSDs in 2 patients. Patient characteristics are summarized in the Table.
Cardiac Catheterization

All 19 patients underwent cardiac catheterization on the same day as their echocardiographic studies. The shunt flow rate and the ratio of pulmonary-to-systemic flow were determined by Fick’s method.\textsuperscript{3,5,7} Full ethical approval was given by the Kurume University Ethics Committee, and informed consent was obtained from each patient or from the patient’s parents.

Instrumentation and Data Acquisition

The 2D image acquisition for 3D reconstruction was performed with a commercially available echocardiographic system (Aloka SSD 2200) that was coupled with a dedicated 3D image-processing unit (Echo-scan, Tomtec). The 3D image acquisitions were performed as in previous studies.\textsuperscript{16–19} Color Doppler imaging was performed with a 5-MHz phase-array transducer. The color Doppler filter was set at 1000 to 1500 Hz. Gain settings were optimized for image quality using a maximal color gain setting for each patient according to a previously described method.\textsuperscript{16–19} In these previous animal and flow model studies, the influences of the color Doppler instrument setting on the transfer of color flow mapping data into a black-and-white video composite data encoding produced the most clearly defined vena contracta and nonvariance color shading produced the most clearly defined vena contracta and proximal flow field FC imaging.\textsuperscript{16–19} We used this setting. The video composite data from the color Doppler images were reconstructed and analyzed with the same Tomtec system, which uses a black and white processing milieu and does not separate the colors.

Determination of the Vena Contracta Area by 3D Reconstruction of VSD Jet

Manipulation of the data set was performed off-line, as described previously.\textsuperscript{16–19} After image alignment, a process of interpolation allowed the Tomtec computer to fill in the gaps between slices for reconstruction of the VSD jet and FC region. The final image was displayed in dynamic or static mode, reviewed frame by frame, and viewed with different projections. From the dynamic 3D data set, we determined the CDVC by cutting the jet zone from distal to proximal, perpendicular to its origin in the VSD, on the ventricular septal surface plane using the software from the Tomtec computer (Figure 1A). This position corresponded to the junction of the smallest cross-section between the FC zone and the VSD jet spray. The cross-sectional area of the CDVC in systole was chosen in the parallel-plane analysis window for review of the 3D data sets.\textsuperscript{18} The timing for measuring the cross-sectional areas of the CDVC was determined by cross-field analysis of the color flow field (Figure 1B).

Patient Characteristics

<table>
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<tr>
<th>Patient</th>
<th>Age</th>
<th>Diagnosis</th>
<th>PAP (S/D/M), mm Hg</th>
<th>SAP (S/D/M), mm Hg</th>
<th>Shunt Ratio</th>
<th>SFR, L/min</th>
<th>3D CDVC Area, cm(^2)</th>
<th>3D CDVC Method</th>
<th>3D FCR Method</th>
<th>2D FCR Method</th>
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<tr>
<td>1</td>
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<td>Perimembranous outlet</td>
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<td>87/50/65</td>
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<td>2.3</td>
<td>1.24</td>
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<tr>
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<td>0.71</td>
<td>0.24</td>
<td>1.00</td>
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<tr>
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<td>74/39/55</td>
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<td>55/12/30</td>
<td>74/39/55</td>
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<td>1.58</td>
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<td>124/65/92</td>
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<td>69/22/44</td>
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<td>0.98</td>
<td>0.55</td>
<td>1.06</td>
<td>0.62</td>
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</table>

RCCP indicates right coronary cusp prolapse; PAP, pulmonary arterial pressure; SAP, systemic arterial pressure; S, systole; D, diastole; M, mean; SFR, shunt flow rate; and FCR, flow convergence region.
determined using the ECG and the flow image on the monitor screen of the Tomtec system. The CDVC cross-sectional area was then measured using a computer trackball. In addition, continuous-wave (CW) Doppler recordings of the VSD flow velocity parallel to the direction of the VSD shunt flow were performed. The velocity-time integral (VTI) was determined by planimetry of the area under the spectral Doppler velocity curve. At least 3 sequential measurements of each variable were averaged. The shunt flow rate (Q) was calculated as the product of the cross-sectional area of the CDVC and the VTI using the flowing formula: Q = CDVC area × VTI × heart rate.

3D Reconstruction of FC Isovelocity Surface

The shape of the FC isovelocity surfaces was 3D reconstructed from different bird’s-eye-view perspectives (Figure 1B). Gray-scale grading, surface rendering, image resolution, and thresholding in the Tomtec computer were optimized to obtain a clear isovelocity surface. Three orthogonal axial distances from the FC boundary to the center of the orifice (a, b, c) were measured (Figure 1B). On the basis of the continuity concept,20,21 these shunt flow rates were calculated by multiplying the isovelocity surface area and their corresponding velocities16,17,22 (Q = S × V, where V indicates aliasing velocity). The isovelocity surface area (S) and the shunt flow rate were then determined using the hemielliptical mathematical equation for the FC isovelocity surface area calculation (shown below) and compared with the shunt flow rate as determined by Fick’s method. The 2D color flow images used as input to the Tomtec computer were videotaped, a representative plane with the clearest isovelocity surface was selected, and the shunt flow rate (Q) was calculated using a single-axis hemispheric FC calculation (Q = 2π1/2F, where r indicates aliasing distance, and V, aliasing velocity) that is commonly used in clinical and experimental studies.

\[
S = \pi ab \times \frac{c^2}{ab} + e \int_0^{\phi_0} \frac{\int_0^{\phi_0} \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}}} \left(1 - \frac{e^2}{e} \right)
\]

where

\[
a > b > c, \quad e = \sqrt{1 - \frac{c^2}{a^2}}, \quad k = \sqrt{1 - \frac{c^2}{b^2} / \sqrt{1 - \frac{c^2}{a^2}}},
\]

and

\[
\phi_0 = \text{Arcsin} \left(1 - \frac{c^2}{a^2}\right)
\]

**Statistical Analysis**

Data are presented as mean ± SD. The 3D CDVC areas were compared with the reference shunt flow rate as determined by Fick’s method. Simple linear regression analysis was used to obtain correlation coefficients between the reference cardiac catheterization flow data and the values measured or calculated by the 3D method. Agreement with 2 measurements was tested according to the method of Bland and Altman.23 Two independent observers (M.I., G.E.) analyzed 20 randomly selected patients at different times. Each observer individually selected the frames to measure and had no knowledge of the results obtained by the other observer. When the color Doppler recordings were analyzed in 20 randomly selected patients by the same observer (M.I.) on separate occasions, measurements of CDVC area and FC surface area were made. P < 0.05 was considered statistically significant.

**Results**

The variable asymmetric geometry of the CDVC and the FC region could be reconstructed and visualized in all patients (Figure 2). The asymmetric oval shapes of CDVC were visualized. The slightly skewed, hemielliptical geometry of the FC region was also visualized. All patients had a left-to-right shunt without a significant right-to-left shunt, as determined by cardiac catheterization. The ratio of pulmonary-to-systemic flow was between 1.4 and 3.9 (median, 2.2; Table).

**Relationship Between the 3D-Measured CDVC Area and the Shunt Flow Rate of VSD**

The results of linear regression analysis between the 3D-measured CDVC areas and shunt flow rate, as determined by cardiac catheterization, are shown in Figure 3. The 3D-measured CDVC areas correlate well with volumetric measurements of the shunt flow rate of VSDs (r = 0.97, P < 0.001). The CDVC areas increased from 0.12 to 1.46 cm² as shunt flow rate increased from 0.19 to 3.61 L/min.
Use of 3D CDVC With CW Doppler for Estimation of the Shunt Flow Rate of VSD

Regression analysis between the shunt flow rate, as determined by cardiac catheterization, and calculated shunt flow rates obtained from 3D vena contracta method. Agreement between shunt flow rates, as determined by cardiac catheterization, and calculated shunt flow rates was examined according to method of Bland and Altman. The 3D-color Doppler echocardiography estimations showed good agreement with the corresponding reference results by cardiac catheterization using the Bland and Altman analysis (mean difference, 0.26±0.45; Figure 4B).

Conventional 2D Hemispheric Versus 3D, 3-Axis FC Isovelocity Surface Method Calculations of Shunt Flow Rate

There was good correlation between the shunt flow rate calculated using the conventional 2D, 1-axis measurement of the FC isovelocity surface area with the hemispheric assumption and the rate determined by cardiac catheterization (r=0.95, P<0.001, Figure 5A). However, the 2D method substantially underestimated the actual shunt flow rate (mean difference, −0.59±0.50 L/min; Figure 5B). In contrast, the 3D, 3-axis measurements of the FC region determined from and measured on the 3D reconstruction correlated well with shunt flow rates and underestimated those rates to a lesser
Reproducibility of Measurement
An excellent correlation was found between CDVC area measurements made by the 2 independent observers \( r=0.97, P<0.001; \) mean difference, \(-0.25\pm0.30\) L/min; Figure 5C).

3D Reconstruction of CDVC
Previous studies have proposed the use of a proximal VSD jet width to estimate the severity of VSD. Several groups, including Hornberger et al.\(^9\) and Teien et al.\(^3\) have shown that the width of the VSD shunt jet is the best predictor of the severity of VSD. In these previous studies, however, the means by which this jet width measurement should be made were not clearly defined and the term “vena contracta” was not used. This is probably because knowledge of the FC and flow dynamic concepts, as manifested in color Doppler flow maps, was incomplete at that time. Other studies first described the location of the CDVC as the smallest connection between the laminar FC region and the distal turbulent jet spray and identified its use for more quantitative evaluations of valvular heart disease.\(^10\)–\(^12\) The concept of the vena contracta is now established in hydrodynamic physics.\(^9\)–\(^12\)\(,18,24,25\) The cross-sectional area of CDVC may correspond to the effective VSD area. Because the flow velocity at the vena contracta is highest along the shunt flow profile, multiplying the vena contracta area by the time integral of CW Doppler velocity through the shunt flow stream can provide shunt flow volume.\(^3\)\(,25\) However, the applicability of this method for determining the shunt flow volume, as obtained by the 2D-measured width of the CDVC and CW Doppler velocity, requires the assumption that the shape of the VSD is relatively uniform in all dimensions and that a single dimensional measurement can accurately represent all dimensions.\(^3\)

Although some morphological alterations of the VSD may conform to this assumption, the majority of pathological changes producing more complex shapes will not (eg, the shape of a doubly committed, subarterial VSD with right coronary cusp prolapse is commonly asymmetrical).\(^26\) Theoretically, to define the CDVC cross section, one could attempt to obtain a 2D image in a plane orthogonal to jet propagation, but in this case, the angle would lead to color flow dropout and distortion. The imaging of the CDVC in a single plane parallel to the direction of flow, as has widely been practiced in reported studies, necessitates an assumption of a circular and/or symmetrical shape that may not hold true in clinical practice. In contrast to the 3D method, the method we propose does not require any geometric assumptions when the 3D computed flow image is used as a substrate for measurement.\(^18\) Other investigators have demonstrated that the shape of the 3D-reconstructed CDVC corresponds well with the orifice shape in vitro.\(^27\) The measurement of the cross-sectional area of the CDVC from a 3D reconstruction should be a useful and potentially accurate method for quantifying the severity of a VSD with complicated geometry in the clinical setting.

Discussion
This is the first study quantifying the VSD shunt flow rate in children using 3D color Doppler flow techniques. Our results suggest that a 3D reconstruction of the CDVC and the FC region may aid in quantifying the VSD shunt flow rate.

3D Reconstruction of FC Regions
According to the continuity principle, the shunt flow and regurgitant or forward flow rates are given as the product of the isovelocity surface area and the aliasing velocity that characterizes the FC.\(^20,21,28–30\) Therefore, an accurate measurement of the isovelocity surface area is required. Many factors may influence the shape of the color Doppler FC isovelocity surface, including instrumentation, physiological factors (frame rate, aliasing velocity, angle dependency, and flow rate), and the geometry of the VSD and surrounding structures.\(^28–30\) Because the conventional 2D Doppler flow mapping method provides only limited views of the FC region, it is possible that the isovelocity shape appears hemispherical in 1 plane but, in reality, may not be a true hemisphere. In this study, the 2D method was consistent with a substantial underestimation of the actual shunt flow rates by the hemispheric model with a single-axis measurement. The 3D method eliminates the need for imaginative mental reconstruction, and it should be helpful in efforts to refine or adjust current FC methods, especially for asymmetric defects.

A 3-axis, 3D-hemielliptic method was used in the present study, which resulted in a better estimation of actual flow rates; however, underestimation still existed. This 3-axis, 3D method was superior to the 2D method because any intricate or unusually shaped surface area could be measured, and it provided a better estimation of actual flow rates. However, this method still requires hemielliptical assumption.\(^16\) The method of directly measuring the FC surface areas was superior to the 3-axis, 3D method because any intricate or unusually shaped surface area could be measured, and it provided the best estimation of the actual flow rate in animals\(^17\) and in a flow model study.\(^19\) However, in some patients, the FC region may be very small, which would make a direct, 3D measurement of the FC surface area difficult. Further study is necessary to investigate the feasibility of directly measuring 3D-reconstructed FC surface areas using a digital color 3D method that does not require any geometric assumptions for quantitative evaluation of the VSD shunt flow rate.\(^17,19\)

Study Limitations
The limitations of our method as used in the present study included the fact that the color Doppler shunt flow images were transferred into the Tomtec 3D computer as video.
composite gray-scale images. Thus, the FC region and the shunt flow jet, including the CDVC, were depicted as black-and-white images with various gray scales in the Tomtec system. This may have resulted in a loss of resolution in the image acquisition and reconstruction method. This loss might cause some difficulties with achieving adequate differentiation of the CDVC or shunt flow jet from tissue on the left ventricular surface. Despite these limitations, the contour of the CDVC could be visualized satisfactorily and analyzed quantitatively in our study. When measuring shunt flow by the 3D CDVC method versus the shunt flow measured at catheterization, there seemed to be an overestimation at the higher flow rate in the present study. In a previous animal study, the 2D CDVC estimation of aortic regurgitant flow rate showed a tendency for overestimation of the corresponding electromagnetic flowmeter as a reference result at the higher flow rates. At the higher flow rate, the limitation of lateral resolution of a conventional echocardiography system might lead to artifactual widening of the flow signal and yield an erroneous overestimation of the shunt flow volumes. This limitation inherent in color Doppler flow mapping for imaging CDVC was extended to the 3D reconstructed flow images. In the future, these problems should be overcome through the use of the digital 3D Doppler flow maps.

Conclusions

Measuring 3D-reconstructed CDVC areas and 3D proximal isovelocity FC surface areas provided more accurate shunt flows than did conventional 2D color Doppler methods. Three-dimensional echocardiographic extraction of intracardiac flow phenomena may aid in quantifying the severity of VSDs.

References

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