Echocardiography

Evaluation of Complex Congenital Heart Diseases with Real-Time Three-Dimensional Echocardiography

Chu-Chuan Lin, Kai-Sheng Hsieh, Ta-Cheng Huang, Ken-Peng Wong, Wen-Hsien Lu and Kaung-Jen Chien

Background. As a beating organ in the human body, the structure and motion of the heart can be depicted best with real-time 3-dimensional (RT-3D) image modality. Traditional M-mode and real-time two-dimensional (2D) echocardiography can be used for diagnosis of complex congenital heart defects, but with these modalities, the type of lesion and its complexity can only be appreciated indirectly, after composition of plane sections of different angles in mind. This study utilized the newly invented echocardiography platform for RT-3D scanning in selected patients with congenital heart diseases and evaluated its clinical applications in those patients.

Materials and Methods. Between February 2003 and April 2003, totally 18 patients of 4 different categories of diagnoses (4 cases with double-outlet right ventricle, 5 cases with tetralogy of Fallot, 4 cases with pulmonary atresia and intact ventricular septum and 5 cases with single ventricle) were enrolled in this study. Scanning in these patients was performed with 2D scanner then the Philips SONOS 7500 system equipped with an Matrix probe. Their ages ranged from 10 days to 12 years, and the body weight ranged from 2.5 to 50 kilograms. Two modes of scanning were used in this study to evaluate the feasibility for diagnosis and analysis of the complex lesions in our patients. Comparison of clinical usefulness was also made with 2D echocardiography.

Results. The time spent for RT-3D scanning (11.4 ± 1.4 min.) was significantly less than that for 2D platform (12.8 ± 1.9 min.) (p < 0.01). Visceral situs was confirmed in 17 (94.4%) patients with the RT-3D platform and 16 (88.9%) patients with the 2D platform. Cardiac connections were analyzed segmentally, and 14 (77.8%) vs 13 (72.2%), 17 (94.4%) vs 16 (88.9), and 18 (100%) vs 18 (100%) patients were confirmed in their venoatrial, atrioventricular, and ventriculoarterial connections, respectively. Difference was found in confirmation of tricuspid and mitral valves in 13 (72.2%) and 10 (55.6%) with RT-3D and 2D platforms, respectively. One full-volume data set in each of 4 patient groups was used to analyze the 3D relationship of the complex lesions and their surrounding structures, and was demonstrated in this study.

Conclusion: The capability of the new RT-3D system for fast, accurate diagnosis of complex congenital heart lesions was demonstrated in this study. Meanwhile, with the RT-3D system, the examiner can delineate the complex intracardiac morphology and 3D relationships easily and intuitively. More clinical information can be derived from the new system, including that which is required for planning surgery. Improvement in image resolution and operation procedure has made this RT-3D scanning system ready for practically clinical application.

Key Words: Three-dimensional echocardiography • Congenital heart disease • Four-dimensional • Full-volume

INTRODUCTION

For decades, the importance of transthoracic echocardiography for the practice of pediatric cardiology could not be overemphasized. It has long been used for final diagnosis of most congenital heart diseases in almost all pediatric cardiology institutes worldwide. At present, it is also introduced in areas of invasive interventions.
These include guiding of various procedures such as pericardiocentesis, device closure of many congenital cardiac defects and positioning of various implants.\textsuperscript{3,4} Most complex congenital cardiac lesions can be diagnosed quickly and accurately with real-time 2-dimensional (2D) echocardiography by experienced pediatric cardiologists. However, in these complex cardiac lesions, their structures, such as valves, outflow tracts and great arteries, usually deviate to a great extent from normal anatomy. Frequently other imaging modalities, such as magnetic resonance imaging, computer tomography, radio-nucleotide scanning, and even angiography, are necessary for ultimate diagnosis before a plan can be made for surgery.\textsuperscript{5,6} The main reason is that the 3-dimensional (3D) relationships of the cardiac structures in these complex lesions are usually hard to understand with conventional 2D plane images. Unlike simple lesions, the 3D structures in complex cardiac lesions are more difficult to construct through reconstruction of serial 2D planes in mind. 3D echocardiography has been in development for more than 2 decades.\textsuperscript{7,8} The methods adopted in earlier models were cumbersome and the resulting 3D images were far from ideal for clinical application, mainly due to rather low resolution of 2D images in earlier machines and sluggish, imprecise hand-sketched 3D images.\textsuperscript{9,10} However, these earlier models were shown to calculate ventricular volumes with high fidelity, especially the right ventricular volume that is hard to calculate from simple mathematical algorithms. For congenital heart disease, 3D reconstructions of good quality were reported in 96% of patients.\textsuperscript{11} The various heart defects displayed in a “surgical view” enhanced the information on intracardiac anatomy that was available from standard 2D echocardiography.

Several years ago, we introduced a dynamic 3D acquisition and processing platform, and our studies demonstrated its capacity of delineating many simple congenital heart lesions in 3D image format.\textsuperscript{12,13} However, this model worked by connecting cables and motor-driven carrier device between the echocardiography scanner and the platform. It took an average of fifteen minutes for complete processing of data set and more time for image optimization and surface rendering. Thus, this old model was far from applicable in clinical settings.

Recently, a commercially available high-end echocardiography scanner equipped with an ingeniously designed probe capable of displaying real-time 3D (RT-3D) echocardiography images was introduced to our department. In this study, scanning with this platform was performed in 18 patients with complex congenital heart diseases. The clinical usefulness and feasibility of delineating the complex cardiac anatomies in these patients was evaluated, and the applicability for clinical use was discussed and compared to that of 2D echocardiography.

**MATERIALS AND METHODS**

**Patient selection**

From February 2003 to April 2003, 18 patients with complex congenital heart diseases were enrolled in this study. Their ages ranged from 10 days to 12 years old, and their body weights ranged from 2.5 to 50 kilograms. The non-invasiveness of the study was explained to the parents and consensus obtained.

Patients were excluded from study if they refused, were hemodynamically unstable, acutely ill, not cooperative or unable to be sedated. The characteristics of these patients are shown in Table 1.

The author, a senior pediatric cardiologist, was blinded to perform echocardiographic scanning of these patients with both traditional 2D echocardiography and the new RT-3D echocardiography platforms, without first being informed of their diagnoses.

**Echocardiography platforms**

The traditional 2D echocardiography platform used in the study was the VingMed System Five scanner (Vingmed Sound, Horten, Norway).

For RT-3D imaging, the recently released Philips SONOS 7500 system was used. It is bundled with an xMatrix probe using breakthrough 2D array technology with thousands of built-in elements. The revolution in technology, coupled with supercomputed signal processing capacity and new 3D image processing technology, enables the system for truly real-time display of 3D images with optimized quality. Furthermore, its iNavigator technology allows instantaneous image cropping and rotation, and the unique probe is capable of performing both 2D or 3D scanning by toggling a button on the screen panel.

In this study, we used 2 modes for 3D image scanning. In the first mode, a 3D sector of approximately
30\(^\circ\) 60 degrees (specific size: 29\(^\circ\) 58 degrees, with high density off) can be displayed on screening in a true real-time, zero-wait fashion wherever the probe is scanning and sweeping in any direction or angle. No ECG or respiratory gaiting is necessary. In the second mode, a full-volume rather than a sector is acquired. ECG gaiting is necessary, and it takes seconds (8 sequential heart beats) to acquire one dynamic, full-volume set (Figure 1).

**Scanning procedures**

Each patient was scanned with traditional 2D, then the RT-3D platform. With both platforms, the author tried to complete the examination by sequential scanning that we used in conventional 2D scanning, that is, parasternal short axis → parasternal long axis → 4-chamber → subcostal → suprasternal views. Then the detailed structures were analyzed and diagnosis conformed with the segmental approach described by Van Praagh.\(^{14}\)

**Table 1.** Patient characteristics

<table>
<thead>
<tr>
<th>No</th>
<th>Diagnosis (2D echo)</th>
<th>Age</th>
<th>Sex</th>
<th>BW(Kg)</th>
<th>Sedation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DORV+subpulmonary VSD+PS</td>
<td>1 month</td>
<td>M</td>
<td>4.0</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>DORV+subpulmonary VSD s/p PAB</td>
<td>1.5 month</td>
<td>M</td>
<td>4.1</td>
<td>10% chloral hydrate</td>
</tr>
<tr>
<td>3</td>
<td>DORV+subpulmonary VSD+PS s/p B-T shunt</td>
<td>32 months</td>
<td>F</td>
<td>13</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>DORV+subaortic VSD+PS s/p B-T shunt</td>
<td>16 months</td>
<td>F</td>
<td>10.2</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>ToF</td>
<td>3 months</td>
<td>M</td>
<td>5.1</td>
<td>Midazolam HCL</td>
</tr>
<tr>
<td>6</td>
<td>ToF</td>
<td>11 months</td>
<td>F</td>
<td>9.8</td>
<td>None</td>
</tr>
<tr>
<td>7</td>
<td>ToF s/p B-T shunt</td>
<td>16 months</td>
<td>M</td>
<td>12.2</td>
<td>None</td>
</tr>
<tr>
<td>8</td>
<td>ToF s/p B-T shunt</td>
<td>6 years</td>
<td>M</td>
<td>18.7</td>
<td>None</td>
</tr>
<tr>
<td>9</td>
<td>ToF s/p B-T shunt</td>
<td>12 years</td>
<td>F</td>
<td>50</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>PA+IVS+PDA</td>
<td>10 days</td>
<td>F</td>
<td>2.5</td>
<td>Midazolam HCL</td>
</tr>
<tr>
<td>11</td>
<td>PA+IVS s/p B-T shunt</td>
<td>8 months</td>
<td>M</td>
<td>6.9</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>PA+IVS s/p valvotomy</td>
<td>14 months</td>
<td>F</td>
<td>10.5</td>
<td>None</td>
</tr>
<tr>
<td>13</td>
<td>PA+IVS s/p valvotomy</td>
<td>5 years</td>
<td>M</td>
<td>16.8</td>
<td>None</td>
</tr>
<tr>
<td>14</td>
<td>SV+PS</td>
<td>1 month</td>
<td>M</td>
<td>4.0</td>
<td>10% chloral hydrate</td>
</tr>
<tr>
<td>15</td>
<td>SV+PS s/p B-T shunt</td>
<td>9 months</td>
<td>F</td>
<td>7.1</td>
<td>None</td>
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<tr>
<td>16</td>
<td>SV s/p Glen shunt</td>
<td>6 years</td>
<td>F</td>
<td>19.6</td>
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<tr>
<td>17</td>
<td>SV s/p Glen shunt</td>
<td>7 years</td>
<td>M</td>
<td>22.1</td>
<td>None</td>
</tr>
<tr>
<td>18</td>
<td>SV s/p Fontan Surgery</td>
<td>12 years</td>
<td>F</td>
<td>32</td>
<td>None</td>
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</table>

DORV = double outlet right ventricle; PA+IVS = pulmonary atresia with intact ventricular septum; SV = single ventricle; PS = pulmonary stenosis; VSD = ventricular septal defect.

**Figure 1.** Process of full-volume acquisition. The entire window was divided into 4 sectors (Left) with preset optimized parameters; Right: acquired full-volume with good alignment of the 4 sub-volume sectors, time of about 8 heart beats required for an acquisition of a full-volume. Sections of various depths can be acquired by cutting from 3 perpendicular axes.
Sedation is not necessary for most patients when performing the traditional 2D or RT-3D scanning. For full-volume acquisition, no sedation is necessary in cooperative patients. Only light sedation, using chloral hydrate (10% aqueous solution) or midazolam hydrochloride (0.1-0.15 mg/kg), is required to keep the patients calm for a few minutes.

With the RT-3D platform, we directly used the 3D probe to search the cardiac structures, performed real-time sector 3D scanning and recorded the dynamic sector 3D clips in the built-in hard disk. In general, we followed the Van Praagh’s segmental approach described above for analysis. However, this could not be applied to our 5 patients (Nos. 14-18) with distorted cardiac axis or with dextrocardia. Thus for these patients, the scanning procedure was modified in order to locate the important cardiac structures and determine the optimal windows for full-volume acquisition. Then ECG leads were connected to and full-volume data was obtained in all patients from optimal positions (parasternal for all patients and subcostal and suprasternal notch for smaller patients or patients with good windows).

Statistical analysis

The feasibility and clinical applicability of the RT-3D were compared to those of traditional 2D echocardiography. The diagnosis of each patient was reviewed and confirmed with the medical records and previous echocardiography reports. Parameters used for comparison include time necessary for complete scanning diagnosis (by reviewing length of tape recording for each patient), ability to tell the situs and cardiac connections and ability to differentiate the right and left ventricles and their valve leaflets.

**Table 2. Comparisons between 2D and RT-3D platforms**

<table>
<thead>
<tr>
<th></th>
<th>2D platform (n = 18)</th>
<th>RT-3D platform (n = 18)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval of exam.</td>
<td>12.8 ± 1.9 min</td>
<td>11.4 ± 4 min</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sedation</td>
<td>4 (22%)</td>
<td>4 (22%)</td>
<td>NS</td>
</tr>
<tr>
<td>Accuracy of diagnosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visceral Situs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>connections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venoatrial</td>
<td>13 (72%)</td>
<td>14 (78%)</td>
<td>NS</td>
</tr>
<tr>
<td>Atrioventricular</td>
<td>16 (89%)</td>
<td>17 (94%)</td>
<td>NS</td>
</tr>
<tr>
<td>Ventriculoarterial</td>
<td>18 (100%)</td>
<td>18 (100%)</td>
<td>NS</td>
</tr>
<tr>
<td>Tricuspid/mitral valve differentiation</td>
<td>10 (56%)</td>
<td>13 (72%)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

NS = not significant.

Statistical analyses of frequency counts were performed with the McNemar chi-square test and a 2-sided, 5% significance level. The means were reported as mean ± SD and compared with the paired t-test.

Qualitative analysis

With the RT-3D platform, we can also evaluate the intrinsic 3D morphology of the heart from the acquired full-volume sets by cutting them from 3 different perpendicular axes at different depths and reversing the directions quickly. One full-volume data set in each of 4 patient groups was used to analyze the 3D relationships of the complex lesions and their surrounding structures, and a representative cut was demonstrated in this study.

RESULTS

In our study, 4 types of complex congenital cardiac defects were included. We successfully performed real-time 3D scanning and full-volume acquisition in all patients.

In Table 2, we have compared the clinical usefulness of the RT-3D platform with the 2D platform. The time spent for RT-3D scanning was significantly less than that for the 2D platform. Visceral situs was confirmed in 17 (94.4%) patients with the RT-3D platform and 16 (88.9%) patients with the 2D platform. Cardiac connections were analyzed segmentally, and were confirmed sequentially. Fourteen (77.8%) vs 13 (72.2%), 17 (94.4%) vs 16 (88.9%), and 18 (100%) vs 18 (100%) patients were confirmed in their venoatrial, atrioventricular, and ventriculoarterial connections, respectively. Difference was found in confirmation of tricuspid and mitral valves in 13 (72.2%) and 10 (55.5%) with RT-3D and 2D plat-
forms, respectively.

In RT-3D scanning for neonates, whose heart sizes are rather small, a 3D sector constitutes about 1 third to 1 half of the whole heart volume. Thus it is faster to complete scanning of an entire heart than in the child. In addition, it takes less time to scan a full volume in neonates than in children. The data sets are digital and readily saved in built-in hard disk by touching 1 button on the screen panel. An average of 30-50 MB (megabytes) is required for each full-volume data set.

In our study there were 4 groups of patients with different diagnosis. In double-outlet right ventricle, both the aorta and pulmonary artery arise mainly from the right ventricle. There is a large ventricular septal defect (VSD), which may be subpulmonary or subaortic in position, and there is absence of mitral-aortic continuity. To identify these, the relationships between mitral & tricuspid valves, VSD and great arteries must be sought. The pulmonary artery was identified by its bifurcation. The experienced pediatric cardiologists may quickly tell this anomaly in the clinics. However, the 3D information such as distance of structures and extent of VSD margins, which are rather important for planning surgery, is not easily obtained with the 2D images only. 3D views around the VSD, valves and great arteries are able to provide such additional information. In Figure 2, the 3D interior structure of a DORV patient is shown both when the atrioventricular valves are opened and closed. In these views, we can easily determine the relationships between the great arteries, VSD and the atrioventricular valves, and also their sizes and axes. The patency of subpulmonary and subaortic areas can also be demonstrated. This information is very important for planning of surgery. Unquestionably, 3D images can better determine a VSD’s size, shape and location than 2D images. Also the examiner can better determine whether VSD is subpulmonary or subaortic in location, and whether there is straddling of the valves across the VSD. Note the different axes of the tricuspid and mitral valves in this case.

In our study, there were 5 patients with tetralogy of Fallot, which included 4 lesions: pulmonary stenosis, right ventricular hypertrophy, VSD and overriding of the aorta. We demonstrated 3D contour of VSD in these patients successfully. The right ventricular outflow tracts, which are rather close to the chest wall in these patients, are more difficult to visualize with traditional echocardiography systems. In this study, they were successfully demonstrated. In Figure 3, we successfully demonstrated the 3D structure and extent of stenosis in the pulmonary infundibulum. In contrast, the single-plane image of 2D echocardiography may mislead the surgeon to overlook the area of hypertrophy necessary to be incised at surgery.

In the situation of pulmonary atresia with intact ventricular septum, the main issue for pediatric cardiologists and surgeons is to determine the possibility for 2-ventricle repair. The Z-index has been widely adopted for a long time as the criteria to predict if a patient can survive the
surgery of right ventricular outflow tract reconstruction. However, in some cases, the growth and contractile pattern of these 3 portions of the right heart (inlet, body, and outlet portion) is even more crucial and can better determine the surgical outcome. Even with the correct diagnosis, the 3D morphology of the right heart cannot be appreciated easily with 2D echocardiography. In Figure 4, we show the hypoplastic right ventricle in 1 of our patients. In viewing the 3D image, we can appreciate the growth of each portion of the hypoplastic right ventricle and their dynamic excursions.

Five patients with single ventricle were included in our study. In these patients, the competence of the atrioventricular valve was a main factor for successful surgical palliation (Fontan procedure). Clefts or deformity of the leaflets, resulting in severe regurgitation, will preclude these patients from direct surgical procedures of anastomosis and valvuloplasty and cardiac transplantation may be warranted. Real-time 2D echo, combined with Doppler and color flow mapping, is able to detect the existence and estimate the extent of valvular regurgitation. However, the number and characteristics of the valve leaflets can only be thoroughly evaluated by dynamic 3D images, before direct open-heart inspection at the opera-
tion room. In 1 of our patients with single ventricle anat-
omy, the real-time 3D echocardiography not only clearly
demonstrated the number and morphological appearance
of the leaflets but also the approximation and con-
formational changes during closure and opening.

DISCUSSION

In Table 3, we summarize the different characteris-
tics of the new RT-3D system used in this study and
compared them to those of the earlier, gated sequential
3D system used in our previous studies.

In our earlier 3D image system, the 2D image acqui-
sition for 3D reconstruction was performed with a com-
mercially available echocardiographic system (VingMed
CFM 800, Vingmed Sound, Horten, Norway) that was
coupled with a dedicated 3D image-processing unit
(Echo-scan, Tomtec, Munich, Germany), and strict
ECG and respiratory gating was required to collect syn-
chronized phases among sequential cardiac cycles. For
better image quality, the patients were asked or sedated
to keep steady breathing and relatively fixed heart rate.
It took at least another 5-10 minutes to process the 3D
images and perform surface rendering to see the details
of the heart. The new RT-3D system with the xMatrix
transducer, housing as many as 3000 elements and inte-
grated into a high-end imaging processing platform, is
the first capable of capturing a cubic sector of spatial
3D echocardiography data information so fast that no vi-
sual delay can be perceived, and usually sedation is not
required during scanning.

Also, the improvement in technology of computer
and probe design have greatly reduced the possible

<table>
<thead>
<tr>
<th>Table 3. Comparison between the real-time and gated sequential systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
</tr>
<tr>
<td>Mode of image acquisition</td>
</tr>
<tr>
<td>Image platform</td>
</tr>
<tr>
<td>Real-time 3D scanning</td>
</tr>
<tr>
<td>Time needed for a full-volume</td>
</tr>
<tr>
<td>Need for off-line processing</td>
</tr>
<tr>
<td>Time needed to load a data set</td>
</tr>
<tr>
<td>Time needed for selecting a view and surface rendering</td>
</tr>
<tr>
<td>Visually intuitive</td>
</tr>
<tr>
<td>Image navigation</td>
</tr>
</tbody>
</table>

Figure 5. 3D morphology of a patient with single ventricle anatomy viewing from apex (en-face view of atrioventricular valve). Left: diastolic phase with the atrioventricular valves opened, when 4 leaflets (arrows) with different morphology can be seen; Right: systolic phase with the atrioventricular valves closed with visual corda tendonea (arrows).
sources of the noises present in the old 3D system.\textsuperscript{15,16} The technical parameters (shading, smoothing, gating, etc.) have been optimally adjusted in the new RT-3D system so that best 3D image quality can be achieved and only little adjustment is needed at scanning, as compared to the old 3D system.

Since conventional 2D echocardiography is sufficient for diagnosis of all these lesions in our patients, in this study we tried to demonstrate the information that only 3D images can provide. Apparently, only 3D images can give us direct perception of depth in cardiac structures. Furthermore, necessary “surgical views” can be generated with 3D images of these complex lesions so that the surgeons are more confident in the operation room.

In this study, we were able to diagnose the cardiac anomalies in all patients with the RT-3D system. The time needed for diagnosis was even shorter than with the 2D platform. The ability to differentiate the segmental connection was also comparable to that of the 2D platform. As with earlier 3D models, the RT-3D was better than the 2D platform in discriminating tricuspid and mitral valves, regarding their leaflet number and morphology (Table 2).

Some aspects of clinical applications were not compared in this study. These included color flow mapping and Doppler evaluation of structural anomalies, and various intracardiac measurements. Color flow mapping and Doppler were not developed and incorporated in the RT-3D platform during the study. Evaluations of shunt patency, conduit flow, and peripheral pulmonary arteries were not compared due to inherent limitation of echocardiography.

At present, no standard transthoracic 3D scanning planes have been developed. However, when performing live 3D scanning, the same scanning sequence was used as for 2D echocardiography. That is, parasternal short axis first, then parasternal long axis, subcostal, and finally suprasternal notch. Modified views were frequently used in our patients with complex lesions. Accurate diagnoses can be made quickly after scanning, since this new system is ready to provide sufficient spatial and temporal resolution for the examiner to differentiate various intracardiac structures and lesions.

The intracardiac anatomies were complex in all of our patients. With live 3D mode, segmental approach and analysis was used for their diagnosis. As with 2D images, the atrial situs was determined by atrial morphology and connection with the liver. The right and left ventricles were discriminated by the number and offset of the atrioventricular valves, and pattern of trabeculation. The great arteries were identified with bifurcation in the pulmonary artery and branches in the aorta. Thus, diagnosis of double-outlet right ventricle was made with both arteries coming out from the right ventricle. The location of ventricular septal defect could be easily determined as subpulmonary, subaortic, or doubly-committed. However, in some cases, the pulmonary or aortic root was only partially located in the right ventricle. In this condition, 3D images will provide direct information such as angulations of the vessels, the shape, dimension and orientation of the ventricular septal defect, and their relationships to the septum and atrioventricular valves. The information is important as to how to create patent right or left outflow tracts with surgery.

In patients with tetralogy of Fallot, a large ventricular and narrow infundibular tract can be seen with 2D images. However, the orientation and size of ventricular septal defect and exact extent of infundibular stenosis can be understood better in a 3D perspective. Reconstruction of right ventricular outflow tract and patch repair of ventricular septal defect can be performed in ways that minimize outflow tract obstruction.

To date, there is no doubt that 3D images are much better in evaluation of the atrioventricular valves. With en-face view, the entire surface area of the leaflets can be visualized, and therefore, the specific locations and shapes of scalloped, prolapsed or cleft leaflets can be easily determined. So, in our cases with diseased atrioventricular valves, such as single ventricle and pulmonary atresia with intact ventricular septum, the 3D images of these cases could better demonstrate the origin of regurgitation needing repair, and the annulus of tricuspid valve in pulmonary atresia with intact ventricular septum can provide better estimation of ventricular growth than using single diameter, when predicting feasibility of 2-ventricular repair.

This is the first time we could see the interior of the heart in a true real-time 3D manner.\textsuperscript{17,18} Unlike the 2D imaging, RT-3D echocardiography presents the echocardiography data information of a whole beating heart at once. Thus, potentially, it will provide additional important information on the vivid heart that 2D images cannot provide.\textsuperscript{19,20} Additional advantages of RT-3D include ability to perform “electronic dissection” of the
Abstract
Heart for viewing. In the platform in our study, sections of any desired depth in three perpendicular directions were possible and very easy, by simply switching the control buttons on the screen panel. This function is especially helpful for our understanding of complex cardiac anatomy in our patients.

An off-line analysis package is available for arbitrary section of any direction and any angle, annotation of 3D location of any structure in the heart, and sophisticated analysis including area and volume calculations.

In this study, we have demonstrated the feasibility and value of this true real-time 3D echocardiography platform in evaluating the cardiac structures in our patients. Future refinement of this system may incorporate the functions of 3D color flow mapping, Doppler, and algorithmic measurements for realization of 3D echocardiography image in clinical application, which should be not far away in the future.

CONCLUSION

The display of true “real-time” 3D echocardiography was feasible even in neonates with body weight as small as 2.5 kilograms. The xMatrix probe, relatively large in size and seemingly impractical for use in pediatric patients, exerted excellent image quality in our pediatric heart patients.

In this study we also demonstrated the capacity of the new-generation real-time 3D imaging system to delineate the structures and lesions, such as the valves and great vessels, in our patients with complex congenital heart diseases.

REFERENCES