Feasibility of real-time three-dimensional transoesophageal echocardiography for guidance of percutaneous atrial septal defect closure

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Aims Intracardiac echocardiography (ICE) and two-dimensional transoesophageal echocardiography (2D TEE) are used in most centres for guiding transcatheter atrial septal defect (ASD) closure. ASDs have complex shapes that are not well characterized with 2D imaging. Real-time 3D TEE (RT3D TEE) provides en-face visualization of the ASD, allowing precise assessment of ASD dimensions. Accordingly, our aims were (i) to determine the feasibility of RT3D TEE to guide ASD closure and (ii) to compare ASD and balloon dimensions (BDs) using RT3D TEE vs. ICE and 2D TEE.

Methods and Results Thirteen patients with ostium secundum ASD underwent transcatheter ASD closure. 2D TEE, RT3D TEE, and ICE images were acquired sequentially. RT3D TEE was feasible in all patients. Comparing RT3D TEE and 2D imaging, the mean difference in long-axis dimension was +0.5 mm (P = NS for both), and −1.4 mm in short-axis (2D TEE, P < 0.05; ICE, P = 0.06). BD was greater with 3D TEE vs. ICE (+0.9 mm).

Conclusion RT3D TEE can be used to guide transcatheter ASD closure with the advantages of lower cost than ICE, and ability to visualize en-face views of the ASD. ASD and BD as measured by RT3D TEE differ when compared with 2D imaging.

Keywords Atrial septal defect; Three-dimensional transoesophageal echocardiography; Intracardiac echocardiography; Amplatzer septal occluder

Introduction

Successful transcatheter closure of secundum atrial septal defect (ASD) is dependent on accurate assessment of ASD size, rim architecture and length, and relationship of the defect to adjacent cardiac structures. These ASD features are of paramount importance in determining the appropriateness of transcatheter closure, device selection, and guidance of device deployment. Historically, guidance of ASD closure device selection and placement was performed with fluoroscopy together with two-dimensional transoesophageal echocardiography (2D TEE). Intracardiac echocardiography (ICE) has emerged as a preferred method for guiding deployment of transcatheter septal occluder devices in some centres because its use has resulted in (i) shorter procedural times and (ii) ability to guide device deployment without the need for general endotracheal anaesthesia.1,2

Atrial septal defects are known to have complex geometry that may be elliptical, oblong, or fenestrated in shape.3–6 These unique shapes are not adequately characterized by 2D imaging. Previous studies have investigated the utility of 3D TEE in the assessment of ASDs,7–9 providing unprecedented en-face dynamic views of ASDs. However, this older method of rendering 3D reconstructions from multiple 2D images was cumbersome, time-consuming, and not applicable to on-line, point of care analysis.

To overcome these limitations, a transducer was recently developed to allow real-time acquisition and on-line display of 3D images. We previously showed the ability to obtain high-quality, 3D, anatomically detailed views of the interatrial septum (IAS) ~85% of the time in more than 200 consecutive patients referred for transoesophageal echocardiography.10,11 Acar et al.12 and Martin-Reyes et al.13 separately recently described the application of this probe in the guidance of transcatheter closure of an ASD and a patent foramen ovale, respectively.

We hypothesized that real-time 3D TEE (RT3D TEE) could provide a suitable alternative to ICE for guidance of
percutaneous ASD closure. In this study, we evaluated the feasibility of RT3D TEE in guiding transcatheter device closure of ostium secundum ASD. Secondly, we compared ASD dimensions as assessed by RT3D TEE, ICE, and biplane 2D TEE.

Methods

Thirteen consecutive patients with ostium secundum ASD meeting clinical criteria for closure were prospectively identified as appropriate for transcatheter approach based on prior 2D imaging (TEE). Informed consent was obtained from all patients. The study was approved by our centre's Institutional Review Board.

Real-time 3D TEE images were acquired using the 3D matrix-array TEE (3D MTEE) probe and IE33 ultrasound machine (Philips Medical Systems, Andover, MA, USA). Similar to the transthoracic echocardiographic matrix array probe (x4; Philips Medical Systems), this probe combines novel electronic circuitry with miniaturized beam-forming technology that accommodates thousands of fully sampled elements into the tip of an otherwise conventional TEE probe, affording the capability of RT3D, biplane 2D, and Doppler imaging. The new 3D MTEE probe can be used in three imaging modes: narrow and wide angle acquisitions as well as the zoom mode. 3D MTEE data sets of the IAS were acquired by first obtaining a biplane view of the IAS from a mid-oesophageal transducer position. Initially, gain settings were optimized using the narrow-angled acquisition mode, which allows RT3D imaging without the need for ECG gating. This mode displays a pyramidal volume of \( \approx 30' \times 60' \). The 3D zoom mode, which displays a smaller, magnified pyramidal volume, was then used to capture 3D data sets of the IAS for on-line quantitative analysis.

Three-dimensional data sets were analysed on-line using ultrasound machine equipped, dedicated 3D software (QLab, Philips). ASD dimensions were measured in the multi-planar reconstruction mode available in the 3DQ plugin for QLab. This tool displays two orthogonal 2D cut planes perpendicular to the IAS. A third orthogonal cut plane provides the en-face view of the ASD from where the long- and short-axis dimensions were measured with the electronic callipers available in the software package (Figure 1).

Intracardiac echocardiography imaging was performed using the 8 Fr AccuNav catheter (Biosense Webster Inc., Diamond Bar, CA, USA) connected to a Sequoia ultrasound machine (Acuson, a Siemens company, Mountain View, CA, USA). Biplane 2D TEE imaging was performed with the 3D MTEE probe and IE33 ultrasound machine. Long- and short-axis ASD dimensions for both 2D TEE and ICE were obtained by identifying the plane that visually appeared to be the greatest and smallest rim to rim distance, and measured from a still frame acquisition (Figure 1).

All measurements from the three different ultrasound modalities were made at the point of care, in real time. The ICE operator was at the foot of the patient and the TEE operator at the patients head. The operators made measurements independently of one another and then recorded them. Those measurements were then reported to the interventionalist. The interventionalist chose the largest of the measurements for initial device sizing. ICE measurements were determined by the physician sonographer operating the ICE system. RT3D TEE and biplane 2D TEE measurements were acquired independently of ICE measurements by a separate physician operating the transoesophageal ultrasound system. All measurements were made at end-systole, when the ASD is known to be at its greatest dimension. Measurements for each modality were recorded on a still frame and reported independently to the interventional cardiologist in an effort to avoid measurement bias from \textit{a priori} knowledge of ASD dimensions from another modality.

Guide wire and sheath placement across the ASD were visualized with both ICE and RT3D TEE in narrow angle and zoom modes. The sizing balloon was expanded with diluted contrast until cessation of flow was achieved as demonstrated by colour Doppler echocardiography ("Stop-Flow Diameter"). The balloon diameter (BD) when the flow was abolished was measured by ICE and RT3D TEE. The BDs for the two echocardiographic techniques were measured as described above. Not all ASDs were sized with a balloon prior to device deployment. This decision was determined by the interventional cardiologist performing the procedure. When balloon sizing was performed, the BD was measured by RT3D TEE and ICE only. 2D TEE and fluoroscopic measurements of BD were not a part of the research protocol, and therefore were not measured or recorded (Figure 2).

The appropriate size closure device was subsequently selected based on the largest dimensions acquired among any of the modalities so as not to undersize the device. In the event that there was a large discrepancy in dimensions, the interventional cardiologist used the stop-flow diameter to select device size. All stages of device deployment could be successfully observed in the Live 3D mode. The left atrial disc was expanded first, followed by the connecting waist and finally the right atrial disc. Gentle push/pull (The Minnesota Wiggle) to assure stability and appropriate apposition to the rims was performed prior to device release. ICE and RT3D TEE images were acquired during each phase of deployment. Final post deployment images were acquired with particular attention to colour Doppler assessment for residual shunt flow (2D TEE and ICE), and demonstration of appropriate ASD rim impingement between the apposing discs of the septal occluder device with RT3D TEE imaging (Figure 3).

Statistics

Results are reported as mean \( \pm SD \). Long- and short-axis ASD dimensions were compared among RT3D TEE, 2D TEE, and ICE. Balloon dimensions were compared among RT3D TEE and ICE only. Student’s t-test was used for continuous variables using a two-tailed P-value of \( <0.05 \) for statistical significance. A Bland-Altman analysis was additionally performed to compare inter-modality differences.

Results

The study group consisted of 13 patients, mean age 35 \( \pm 12 \) years (range: 9–52). All defects were closed with the Amplatzer Septal Occluder (AGA Medical Corp., Plymouth, MN, USA). Mean device size was 28 mm (range: 15–38). Mean fluoroscopy time was 8.1 min (range: 4.1–14 min) and mean total procedure time was 49 min (range: 9–80 min). ASD closure was successful in all 13 patients.
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Figure 2  Balloon dimension (BD) as measured by 2D TEE, ICE, and RT3D TEE. The arrows indicate the expanded balloon in the left atrium on this still frame from a narrow angle acquisition. The bottom panels show three orthogonal cut planes from a multi-planar reconstruction view. BD can be measured from the en-face view of the balloon as it traverses the atrial septal defect as seen in the bottom right panel.

Figure 3  Real-time three-dimensional transoesophageal echocardiography acquisition post deployment of an Amplatzer Septal Occluder. The left (A) and right (B) atrial discs can be visualized with exquisite detail. Also demonstrated in (C), (D), and (E), as indicated by the arrows, the rims of the ASD are well apposed between the discs. Assessment of residual shunt with colour Doppler can be performed with the 3D multi-array TEE probe (not depicted here).
RT3D TEE imaging was feasible in all 13 patients, providing high-quality images suitable for analysis. RT3D TEE was capable of providing diagnostic quality imaging for all phases of ASD assessment and closure. Qualitatively, 3D imaging was superb in all patients. There was no dropout or reconstruction artifact present in the 3D acquisitions. With Live 3D imaging, the interventionalist and echocardiographer were afforded not only en-face views of the ASD, but also of the spatial orientation, anatomic position and relationship of adjacent cardiac structures, the delivery catheter, and the closure device itself; available from one angle and a stationary oesophageal position in most cases. 2D imaging, whether it was ICE or 2D TEE, required frequent probe manipulation and angle adjustment to capture the anatomy or structure of interest.

Long-axis dimensions in millimetres by RT3D TEE, 2D TEE, and ICE were $25 \pm 9$, $25 \pm 10$, and $24 \pm 10$ mm, respectively (Table 1). There were no statistically significant differences in mean long-axis dimension among the three imaging modalities. However, the mean of the differences in long-axis dimension across modalities would suggest that 2D imaging in general yields a smaller long-axis dimension (mean difference $= 0.5$ mm) when compared with RT3D TEE. Furthermore, there was considerable variation in measurements. In 6 of 13 cases, the difference between 3D and ICE was $> 1$ mm, and in two cases in particular that difference was 9 and 11 mm, respectively. The Bland–Altman analysis of long-axis dimension showed a similar bias but narrower limits of agreement with 2D TEE ($\pm 5.87$ mm) as opposed to ICE ($\pm 8.66$ mm) when compared with RT3D TEE (Figure 4).

Short-axis dimensions were $18 \pm 7$, $20 \pm 8$, and $20 \pm 7$ for RT3D TEE, 2D TEE, and ICE, respectively. When Compared with 3D TEE, ICE, and 2D TEE tended to yield larger short-axis dimensions of the ASD. There was a statistically significant difference in the mean difference in short-axis dimension as measured by RT3D TEE and 2D TEE ($-1.4$ mm, $P = 0.001$). The mean difference in short-axis dimension as measured by 3D TEE and ICE was not statistically significant; however, there was a trend towards a difference in this small group of patients ($-1.4$ mm, $P = 0.06$). Short-axis dimensions as measured by RT3D TEE differed by $>1$ mm in seven and five patients compared with 2D TEE and ICE, respectively, including two patients with differences of 6 mm by ICE compared with 3D TEE. The Bland–Altman analysis again confirmed a similar bias, but narrower limits of agreement with 2D TEE ($\pm 2.39$ mm) compared with ICE ($\pm 4.87$ mm) as depicted in Figure 4.

Balloon dimensions measured by RT3D TEE were available for only 7 of 13 patients (Table 1). BDs were not acquired in

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Long-axis, short-axis, and balloon dimensions ($n = 7$) in mm (mean $\pm$ SD), for the echocardiographic techniques</th>
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<td></td>
<td>3D TEE</td>
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<tr>
<td>LAX (mm) range</td>
<td>$25 \pm 9$</td>
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<tr>
<td>SAX (mm) range</td>
<td>$18 \pm 7$</td>
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<tr>
<td>BD (mm) range</td>
<td>$27 \pm 7$</td>
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The three right-sided columns represent the mean difference in dimensions and the range of differences comparing RT3D TEE with ICE and 2D TEE, and 2D TEE with ICE. Only the difference of short-axis dimension as measured by RT3D TEE and 2D TEE was statistically significant; however, there was a trend towards a statistically significant difference comparing short-axis dimension by RT3D TEE and ICE. There is considerable range of measurement differences comparing 3D and 2D imaging techniques. (LAX, long axis; SAX, short axis; BD, balloon dimension).

*$P < 0.05$.  
1$P = 0.06$.  
†$P = 0.08$.

![Figure 4](image-url) The Bland–Altman analysis comparing long-axis dimensions (upper panels), with short-axis dimensions (lower panels) of atrial septal defect size as measured by real-time three-dimensional transoesophageal echocardiography (RT3D TEE), intracardiac echocardiography (ICE), and 2D TEE. 2D TEE and ICE showed similar bias, but 2D TEE had narrow limits of agreement when compared with RT3D TEE.
the six remaining patients because balloon occlusion of the ASD was not performed in those patients as per the discretion of the interventionalist performing the procedure. In the seven patients in whom measurements were possible, BD by RT3D TEE was slightly larger than ICE-derived dimensions ($27 \pm 7$ vs. $26 \pm 7$ mm). The mean difference was $+0.9$ mm (range: $-1$ to $+2$ mm).

**Discussion**

Percutaneous closure of secundum ASD is becoming more commonplace in academic medical centres worldwide. ICE is a preferred method for guiding transcatheter closure of ASDs where it is available. Due to the high cost of the ICE catheters ($2500$ USD per non-reusable catheter) and the need for a specific ultrasound machine (Acuson, Siemens) and technical expertise, 2D TEE continues to be used in most centres worldwide. In this study, we demonstrated the feasibility of a new transoesophageal probe that delivers RT3D rendered images of the ASD. This novel probe was capable of guiding each phase of ASD closure, from preclosure assessment to guide wire and sheath placement to balloon occlusion, and finally device delivery, release and post-closure assessment.

Compared with its 2D counterparts, there are distinct advantages of RT3D TEE imaging deserving mention. For one, the images afforded by the 3D MTEE probe are unique and extraordinary. It allows the operator a dynamic en-face view of the ASD in real time. The entire rim and adjacent cardiac structures can be visualized from one acquisition. Further, with appropriate system equipped software, the operator can manipulate the 3D data set for advanced analysis at the point of care. Accurate dimensions of the ASD or related cardiac structures are accessible from one acquisition rather than through a trial and error process of micro manipulations of standard 2D probes, be it conventional TEE or ICE.

Imaging in two dimensions limits the operator’s ability to adequately characterize the 3D shape of the ASD, leaving too much to mental reconstruction and imagination. While ASDs are usually single and sometimes elliptical, they are known to have complex ovoid or egg-like shapes, or possibly contain multiple defects or fenestrations. Accordingly, dimensions measured by RT3D TEE will differ when compared with those measured with 2D TEE or ICE. This study showed that 2D TEE and ICE are more likely to provide a smaller long-axis dimension, and larger short-axis dimension when compared with RT3D TEE. Figure 5 demonstrates how 2D imaging might misrepresent ASD size. While this difference is frequently small and inconsequential, there were two patients in this study with a difference in long-axis dimension of $\sim10$ mm. It is unclear if such measurement differences would impact device selection. In the two cases referenced here, it did not, because the balloon dimension or stop flow diameter was similar among the three ultrasound modalities. However, these measurement differences may help to determine whether the patient is appropriate for percutaneous closure at all.

Balloon dimensions as measured by RT3D TEE and ICE were less divergent although the mean difference in dimension was slightly higher with RT3D TEE ($+0.9$ mm, range $-1$ to $+2$). With balloon distention, the irregularly shaped ASD assumes a more circular geometry. The balloon dimension, regardless of 2D cut plane, would therefore be similar. The slightly larger measurement with 3D TEE may be attributable to the choice of 2D imaging plane, as described previously; it may not be the longest dimension of the balloon as it passes through the ASD, as is demonstrated in Figure 5.

**Limitations**

Although these patients were consecutive and unselected, this is a small study. A larger trial with a greater number of patients will better define the utility of this new probe in all patients referred for percutaneous closure of secundum ASDs. Also, we did not assess the feasibility of the RT3D TEE probe in patients $<60$ kg. If there is not sufficient depth between the probe and the ASD as might be the case in patients of smaller size or those with a small left atrium, the ASD may only partially lie in the field of the pyramidal 3D data set.

![Figure 5](image-url) This figure illustrates the pitfalls of two dimensional assessment of atrial septal defects (ASDs). If the operator does not choose the appropriate angle and probe location, the ASD dimensions will not be accurately characterized. This example demonstrates the underestimation of long-axis and overestimation of short-axis dimensions with 2D imaging. (SVC, superior vena cava; AO, aortic root; TV, tricuspid valve; IVC, inferior vena cava; LAX, long axis; SAX, short axis).
Conclusion
Real-time 3D TEE provides unique, dynamic en-face views of ASDs not possible with 2D imaging. ASD dimensions as measured by 3D TEE differ slightly when compared with 2D imaging which is likely related to operator selection of 2D imaging plane. Finally, while ICE will likely remain the preferred method due to faster procedure times, and independence from general anaesthesia, 3D TEE is a feasible alternative to imaging guidance during transcatheter closure of ASDs.

Conflict of interest: Dr. Roberto Lang is the recipient of an equipment grant from Philips Medical Systems. Drs. Roberto Lang and Lissa Sugeng are members of the Philips Speakers Bureau.

References