Influence of atrial septal defect anatomy in patient selection and assessment of closure with the Cardioseal device

A three-dimensional transoesophageal echocardiographic reconstruction


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Background The maximal diameter of the defect and the dimensions of the septal rims are essential parameters for the selection of optimal cases for device closure. Neither two-dimensional echocardiography nor balloon catheter sizing provide optimal data. Unique three-dimensional echocardiography might help to improve patient selection and assessment of results. Our aim was to optimize transcatheter closure of secundum type atrial septal defects using three-dimensional echocardiography.

Methods Sixteen patients enrolled in a protocol for atrial septal defect transcatheter closure with the Cardioseal device underwent transoesophageal two- and three-dimensional echocardiography. Maximal diameter and tissue rim of the atrial septal defect were measured and compared by both methods. In the 12 patients selected for closure, the balloon stretched diameter was compared to three-dimensional echocardiography measurements. Device placement was assessed by two- and three-dimensional echocardiography.

Results The shape of the atrial septal defect appeared variable on three-dimensional views: round in nine patients but complex (oval, raquet-shaped, multiple) in seven patients. The surface area of the atrial septal defect varied by 68 ± 15% during the cardiac cycle. The correlation between atrial septal defect maximal diameters measured by two-dimensional transoesophageal echocardiography and three-dimensional echocardiography was better in round defects (y=1×+1.6, r=0.99) than in complex defects (y=0.7×−0.5, r=0.88). The antero-superior rim could only be properly assessed by three-dimensional echocardiography. In 12 patients the correlation between stretched diameter and three-dimensional echocardiography maximal diameter was poor (y=0.3×+13, r=0.41). After placement of the device, three-dimensional echocardiography enabled the mechanism of residual shunting to be understood in three patients.

Conclusions Dynamic three-dimensional echocardiography enhances the understanding of the anatomy and physiology of atrial septal defect and should be an important process in future initiatives for device closures.

Key Words: Atrial septal defect, transcatheter procedures, echocardiography, three-dimensional reconstruction.

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the atrial septal defect anatomy on these measurements is unknown.

Three-dimensional echocardiography provides unique ‘en face’ views of intracardiac structures such as the mitral valve and the atrial septum. Previous studies have shown the feasibility of three-dimensional echocardiography reconstructions of atrial septal defects. New information by means of the cardiac cycle with three-dimensional echocardiography, regarding the shape of the defect and the surface area have recently been reported. Three-dimensional echocardiography may help to assess the position of the device after its deployment. We report our experience of three-dimensional echocardiography for: (1) patient selection according to the atrial septal defect anatomy and (2) early assessment of transcatheter atrial septal defect closure by the Cardioseal device.

Methods

Study population

Sixteen patients referred for transcatheter closure of a secundum atrial septal defect were enrolled. There were six males and 10 females. The mean age was 14 ± 5 years (range 5-20 years). All patients had previously been studied by transthoracic two-dimensional echocardiography. The criteria for inclusion in the study were: secundum atrial septal defect with evidence of right ventricular overload, a maximal atrial septal defect diameter of 25 mm and a minimal circumferential rim of 4 mm by transthoracic two-dimensional echocardiography.

Two-dimensional transoesophageal echocardiography

While the patient was under general anaesthesia, two-dimensional transoesophageal echocardiography was performed with a multiplane 5–7 MHz probe connected to an Acuson Sequoia C256 (Acuson, Mountain View, CA, U.S.A.) platform. We measured the maximal diameter of the atrial septal defect and the dimensions of tissue surrounding the defect: antero-superior rim (distance from the aorta), antero-inferior rim (distance from the tricuspid valve annulus), postero-superior rim (distance from the superior vena cava), postero-inferior rim (distance from the inferior vena cava).

Three-dimensional echocardiography

The two-dimensional echocardiography system was then connected to a three-dimensional system (Echo-scan TomTec GmbH, Munich, Germany). Rotation of the transoesophageal probe was controlled by steering logic for controlled image acquisition. Electrocardiogram and respiratory gating by thoracic impedance measurements ensured optimal spatial and temporal registration of the cardiac images. RR intervals were predetermined with a variability of 100 ms or less. Respiration was gated at the end-expiratory phases. The reference position was a basal transverse plane to image the long axis of the right atrium. From this reference image, 90 sequential cross-sections acquired every 2° were obtained, each during a complete cardiac cycle, and stored in the computer memory. An average of two acquisitions per patient was performed and the one with minimal motion artifact was chosen for three-dimensional measurements. The recorded images were formatted in their correct rotational sequence according to their ECG phase in volumetric data sets. Post-processing of the data sets was performed offline by using the analysis program of the system (Echo-view, TomTec GmbH). To fill the gaps in the far fields, a trilinear cylindrical interpolation algorithm was used. From the conical data volume, specific cut planes were used for three-dimensional echocardiography reconstructions to image en face the atrial septal defect and the rims surrounding the defect from both the right and the left atrium. A transparency was placed over the three-dimensional echocardiography right-sided view of the atrial septal defect. The surface area of the atrial septal defect was traced using an off-line measurement system (Freeland cine view version 4, TomTec). The following data were looked for and analysed: (1) shape of the secundum atrial septal defect; (2) surface area of the defect with calculation of its variations during the cardiac cycle (frame rate of 25 images per second); (3) maximal diameter and rim dimensions from the right-sided view when the defect appeared maximal in size.

Transcatheter device closure

Transcatheter closure with the cardioseal device was undertaken when the tissue rim was >4 mm and the maximal diameter of the atrial septal defect <25 mm as assessed both with two-dimensional transoesophageal echocardiography and three-dimensional echocardiography. The stretched diameter of the atrial septal defect was measured by the balloon transcatheter method. After placement of the device, two-dimensional transoesophageal echocardiography imaged each disk of the device and its relation to the atrial septum. Two-dimensional colour Doppler imaging was used to assess residual atrial shunting. Three-dimensional acquisition was performed immediately after device deployment. Views from the left atrium and from the right atrium were reconstructed. The position of the fourarms of each disk were analysed from both sides of the atrial septum.

Statistical analysis

Two-dimensional and three-dimensional echocardiographic atrial septal defect maximal diameter measurements were done by blinded observers and also
compared with balloon occlusive stretched diameter measurements. Data are expressed as mean ± SD. Comparisons between measurements were done by paired t test for continuous variables, linear regression analysis and calculation of the mean difference. Inter-observer and intra-observer variability for measurement of maximal diameter by three-dimensional echocardiography were determined in all studies. Comparison measurements were made on separate three-dimensional echocardiography reconstructions.

Results

Three-dimensional echocardiographic reconstructions allowed optimal imaging of the secundum atrial septal defect in all 16 patients. The mean acquisition time was 80 s with a range of 50 to 200 s, depending on the patient’s heart rate and respiratory variability. Storage of the data in the three-dimensional system required 120 s. Each en face view reconstruction of the atrial septum required an average of 5 min. Three views (two from the right side and one from the left) were reconstructed per patient. Therefore atrial septal defect maximal diameter and rim measurements by three-dimensional echocardiography required a mean time of 20 min.

Shape and circumference of the atrial septal defect

As analysed from the three-dimensional atrial views, the morphology of the defect appeared very variable. Nine patients had a circular defect (Fig. 1) but in the remaining seven, the defect had a more complex geometry, oval in four patients, raquet-shaped in one patient, multiple in two patients (Fig. 2). As measured from the three-dimensional atrial views through the cardiac cycle (Fig. 3), the surface area of the defect varied by 68 ± 15%, being maximal during ventricular systole (1.7 ± 0.9 cm²) and minimal during atrial systole (0.4 ± 0.3 cm²) (Fig. 4).

Maximal diameter and rims by two-dimensional and three-dimensional echocardiography

The correlations between the atrial septal defect maximal diameter measurements by two-dimensional transoesophageal echocardiography and three-dimensional echocardiography are reported in Table 1. The mean difference between the two methods varied with the shape of the defect. In patients with a round shape, the mean difference was minimal (2 ± 0.5 mm) while in patients with a complex morphology the mean difference was maximal (6 ± 3 mm). In one patient with multiple defects the maximal diameter by two-dimensional transoesophageal echocardiography was 16 mm (taking account only one hole) whereas three-dimensional views showed two separate holes with a maximal diameter not compatible with transcatheter closure (Fig. 5). In one patient with a raquet-shaped defect two-dimensional transoesophageal echocardiography underestimated the maximal diameter of 8 mm and the patient was excluded from the protocol. Inter-observer and intra-observer variability for three-dimensional echocardiography maximal diameter were, respectively, 2.3% and 1.4%.

A close correlation was found between two-dimensional transoesophageal echocardiography and three-dimensional echocardiography measurements for antero-inferior, postero-superior and postero-inferior rims (Table 2). All these rims were >4 mm. For the antero-superior rim the correlation had less strength (r=0.7). In three patients the distance between the defect and aorta were <4 mm by two-dimensional transoesophageal echocardiography while the three-dimensional views showed an adequate antero-superior rim (Fig. 6).

Finally, 12 patients were selected by three-dimensional echocardiography for transcatheter closure of their atrial septal defect with a cardioseal device (maximal diameter <25 mm and surrounding rims >4 mm). The ratio between the device size and the atrial septal defect maximal diameter was 1.8. In four patients with a larger defect the procedure was aborted and the patients referred to surgery. In three of them, the surgeon found a large atrial septal defect with a diameter
>25 mm, as measured on an arrested heart; the last patient is still waiting for surgical closure.

Device placement

In the 12 patients selected for device occlusion, the correlation between the balloon stretched diameter and the three-dimensional echocardiography maximal diameter of the defect was poor with $r=0.41$ (Table 3). Moreover, it varied with the shape of the defect. In patients with a circular defect the correlation was better ($r=0.68$) with a mean difference of 0.8 ± 2 mm; in cases with a complex morphology, the correlation was very poor ($r=0.35$).

Early follow-up studies

The Cardioseal device was released successfully in all 12 patients. Nine of them had no residual shunt, as assessed by two-dimensional colour Doppler imaging. Multiple orthogonal planes obtained by two-dimensional transoesophageal echocardiography showed a correct
placement of the device. The three-dimensional echocardiography views confirmed the right position of the device and offered direct visualization of the four arms of each disk on the right and left sides of the atrium (Fig. 7). The two-dimensional transthoracic echocardiography, which was performed the day after, did not show any residual shunt. Three of the 12 patients had a residual shunt localized near the superior vena cava.

While the assessment of the exact shunt mechanism was difficult to figure out by two-dimensional transoesophageal echocardiography, the three-dimensional echocardiography views showed the postero-superior arm of the device floating in the right atrium (Fig. 8). In one patient the residual shunt by two-dimensional colour Doppler imaging was significant and the device was withdrawn and replaced successfully by another one. In the remaining two children, the device was left in place since the residual shunt was very mild.

Discussion

Three-dimensional reconstructions of secundum atrial septal defects enhanced the understanding of the anatomy and the physiology of these lesions. Our study showed that three-dimensional echocardiography helped in patient selection before transcatheter occlusion as well as in the final determination of device placement.

Atrial septal defect anatomy

Pathologists have described the atrial septum as a concave convex structure and a secundum defect as a single or multiple hole(s) around the fossa ovalis with a variable diameter[16]. Such studies do not reflect the in vivo situation and the shape analysis of the defect must be assessed on a beating heart. Two-dimensional echocardiography can cut the defect in different planes but does not reflect its true shape. Three-dimensional echocardiography mimics the atriotomy view on a beating heart and allows the atrial septal defect to be described through the cardiac cycle[13,15]. One of our most striking findings was the great variability of the shape of the atrial septal defects. A round morphology was only found in half of the patients, the other defects being oval, raquet-shape or multiple. Moreover, our study showed, as did that of Franke et al., that the surface area of the atrial septal defect changed significantly during the cardiac cycle, with a maximum size in late ventricular systole and a minimum size in late left ventricular systole.

Table 1 Atrial septal defect maximal diameter measurements by two-dimensional transoesophageal echocardiography and three-dimensional echocardiography

<table>
<thead>
<tr>
<th></th>
<th>2DE (mm) (mean ± SD)</th>
<th>3DE (mm) (mean ± SD)</th>
<th>Mean diff</th>
<th>Line of identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population</td>
<td>15.7 ± 5 (10–25)</td>
<td>19.4 ± 5 (12–30)</td>
<td>3.8 ± 3</td>
<td>y = 0.8 x + 0.62 r = 0.83</td>
</tr>
<tr>
<td>Round shape</td>
<td>17.1 ± 4 (13–25)</td>
<td>19.1 ± 4 (15–27)</td>
<td>2 ± 0.5</td>
<td>y = 1 x + 1.6 r = 0.99</td>
</tr>
<tr>
<td>Complex shape</td>
<td>13.4 ± 5 (10–25)</td>
<td>19.8 ± 6 (12–30)</td>
<td>6 ± 3</td>
<td>y = 0.7 x – 0.5 r = 0.88</td>
</tr>
</tbody>
</table>

ASD = atrial septal defect; 2DE = maximal diameter obtained by two-dimensional transoesophageal echocardiography; 3DE = measurements obtained by three-dimensional echocardiography; Mean diff = difference between the two methods.
ventricular diastole\textsuperscript{[14]}. These findings should have implications in patient selection for transcatheter atrial septal defect closure.

**Patient selection for device closure**

Two crucial parameters have to be measured to select patients for transcatheter closure of an atrial septal defect: the maximal diameter of the defect in order to choose a device with the appropriate size; and the tissue rim dimensions all around the defect to optimize the placement of the device\textsuperscript{[1-4]}. In the absence of gold standards, the balloon catheter technique is used as a reference to size the defect. It gives a *stretched* diameter but our study clearly showed a very poor correlation between the stretched diameter and the three-dimensional echocardiography maximal diameter, particularly in atrial septal defects of complex shapes: balloon measurement overestimates the size of round defects by stretching the septum tissue and underestimates the size of multiple defects by measuring only one hole. Furthermore, two-dimensional transoesophageal echocardiography is currently used to assess the

### Table 2  Tissue rim measurements by two-dimensional transoesophageal echocardiography and three-dimensional echocardiography

<table>
<thead>
<tr>
<th></th>
<th>2DE (mm) mean ± SD (range)</th>
<th>3DE (mm) mean ± SD (range)</th>
<th>Mean diff</th>
<th>Line of identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS</td>
<td>7.2 ± 2 (1-12)</td>
<td>8.5 ± 2 (5-10)</td>
<td>1.3 ± 1</td>
<td>$y=0.6 \times +0.3 \quad r=0.70$</td>
</tr>
<tr>
<td>PS</td>
<td>10.2 ± 6 (7-28)</td>
<td>11.3 ± 5 (8-25)</td>
<td>1.1 ± 2</td>
<td>$y=0.8 \times +0.2 \quad r=0.93$</td>
</tr>
<tr>
<td>AI</td>
<td>13.6 ± 5 (7-28)</td>
<td>12.4 ± 4 (7-29)</td>
<td>1.2 ± 1</td>
<td>$y=0.9 \times +0.1 \quad r=0.95$</td>
</tr>
<tr>
<td>PI</td>
<td>10.4 ± 4 (8-24)</td>
<td>9.3 ± 3 (7-23)</td>
<td>1.1 ± 2</td>
<td>$y=0.85 \times +0.3 \quad r=0.93$</td>
</tr>
</tbody>
</table>

2DE=rim surrounding the atrial septal defect obtained by two-dimensional transoesophageal echocardiography; 3DE=measurements obtained by three-dimensional echocardiography; Mean diff=mean difference between the two methods; AS=antero-superior rim; PS=postero-superior rim; AI=antero-inferior rim; PI=postero-inferior rim.
atrial septal defect size\[^{16,7,17,18}\] but, again, our three-dimensional echocardiography study pointed out how the shape of the defect might alter the accuracy of two-dimensional transoesophageal echocardiography diameter calculations. In round atrial septal defects, the two-dimensional ultrasound beam may cut the defect in its maximal diameter but this is no longer true in defects of complex shapes: two patients who were said to have a maximal diameter compatible with transcatheter closure after two-dimensional transoesophageal echocardiography were excluded after three-dimensional echocardiography reconstruction which showed a large raquet-shaped defect and multiple holes. In addition, the variation of the atrial septal defect surface area through the cardiac cycle increases the difficulty of measuring the maximal diameter by selecting the right two-dimensional frame.

Two-dimensional transoesophageal echocardiography in our study was an accurate method to estimate the tissue rim surrounding the defect, except for the antero-superior rim. The three-dimensional views of the rim separating the defect from the aortic wall allowed transcatheter closure to be selected for three patients who had been excluded by two-dimensional transoesophageal echocardiography for insufficient tissue (<4 mm). In these three cases, dynamic three-dimensional views from the right atrium showed that the antero-superior rim was floating and therefore was not in the same plane.

### Table 3 Atrial septal defect maximal diameter vs balloon-stretched diameter

<table>
<thead>
<tr>
<th></th>
<th>Cath (mm) (mean ± SD)</th>
<th>3DE (mm) (mean ± SD)</th>
<th>Mean diff</th>
<th>Line of identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population</td>
<td>17.9 ± 3 (12–20)</td>
<td>17.7 ± 4 (13–27)</td>
<td>0.2 ± 4</td>
<td>y=0.3×+13 r=0.41</td>
</tr>
<tr>
<td>(n=12)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Round shape</td>
<td>18 ± 2 (12–20)</td>
<td>17.1 ± 3 (15–27)</td>
<td>0.8 ± 2</td>
<td>y=0.5×+9.5 r=0.68</td>
</tr>
<tr>
<td>(n=6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex shape</td>
<td>17.8 ± 4 (15–20)</td>
<td>18.2 ± 2.5 (12–27)</td>
<td>0.3 ± 5</td>
<td>y=0.24×+13 r=0.35</td>
</tr>
<tr>
<td>(n=6)</td>
<td></td>
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<td></td>
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</tbody>
</table>

ASD=atrial septal defect; Cath=balloon-stretched diameter obtained by transatrial balloon catheter; 3DE=maximal diameter obtained by three-dimensional echocardiography; Mean diff=mean difference between the two methods.
as the posterior rims near the vena cava. The two-dimensional planes were cutting the posterior rim, the defect and the aortic wall partly excluding the anterosuperior rim. Therefore its size was underestimated by two-dimensional transoesophageal echocardiography. In other words, three-dimensional echocardiography reconstructions of the atrial septal defect helped greatly to select patients for transcatheter device closure.

Transcatheter device placement

Colour Doppler imaging by two-dimensional transoesophageal echocardiography allowed residual atrial shunting to be assessed after deployment of the Cardioseal device. The position of the device was easily understood by three-dimensional echocardiography which gives direct views of each disk from both sides of the atrium. Two-dimensional imaging does not allow for visualization of the edges of each arm. Therefore multiple orthogonal planes were necessary to appreciate, albeit indirectly, the placement of the edges of each disk. Direct en face three-dimensional views could simultaneously and directly image all four arms of the two opposed disks. The Cardioseal device appears in its spatial reality like an umbrella opened from both sides of the atrium. Three-dimensional echocardiography provided valuable information on the reasons for the residual atrial shunts in three of our patients. The indication in one patient to withdraw the device was based on combined two-dimensional colour Doppler imaging and three-dimensional echocardiography. Because of the limited number of patients, extensive conclusions as to the potential causes of the abnormal device placements are not suitable in this study.

Limitations

Three-dimensional reconstructions are available offline only. Further improvement to decrease the time of
Conclusions

Three-dimensional echocardiography enhances the understanding of the anatomy and the pathophysiology of secundum atrial septal defects and should be an important process in future initiatives for transcatheter device closure.

References


