Dynamic Changes of Atrial Septal Defect Area: New Insights by Three-dimensional Volume-rendered Echocardiography with High Temporal Resolution*

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Aims: The purpose of this study was: (i) to record dynamic changes in the area of atrial septal defects (ASD) during a cardiac cycle, and (ii) to investigate factors which influence ASD dynamics. Implementation of new software modifications allowed the frame rate to be doubled, as compared to usual techniques.

Methods and Results: Twenty patients were examined using transoesophageal three-dimensional (3D) echocardiography. In 10 patients the 3D dataset was recorded with a frame rate of 25 Hz, in another 10 patients with a frame rate of 50 Hz. The ASD area was planimetried for each picture and the changes analysed over time. The ASD area showed dynamic changes during the cardiac cycle with an end-systolic maximum and end-diastolic minimum. The influence of the various phases of the cardiac cycle on area changes could be differentiated especially at higher temporal resolution. The relative change in ASD area showed no significant relationship to Qp/Qs ratio, mean ASD size or heart rate. By contrast, there was a slight inverse correlation to age (r = −0·45, P<0·05).

Conclusion: Transoesophageal 3D volume-rendered echocardiography permits quantitative recording of ASD dynamics. The ASD area changes are influenced especially by the various phases of the cardiac cycle.

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Key Words: three-dimensional echocardiography; atrial septal defect; cardiac cycle; temporal resolution.

Introduction

Compared to two-dimensional (2D) echocardiography, three-dimensional (3D) echocardiography has a greater potential for quantitative recording of complex spatial structures[1–3]. This has been demonstrated especially for the analysis of ventricular volume, mass and function[4–7]. Smaller cardiac structures, such as cardiac valves and septum defects, set particularly high requirements for spatial and temporal resolution[8–12]. In the present study, implementation of new software made it possible to double the frame rate. The objective of the study was: (i) to record dynamic changes in the area of atrial septal defects (ASD) during the cardiac cycle, and (ii) to investigate the factors which influence ASD dynamics.

Methods

Twenty patients (15 female, five male) with ASD were examined. The age was between 14 and 86 years (39 ± 20 years). Nineteen patients were in sinus rhythm, and one patient showed atrial fibrillation.

Transoesophageal 3D Echocardiography

A 5 MHz multiplane probe was used for transoesophageal examination (Toshiba SSA 380A system). Guided by the 3D unit, (TomTec EchoScan system), 90 rotation levels at intervals of 2° were recorded. In 10 patients acquisition was performed at a frame rate of 25 Hz, in 10 patients at 50 Hz (TomTec Inc., Unterschleißheim).

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The 3D data analysis was made using the TomTec EchoView 4.1 program. Within the 3D dataset, one level was first set through the right (or left) atrium running parallel to the interatrial septum, making an ‘en face’ view of the interatrial septum and the ASD possible (Fig. 1). Threshold values for discrimination between tissue and fluid were individually set using the grey-value information of the 3D dataset. The threshold was set so that the defined border tissue/fluid corresponded to the transition atrial septum/defect in the anyplane mode. Using rendering algorithms, the volume-rendered picture was finally constructed and the ASD planimetried. The ASD was depicted throughout the cardiac cycle (Fig. 2). The change in ASD area over time was illustrated in a diagram. The following phases were defined using the opening and closing movement of mitral and aortic valves in the 3D dataset: (1) isovolumetric ventricular contraction (closing of the mitral valve to opening of the aortic valve); (2) ventricular ejection (opening of the aortic valve to closing of the aortic valve); (3) isovolumetric ventricular relaxation (closing of the aortic valve to opening of the mitral valve); (4) passive diastolic ventricular filling (first opening and closing movement of the mitral valve); (5) atrial contraction (second opening and closing movement of the mitral valve). When the temporal resolution was too low for precise determination, only systole and diastole were defined.

Figure 1. (Left). Three-dimensional anyplane image of the ASD and surrounding structures. A line of intersection is set through the right atrium running parallel to the interatrial septum, making an ‘en face’ view of the interatrial septum and the ASD possible. (Right). View after volume-rendered reconstruction from right-lateral through the right atrium. *=ASD; CS=coronary sinus; LA=left atrium, RA=right atrium, RV=right ventricle; SVC=superior vena cava.

Figure 2. Dynamic changes in ASD area. View from right-lateral through the right atrium. The ASD area attains its greatest size at the end of the ventricular systole with maximum filling of the atria (left frame). During the diastole, the ASD area decreases and attains its minimum at the end of the atrial contraction (right frame). Note the variations in size and shape (five frames out of 16).
Table 1. Analysis of intra- and interobserver variability with respect to ASD planimetry. Comparison measurements were made once with the same values for threshold as the baseline measurements, and once with newly-selected values.

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>Mean diff. ± SD (mm²)</th>
<th>Limits of agreement</th>
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<tbody>
<tr>
<td>Intraobserver (threshold identical)</td>
<td>0.99 (P&lt;0.01)</td>
<td>2 ± 27 mm² (P=ns)</td>
<td>− 52 and 56 mm²</td>
</tr>
<tr>
<td>Intraobserver (threshold new)</td>
<td>0.95 (P&lt;0.01)</td>
<td>0 ± 40 mm² (P=ns)</td>
<td>− 80 and 80 mm²</td>
</tr>
<tr>
<td>Interobserver (threshold identical)</td>
<td>0.97 (P&lt;0.01)</td>
<td>18 ± 28 mm² (P&lt;0.01)</td>
<td>− 38 and 74 mm²</td>
</tr>
<tr>
<td>Interobserver (threshold new)</td>
<td>0.94 (P&lt;0.01)</td>
<td>9 ± 44 mm² (P&lt;0.01)</td>
<td>− 79 and 97 mm²</td>
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r = correlation coefficient, diff. = difference, SD = standard deviation.

The shunt volume was measured during the 2D echocardiographic examination by determining the pulmonary and systemic flow using a pulsed Doppler[13,14].

Inter- and Intraobserver Variability of ASD Planimetry, Influence of Threshold Values

To determine the intra- and interobserver variability, taking the influence of the selection of the threshold value into account, the planimetric measurements of the ASD were made following these five steps (10 randomly selected patients): (a) Observer 1; (b) Observer 2 with the threshold values of Observer 1; (c) Observer 2 with newly-selected values for threshold; (d) Observer 1 with the initial values for threshold, and (e) Observer 1 with newly-selected threshold values. There were close correlations for all comparative measurements (Table 1). The values of mean deviation show a somewhat lower intra- than interobserver variability. New definition of threshold by the observers prior to reconstruction led to greater mean deviation.

Statistical Analysis

The ‘Statistical Package for the Social Sciences 8.0’ was used for statistical data analysis. The Wilcoxon signed ranks test was applied to compare groups with respect to systematic differences. Correlations between methods were determined by regression analysis. The difference between two measurements were set in relation to the means of two measurements to determine the intra-/interobserver variability[15].

Results

Relationship of ASD Area Changes to the Phases of the Cardiac Cycle

A mean of 15 ± 3 (8–19) pictures were recorded per cardiac cycle in the patients at a frame rate of 25 Hz, and 31 ± 7 (22–40) pictures in patients at 50 Hz. Figure 3 shows the changes in defect area over time in patients with different temporal resolution. With increasing picture rates, more detailed descriptions of area changes could be achieved. It can be seen that the changes of ASD area are influenced by the various phases of the cardiac cycle: the defect increases to its maximum during ventricular ejection. During passive ventricular filling, the defect area decreases and the minimum defect area is reached at the end of atrial contraction. In some patients atrial contraction was associated with a second marked decrease of defect area (Fig. 3C, D), while in other patients there was no significant effect on the rate of area decrease. The ASD area changes little during the phases of isovolumetric ventricular relaxation and contraction.

The individual patients showed considerable variations in ASD dynamics and motion pattern. Figure 4 shows the mean changes of defect area during the cardiac cycle for the patients examined at 50 Hz.

Relative Change of Defect Area During the Cardiac Cycle

The maximum opening area was 268 ± 167 mm², the mean opening area 199 ± 128 mm² and the minimum opening area 127 ± 91 mm². The relative area change (= maximum area/minimum area) as a measure of ASD dynamics varied markedly between the individual patients (1.3–5.4; mean 2.3 ± 1.0). There was a slight inverse correlation to the age of the patient (r = −0.45; P<0.05). On the other hand, the size of the ASD, the Qp/Qs ratio and heart rate showed no influence on the relative change in area (Table 2).

Discussion

It is not only possible to obtain spatial presentation of cardiac anatomy using 3D echocardiography, but there are also new possibilities for quantitative recording of cardiac structures and function parameters which are unavailable with 2D echocardiography. Due to technical limitations, the potential of the method has, however, only been partially exploited to date. With respect to 3D echocardiographic diagnostics of ASDs, initial studies thus addressed the spatial presentation and qualitative description[16–20]. More recent studies validated in vitro and in vivo 3D echocardiography for determination of
shape, the defect diameter and the distance between ASD edges and the surrounding structures\(^{21–27}\). This is decisive for catheter-interventional or surgical closure\(^{28,29}\). Franke \textit{et al.} were the first to deduce ASD area indirectly using a summation procedure of multiple 2D slices in the anyplane mode\(^{30}\). They were also able to demonstrate that the ASD area attains its maximum end-systolic and its minimum end-diastolic.

The most important result of our study is that an ASD does not only increase and decrease in size during the cardiac cycle. The defect area attains its maximum end-systolic and its minimum end-diastolic. An increasing number of pictures makes it possible to more precisely differentiate the influence of the individual phases of the cardiac cycle. In patient A (eight frames) and B (13 frames), the 3D acquisitions were made at a frame rate of 25 Hz, in the patients C and D (26 and 34 frames, respectively) at 50 Hz. I=isosvolumetric ventricular relaxation; II=passive diastolic ventricular filling; III=atrial contraction; IV=isosvolumetric ventricular contraction; V=ventricular ejection.

Figure 3. Presentation of ASD area changes in dependence on the phases of the cardiac cycle. The defect area attains its maximum end-systolic and its minimum end-diastolic. An increasing number of pictures makes it possible to more precisely differentiate the influence of the individual phases of the cardiac cycle. In patient A (eight frames) and B (13 frames), the 3D acquisitions were made at a frame rate of 25 Hz, in the patients C and D (26 and 34 frames, respectively) at 50 Hz. I=isosvolumetric ventricular relaxation; II=passive diastolic ventricular filling; III=atrial contraction; IV=isosvolumetric ventricular contraction; V=ventricular ejection.

Figure 4. Mean changes in defect area during the cardiac cycle (patients examined at a frame rate of 50 Hz). The area change shows a complex pattern over the course of the cardiac cycle. Overall, the minimum defect area was about half the size of the maximum, but there was a great variability in the extent of relative area change.
the cardiac cycle, but shows a differentiated pattern of area changes depending on the phases of the cardiac cycle. Our observations support the concept, worked out by Franke et al., that the area changes are primarily caused by systolic and diastolic translation of the atrioventricular plane. Atrial contraction is another influencing factor: the ASD area attains its minimum at the end of atrial contraction. However, it was conspicuous that the dynamics (that is, the difference between maximum and minimum defect areas) varied widely in the individual patients. We did not find influence of the defect size, $Q_p/Q_s$ ratio and heart rate on ASD dynamics in our patient group. Age and the relative area change showed a slight inverse correlation. Reduced translation of the atrioventricular plane caused by age-related changes in ventricular compliance might be an explanation. Lange et al. had also reported this correlation in their study, while Maeno et al. found no correlation between age and relative area change.

### Limitations

There is no procedure with which changes in defect area during the cardiac cycle could be comparably depicted with similar temporal resolution. The results of our study can therefore not be checked against a reference method. The spatial presentation of an ASD in a 3D picture is influenced by the selection of threshold values prior to volume rendering. This will affect the assessment of ASD size. We were able to demonstrate that the observer-dependent setting of the threshold leads to a lack of precision in determining the area. A comparative study with balloon sizing to exactly quantify this error was not, however, performed. In addition to influence of threshold selection, there are slight imprecisions in ASD depiction due to the thick depiction of peripheral structures in the volume-rendered mode. On the other hand, limited spatial resolution sometimes leads to incomplete visualization of the ASD contour.

### Clinical Implications and Perspectives for the Future

The variations in dynamics and configuration of ASDs are so pronounced that 2D echocardiographic examination alone prior to device placement is not sufficient to determine the maximum defect area. Three-dimensional echocardiography would thus in theory be an adequate examination technique, but this is presently limited especially by the problem of threshold definition. Until this problem is solved, balloon sizing will remain the ‘gold standard’ for determining the maximum area. Improved temporal resolution makes possible a more precise depiction of movement processes in the beating heart. New insights into the physiology and pathophysiology of the heart can thus be obtained. Digital data transfer techniques will perhaps permit considerably higher picture rates in the 3D dataset.

### Conclusion

Transoesophageal 3D volume-rendered echocardiography permits direct recording of the instantaneous ASD area and a quantitative description of changes during a cardiac cycle. A recording technique with high temporal resolution reveals complex ASD dynamics, which is influenced by, among other things, the various phases of the cardiac cycle. Three-dimensional echocardiography thus opens new possibilities for description and quantitative analysis of cardiac movement processes.

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### References

Echocardiography and Atrial Septal Defect Area


