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in
PAEDIATRIC
CARDIOLOGY

Images Paediatr Cardiol. 2002 Jul-Sep; 4(3): 4–20.

PMCID: PMC3232520

Three-dimensional echocardiography of ventricular septal defects

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Abstract

Three-dimensional echocardiography is increasingly available. We report our experience with 3D reconstructions of ventricular septal defects: Unique images of all different types of ventricular septal defects are reconstructed from left and right ventricular en-face views. The images are discussed according to pathological classifications. The images shown in this article include all landmarks used in pathological classifications of ventricular septal defects to distinguish the different types of the defects and their extension directions. The possibility of visualizing the whole circumference prevents the examiner from under- or overestimating the size of a defect and gives the interventionalist a useful tool for patient and device selection for interventional VSD closure.

MeSH: Three-dimensional echocardiography, Ventricular septal defect, Heart defects, congenital

Introduction

Echocardiography is the major diagnostic tool in pediatric cardiology. Echocardiography progressed from M-mode to B-mode and Color Doppler imaging. Today B-mode is routinely used in clinical practice for the diagnosis of congenital heart disease and to plan surgical procedures.¹ Two-dimensional echocardiography visualizes the anatomy of the heart in two-dimensional spatial images displayed in real-time, moving pictures. The examiner as well as the viewer have to combine a lot of different cutplanes to imagine the complex three-dimensional anatomy of the human heart. This is difficult especially when complex congenital heart disease is present.^{1,2}

Three-dimensional echocardiography displays the underlying morphology in three spatial dimensions by additionally simulating the impression of depth on the screen. Since the pictures are also moving one might call it “four-dimensional echocardiography”.

In two-dimensional echocardiography, complete visualization of the circumference of a ventricular septal defect (VSD) cannot be achieved by a single 2D-plane.¹ There are situations in which the circumference of a ventricular septal defect needs to be defined: A VSD with an overriding arterial valve creates a cone of space with the valve as the base. We define the right ventricular margin of the cone of space as the right ventricular circumference and the left ventricular margin as the left ventricular circumference of the defect.

In two-dimensional echocardiography, it is not possible to simulate intraoperative views. In some two dimensional cutplanes the complexity of the situation can be underestimated: The region of interest or at least parts of it could be missed or underestimated if it is not in the standard cutplanes allowed by the acoustic windows of the thorax.

Since several years attempts have been made to develop 3-D images from 2-D cutplanes but over the last five years, the availability of more powerful computers and software made the first experiences and studies of 3-D echocardiography possible.^{3–6}

Vogel et al.⁷ compared 3-D echocardiographic findings with anatomical specimens and could display the underlying anatomy accurately. Intraoperative views can be also successfully simulated by 3-D echo.^{8,9} There are several studies dealing with the quantitative and qualitative assessment of atrial septal defects^{10–12} by 3-D echocardiography and only a few dealing with ventricular septal defects that proved the feasibility of 3-D echo in depicting the exact size and position of ventricular septal defects in vitro and in vivo.^{1,2}

This study investigates the feasibility of transthoracic three-dimensional echocardiography in visualizing the three-dimensional morphology of all three kinds of VSDs – perimembranous, muscular and doubly committed.^{13,19}

The results are compared to the findings at surgery and to two-dimensional echocardiography to evaluate the presence of additional information as well as the limitations of the 3-D images compared to 2-D echocardiography.

We also report our experiences in optimizing data-acquisition and in using 3D reconstruction software. With regard to the clinical use in the future, the study suggests standard cutplanes for both the right and the left ventricular aspects of the ventricular septal defects. To describe the defect's position the standard cutplane should contain all landmarks of the interventricular septum used by pathologists to categorize the ventricular septal defects. We used the classification of McCarthy, Ho and Anderson published in this journal.

The most common types of ventricular septal defects affect the membranous septum and can be subclassified according to their extension into the surrounding parts of the ventricular septum. They are called perimembranous, the distinguishing feature is fibrous continuity between the atrioventricular and the aortic valves.¹³

The right ventricular septal surface is divided into three parts: inlet, apical-trabecular and outlet septum. Defects of the outlet septum are in most cases associated with the malalignment of the muscular outlet (or infundibular)

septum.¹³ According to Mc Carthy, Ho and Anderson the muscular outlet septum mainly consists of a free-standing extracardial part.¹⁹

Typical for doubly committed or juxtaarterial septal defects is direct fibrous continuity between the aortic and pulmonary valve. Both valves form the roof of those defects. Hearts with doubly committed defects are related to those hearts with a conotruncal malformation.¹⁹ If a defect has exclusively muscular borders, it is called a muscular VSD.

Materials and methods

We examined a total number of 14 patients aged from 3 days to 6 years. The median age was 21 months. 8 children had perimembranous ventricular septal defects, 1 had tetralogy of Fallot and 2 had tetralogy of Fallot with pulmonary atresia, 1 had a VSD associated with left ventricular outflow tract obstruction, 1 had a doubly committed VSD and 1 child with a muscular VSD. In 13 from 14 cases the data acquisition was performed using a transthoracic imaging probe, since most of the children were too small for using transesophageal echocardiography. In a 4 year old patient a transesophageal imaging probe was used. The examination took place under sedation at the end of cardiac catheterization, reducing movement artifacts and malalignment of the 3-D dataset.¹⁰ No child received specific sedation for 3D data acquisition. We used a rotational scanning method as it is the most reliable scanning method to create 3-D datasets.^{15–17,10} For raw data acquisition, a Hewlett Packard Sonos 5500 echo machine with a R 5012 rotational probe was used. A motor in the handle of the probe rotates the transducer 180° and creates a cone-like volume. The transducer rotates in increments of 2°. At each angle a complete cardiac cycle is recorded (up to 30 frame/s). To make sure that the frames at the different angles are recorded at the same time of the cardiac and respiratory cycle the motor is triggered by EKG and respiratory recordings. When the EKG and respiratory gatings meet predetermined limits equal for every angle the images are stored and the transducer moves to the next angle.¹¹ To place the structure of interest in the center of the conic volume the online 2-D image was used as a reference image. In all but one patient a subcostal approach was performed as we found it to be the best approach to get an unobstructed acoustic window to create a data-cone. The 2-D reference image for orientation was a subcostal coronal view. To get optimal raw data sets for reconstruction the gain was put 15% higher than normal, compound was put 15% lower than normal.

The digital raw data output was transferred to a Tomtec reconstruction computer and loaded and post processed into Echo-view software.⁸ Based on 2-D images in the x-,y- and z-axis for orientation cutplanes at any angle can be selected, moved and rotated. Based on the selected 2-D cutplane a 3-D image is calculated by adding parallel 2-D slices up to 10mm to the selected cutplane. The gaps between the slices are calculated by integration. 3-D effects are achieved by a combination of distance, gradient and texture shading as described previously.¹⁸ For optimal image display, threshold level variations were used.¹ By using a high threshold, objects distant from the viewer are eliminated which results in a loss of information; by using a low threshold, even distant objects are visualized but if they are projected in one plane, it is difficult to distinguish them. We therefore used an average

threshold level of 15 of a scale of 40. Transparency changes had only a small impact on image display.

Standard cutplanes for membranous ventricular septal defects were placed parallel to the interventricular septum in the left ventricular outflow tract for left ventricular “en face” views. To view the defects from the right ventricular aspect the cutplane was again placed parallel to the septum cutting the tricuspid valve orifice.

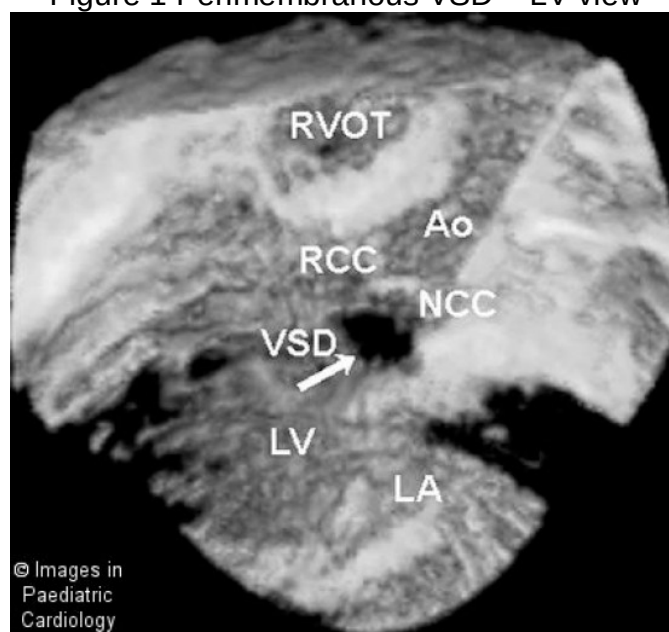
Results

Perimembranous septal defects

The landmarks used in pathological specimens to describe the location of perimembranous VSDs can be used in 3-D reconstructions as well. Figure 1 shows the three-dimensional reconstruction of the interventricular septum in a 3 month old girl seen from the left ventricular aspect. A defect can be seen beneath the aortic valve in the left ventricular outflow tract. The sinus of the right-coronary cusp of the aortic valve is cut in a sagittal axis. The defect is situated beneath the commissure to the non-coronary cusp in the typical membranous region. Since the largest part of the defect is located beneath the right-coronary cusp, the extension of the defect can be described as anterior-superior. The whole circumference of the defect, its shape and all its borders are visualized in figure 1 which is visualized ‘en face’.¹ Anterior-superior to the left ventricular outflow tract, a part of the right ventricular outflow tract is shown. Parts of the left atrium can be seen posteriorly.

A small remnant of tissue separates the roof of the defect and the non-coronary cusp which is typical for perimembranous trabecular defects.¹⁴ A muscular bar is visible at the anterior margin of the VSD. It separates the right coronary cusp from the defect.¹⁴

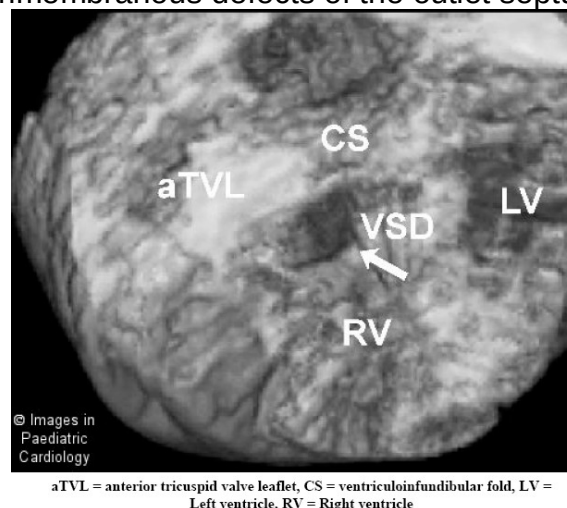
Figure 1 Perimembranous VSD – LV view



Ao = Aorta, LA = Left atrium, LV = Left ventricle, NCC = Non-coronary cusp, RCC = Right-coronary cusp, VSD = Ventricular septal defect

Figure 2 is a right ventricular “en face” view of the same defect. The free wall of the right ventricle is removed so that the right side of the interventricular septum is visible. The defect appears directly beneath the ventriculoinfundibular fold far removed from the pulmonary valve. The white structure to the left of the defect is the anterior leaflet of the tricuspid valve.

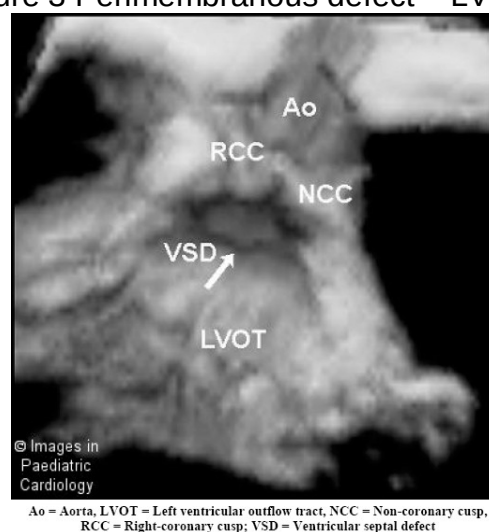
Figure 2 Perimembranous defects of the outlet septum – RV view



All structures used by Soto et al. to describe perimembranous trabecular defects are imaged in figure 2 as well. The muscular outlet septum as the roof of the defect, the septal tricuspid valve leaflet as the posterior rim, the inlet septum as the floor merging anterior to the trabecular septum.

Figure 3 gives a good example for the relation of a typical perimembranous septal defect to the aortic valve. The reconstruction shows the defect “en face” in the left ventricular outflow tract in a 4-month old girl. Compared to Figure 1 it is enlarged. The aortic valve is cut in a sagittal axis. The sinus of the right-coronary cusp and the sinus of the non-coronary cusp with the commissure between them are shown. The defect is covered by remnants of the membranous septum.¹

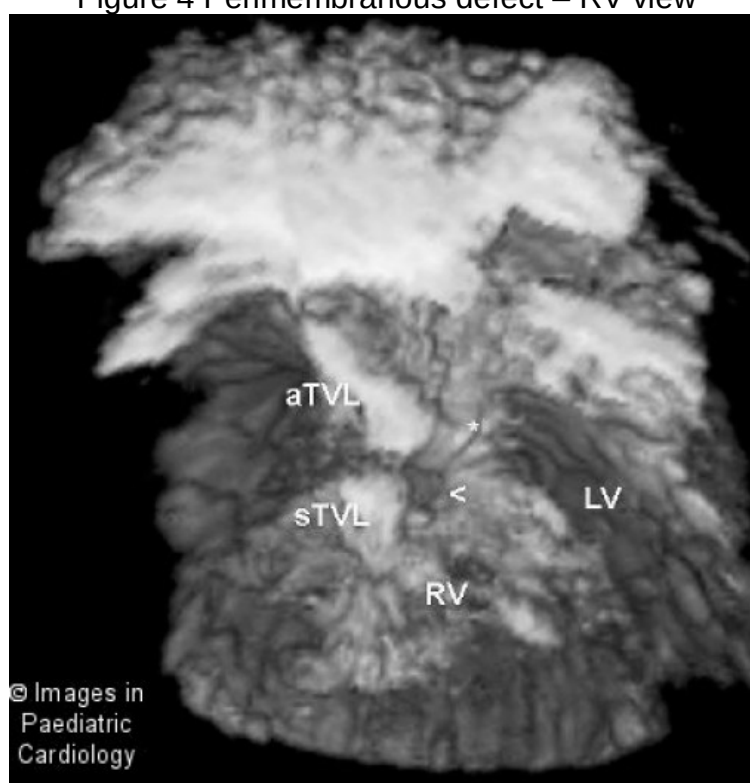
Figure 3 Perimembranous defect – LV view



In contrast to figure 1, the aortic valve forms much of the defect's roof: There is no remnant of tissue between the non-coronary cusp and the defect visible in figure 3. There is no muscle bar between the right coronary cusp and the anterior margin of the defect. Soto et al. uses these criteria to distinguish perimembranous trabecular defects (figure 1) from perimembranous inlet defects (figure 3).¹⁴

The inlet position of the defect in figure 3 becomes obvious in the overview of the right ventricular septal surface as well: Figure 4 shows the septal and anterior leaflets of the tricuspid valve and their commissure. Whereas the defect in figure 2 has a close relation to the anterior tricuspid valve leaflet the defect in figure 4 is located beneath the septal cusp. This implicates the inferior and posterior extension of the defect. Its atrial border is completely formed by the tricuspid valve anulus.¹⁴ The muscular outlet septum is not the superior roof of the defect since a muscle bar is visible which separates the two structures.

Figure 4 Perimembranous defect – RV view



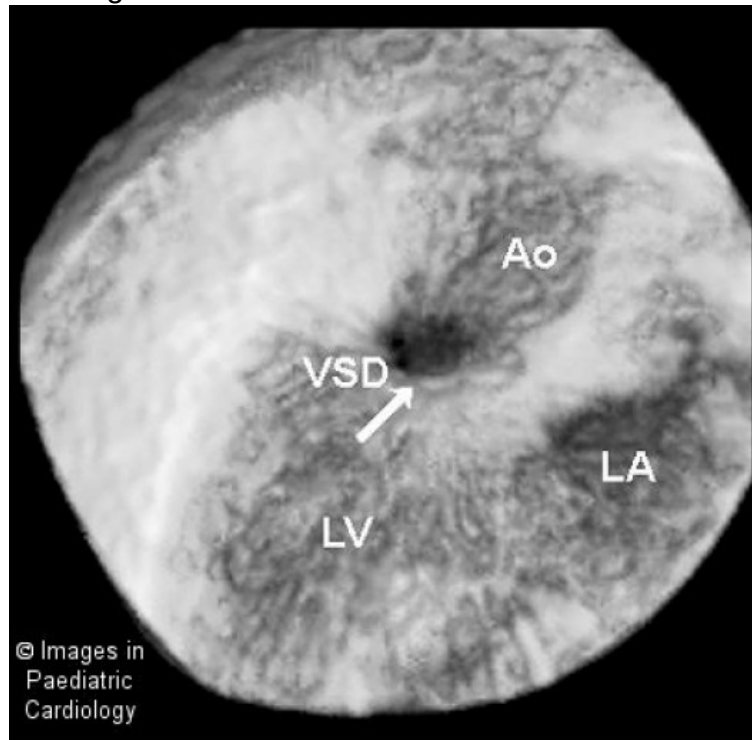
aTVL = Anterior tricuspid valve leaflet, LV = Left ventricle, RV = Right ventricle, sTVL = septal tricuspid valve leaflet, Arrow indicates the ventricular septal defect Asterisk: Muscular outlet septum

Figure 5 shows the reconstruction of a heart with tetralogy of Fallot and pulmonary atresia (patient: female, age 5 months). The muscular outlet septum is malaligned anteriorly and to the right resulting in a large VSD, dextraposition of the aorta and pulmonary hypoplasia. In this patient, the reconstruction of the left ventricular septum and the left atrium shows the VSD from a left ventricular en face view. The ascending aorta is cut in a sagittal axis and overrides the defect.

A right ventricular “en face” view is helpful to analyze the position of the right ventricular septal surface in this patient (Figure 6): A VSD is visible: Its atrial

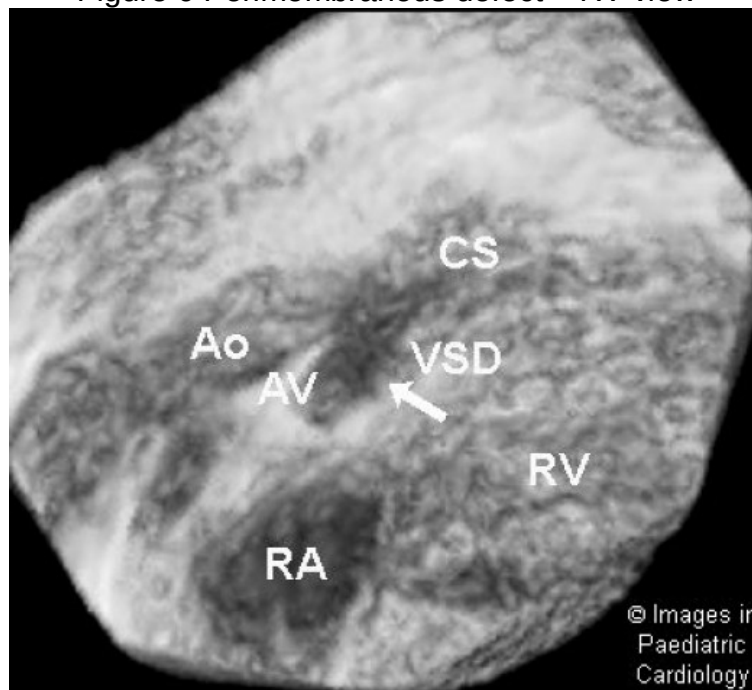
margin is formed by the tricuspid valve which becomes continuous with the right ventricular part of the aortic valve. The muscular outlet septum forms the anterior rim of the defect merging with the trabecular septum at the anterior inferior rim.¹⁴

Figure 5 Perimembranous defect – LV view



Ao = Aorta, LA = Left atrium, LV = Left ventricle, VSD = Ventricular septal defect

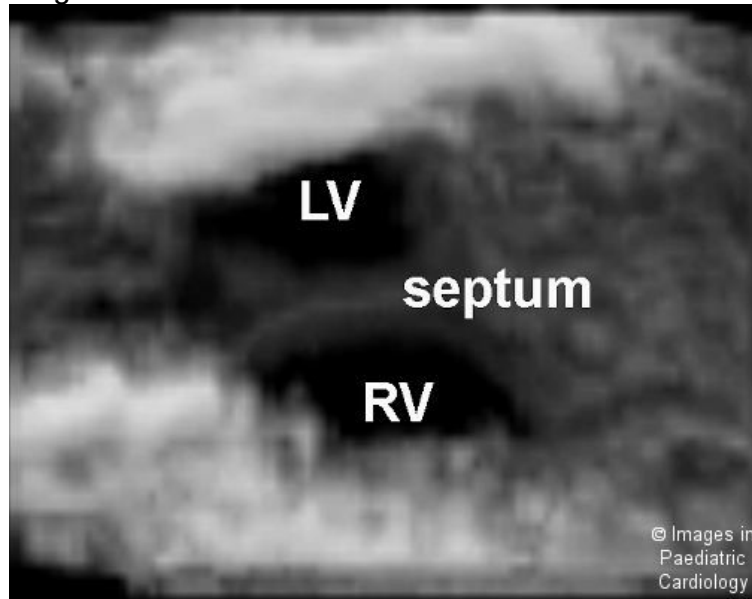
Figure 6 Perimembranous defect – RV view



Ao = Aorta, AV = Aortic valve, CS = malaligned muscular outlet septum, RA = Right atrium, RV = Right ventricle, VSD = Ventricular septal defect

The different grey scale values indicate the rightward malalignment. The aorta, in contrast to normal hearts is visible from the right ventricular “en face” view which proves the dextraposition of the vessel. Compared to Figures 2 and 4 the right ventricular myocardium is hypertrophic. In a view from the aorta towards the ventricles looking on the crest of the interventricular septum the degree of overriding of the aorta can be shown. In Figure 7 the crest of the septum divides the crosssection of the aorta into two halves. The degree of overriding in this patient is 50%.

Figure 7 Perimembranous defect – view from aorta



LV = Left ventricle, RV = Right ventricle, Septum = Crest of the interventricular septum

Figure 8 and 9 show the reconstruction of a heart with repaired tetralogy of Fallot with pulmonary atresia (patient: male, age 6 month) The overriding aorta was completely connected to the left ventricle through the VSD by a patch. Blood supply to the lungs was provided by a right ventricle to pulmonary artery conduit.

Figure 8 Perimembranous defect – LV view

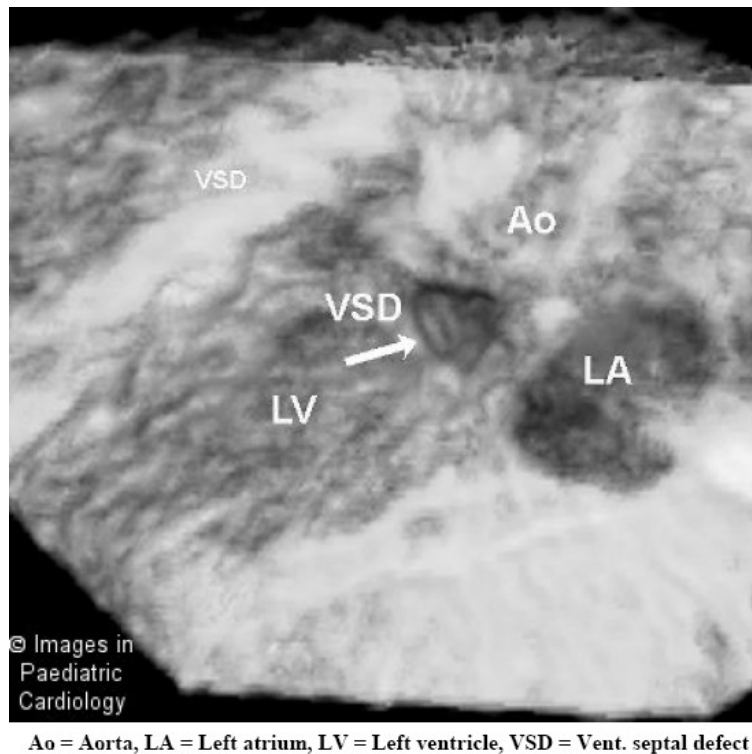
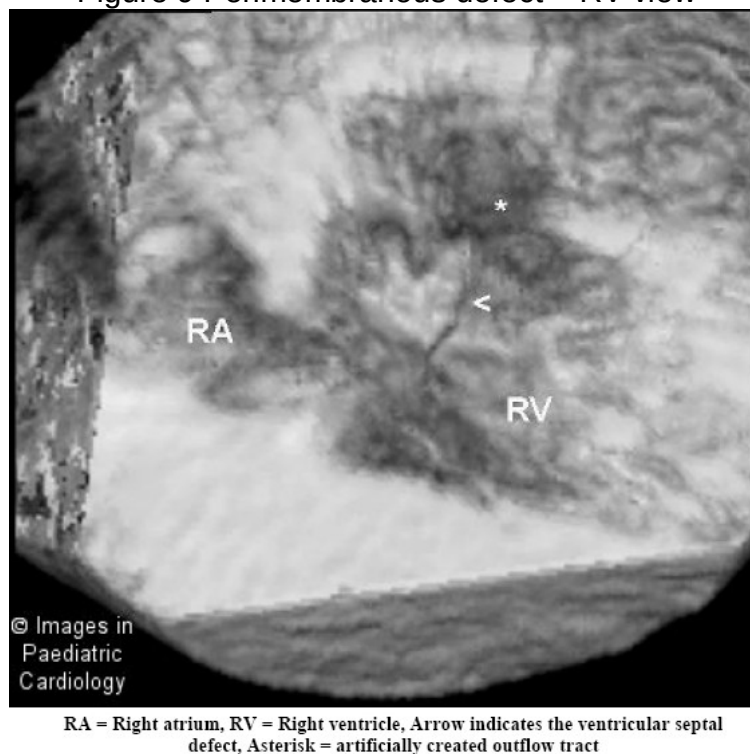


Figure 9 Perimembranous defect – RV view

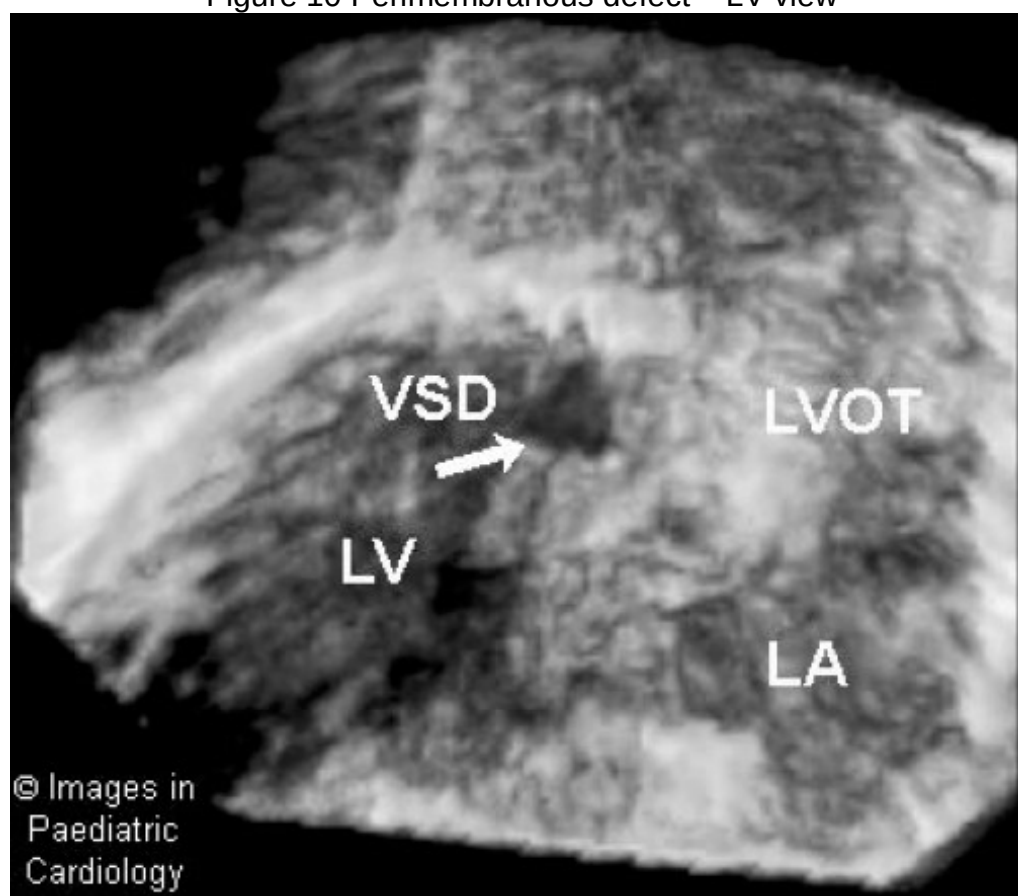


The VSD is viewed en face in figure 8. Since the patch was sutured from the right ventricular side, the complete left ventricular borders of the VSD with the overriding aorta are visible. The different grey scale values of the patch simulate the bulge of the patch into the right ventricle due to the dextraposition of the aorta. As additional structures, the left atrium and the typical bulled shaped left ventricular cavity are visualized in this image.

The 3-D effects in figure 9 show the bulge of the VSD-patch in the right ventricle. It is sutured at the right ventricular part of the aortic valve annulus to connect the aorta solely to the left ventricle. At the same position the aortic valve is visible in figure 6. At the position of the malaligned outlet septum an artificially created right ventricular outflow is visible in figure 9.

A VSD associated with left and posterior malalignment of the muscular outlet septum appears in figure 10 (patient: male, age 5 days). The VSD is shown in the standard left ventricular en face view including ventricular septum, left atrium and left ventricular outflow tract. It has a triangular shape. The left ventricular outflow tract is heavily obstructed shown by the high grey scale values between the VSD and the left atrium. This obstruction in the left ventricular outflow tract is due to the malalignment of the outlet septum to the left and posteriorly. The outlet septum bulges into the left ventricular outflow tract.

Figure 10 Perimembranous defect – LV view



LA = Left atrium, LV = left ventricle, LVOT = Left ventricular outflow tract,
VSD = Ventricular septal defect

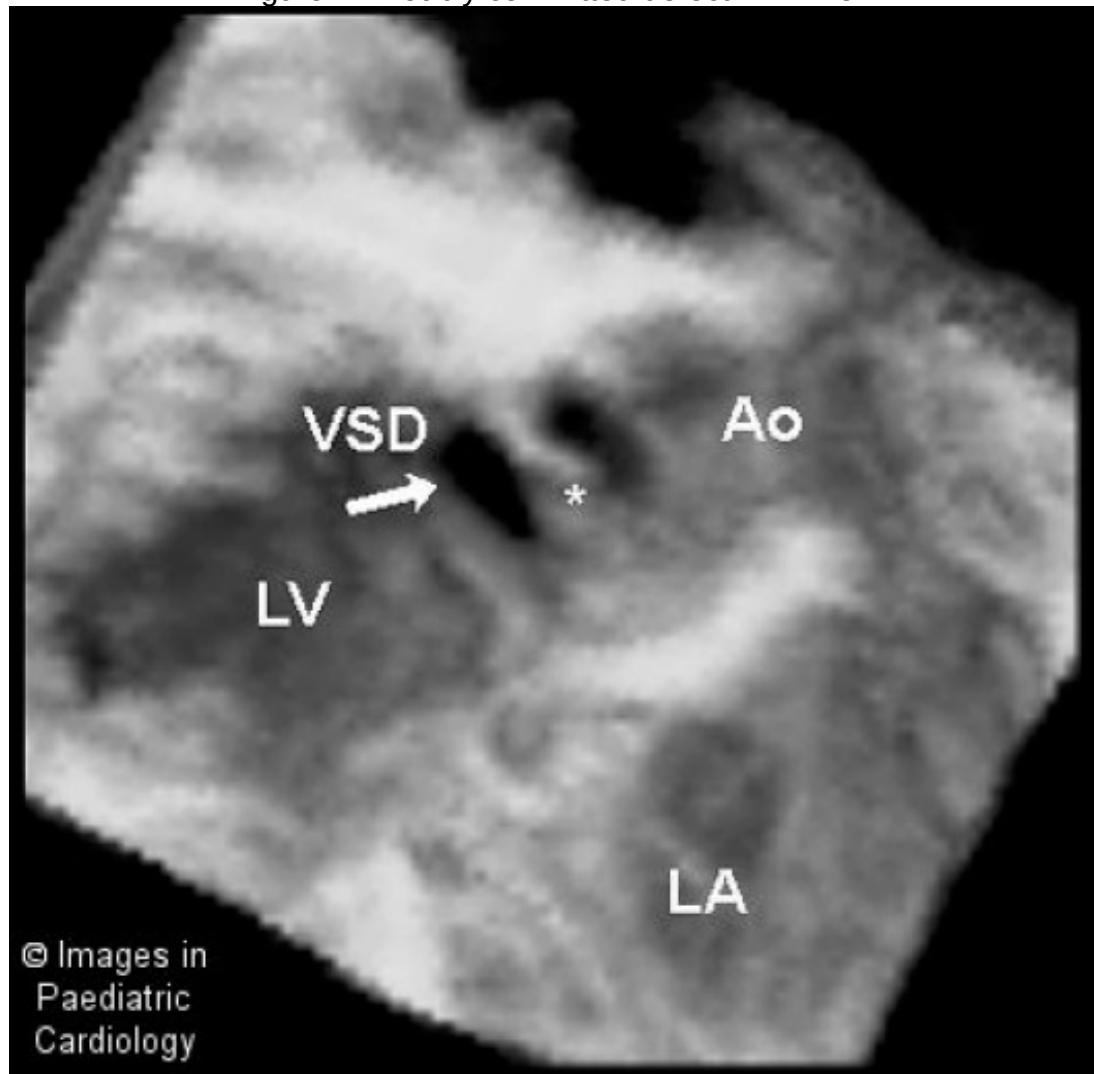
Doubly committed or juxtaarterial defects

Figure 11 shows a defect situated in the left ventricular outflow tract (patient male, age 5 month). The reconstruction shows the left ventricular septal surface, the ascending aorta and the left atrium. The aortic valve leaflets are cut in a sagittal axis and are projected directly over the defect indicating the very close relation between the valve and the defect. Compared to the

perimembranous septal defect in figure 1 the defect has a more anterior position- it has no fibrous continuity to the mitral valve.

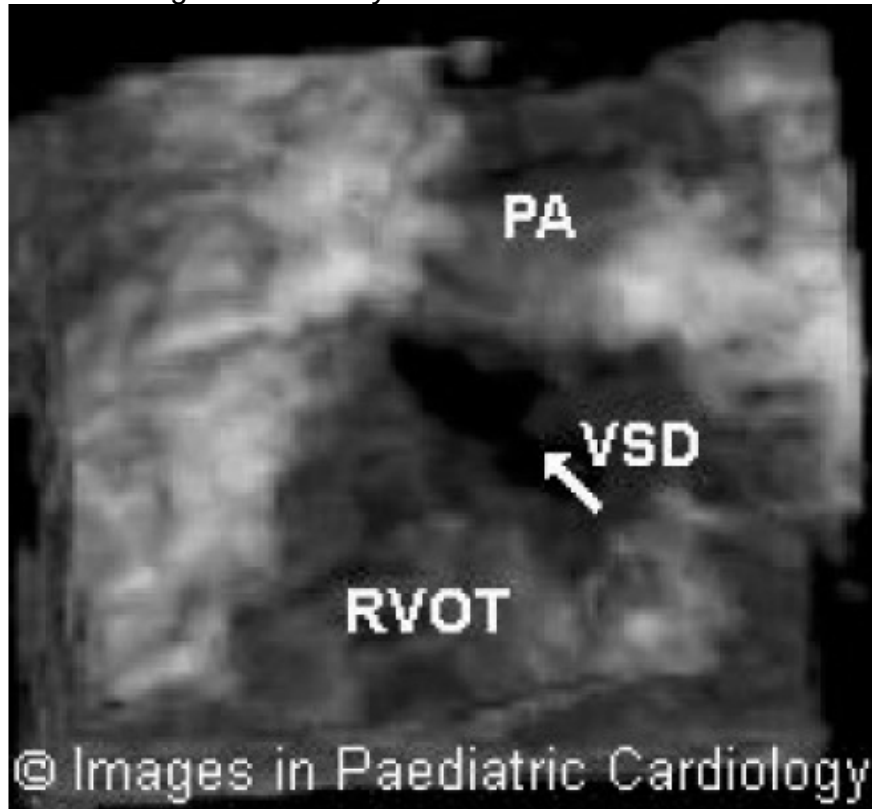
Figure 13 shows the relation between the VSD and the pulmonary valve. The reconstruction is based on a plane cutting the heart in a very anterior position so that only the right ventricular outlet and the pulmonary artery are visible. The defect appears directly beneath the pulmonary valve orifice. The defect imaged in figures 11 and 12 has a very close relation to both the aortic and the pulmonary valves, it is 'doubly committed'.

Figure 11 Doubly committed defect – LV view



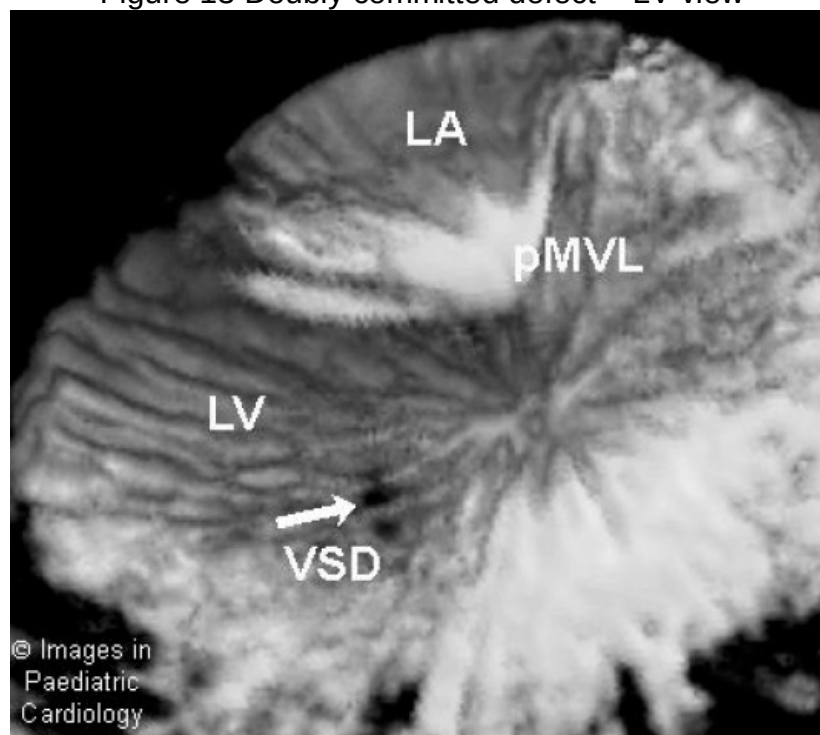
Ao = Aorta, LA = Left atrium, LV = Left ventricle, VSD = Ventricular septal defect, Asterisk = Aortic valve

Figure 12 Doubly committed defect – RV view



PA = Pulmonary artery, RVOT = Right ventricular outflow tract, VSD = Ventricular septal defect

Figure 13 Doubly committed defect – LV view

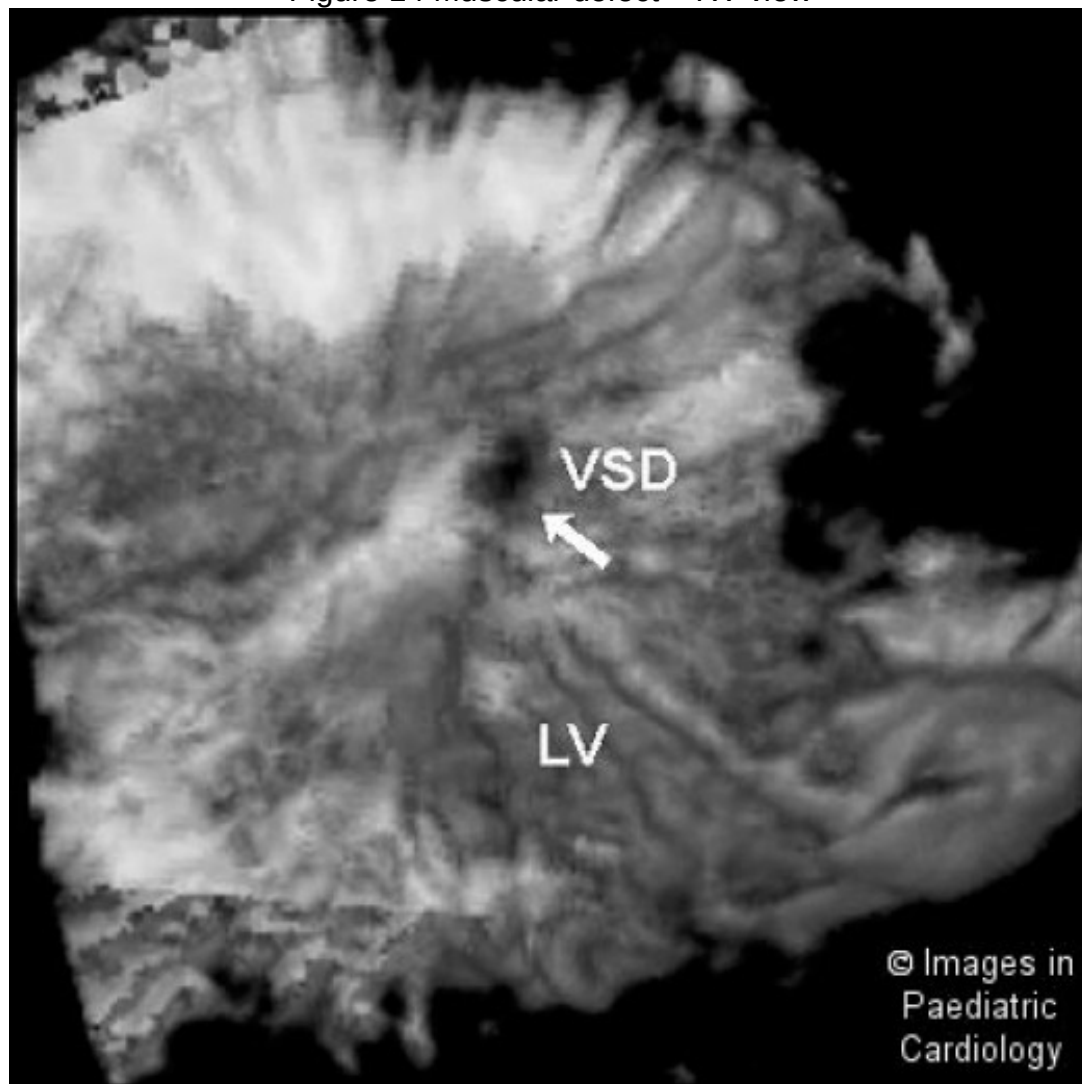


LA = Left atrium, LV = Left ventricle, pMVL = Posterior Mitral valve leaflet, VSD = Ventricular septal defect

Muscular defects

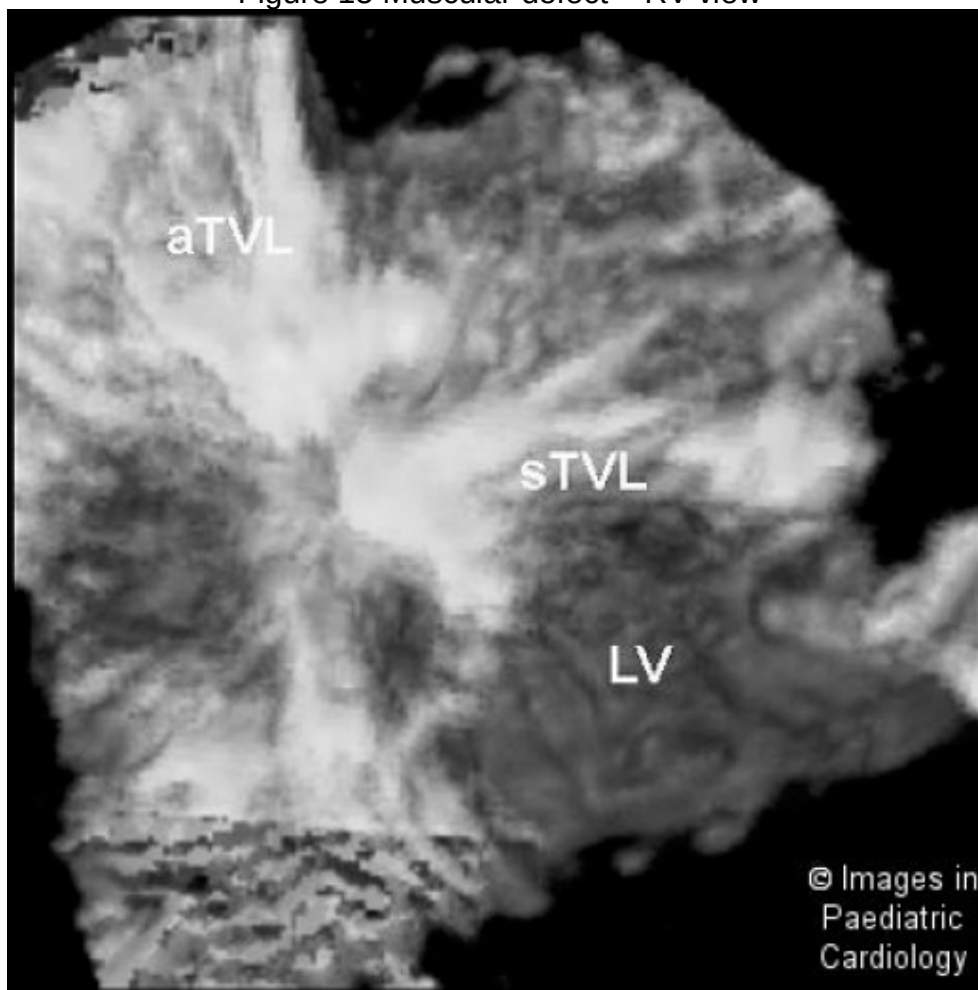
Muscular ventricular defects can affect all components of the muscular part of the interventricular septum.^{14,19} The reconstruction in figure 13 is based on a transesophageal echocardiographic acquisition (patient: male, age 6 years). Left atrium, muscular interventricular septum of the left ventricle and the posterior mitral valve leaflet are visualized. All borders of the defect are muscular, it is distant from either the aortic valve (not visible) and the mitral valve. The defect has an oval shape and is bridged by a single trabeculation. The VSD from the right ventricular aspect is shown in figure 14. Parts of the septal leaflet of the tricuspid valve are shown close to the defect. The septal leaflet hides the VSD in systole (figure 15).

Figure 14 Muscular defect – RV view



LV = Left ventricle, VSD = Ventricular septal defect

Figure 15 Muscular defect – RV view



aTVL = anterior tricuspid valve leaflet, LV = Left ventricle, sTVL = septal tricuspid valve leaflet

Discussion

The study showed that the visualization of ventricular septal defects by transthoracic three-dimensional imaging is possible from either the left and the right ventricular aspect in detail. The standard views that were used are very similar to the impressions the viewer gets when looking on pathological specimens. Even detailed components of the interventricular septum used to distinguish the different extension direction are simulated in the images.

One of the advantages for the clinician of this views is the visualization of the whole circumference of the defect. For example, the right ventricular circumference is important for surgery planning. As interventional closure of some VSD types is becoming a therapeutical option, knowledge of all VSD-borders and relations to the valves is important for the selection of patients and devices.

The visualization of the whole circumference of the defect prevents the viewer from underestimating the size of a ventricular septal defects as can happen when in 2-D cutplanes limited by the acoustic window of the thorax, only the smallest diameter is displayed.

The limitations of transthoracic three-dimensional echocardiography are the low resolutions of the transducers. It is difficult to image the dynamic morphology of cardiac valves by the transthoracic approach. However the leaflets were imaged sufficiently enough to use them as landmarks for VSD-classification. The time needed for the acquisition and reconstruction phase is still very long for clinical use. But these problems could be solved in future by more powerful computers and software. Moreover, ventricular volumetry is an interesting and promising new aspect of three-dimensional echocardiography in the future.²⁰

Acknowledgments

This article contains material from the doctoral thesis of Martin Hoch at the Medical faculty, University of Munich, in progress.

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