CHAPTER 8

3D Live Echocardiography with Matrix Probes

Fabrizio Taddei*, Laura Franceschetti, Giuliano Farina and Gianpaolo Grisolia

Departement of Obstetrics and Gynecology Azienda Ospedaliera "C.Poma" - Mantova - Italy

Abstract: Real-time four-dimensional (4D) echocardiography is the examination of the fetal heart in the three spatial dimensions plus motion.The matrix probe's technology allows direct volume scanning by electronically interrogation of a region of interest and acquisition of a pyramidal volume of ultrasonographic data. This technology has the potential to minimize motion artifacts associated with 3D/4D ultrasonography with a satisfactory spatial resolution.The system allows beam steering and focusing in the 3D volume dataset, making it possible to simultaneously examine two different planes of section of the same structure, in real-time, without resolution loss (*Live xPlane imaging*). The system achieves a pyramidal volume of data, creating a new real-time 3D moving imaging mode called *Live 3D Volume Imaging*, without the use of software-reconstructed section planes. Combination with Doppler techniques creates a new imaging option: *Full Volume 3D imaging.* The technique of *Thick Slice Live Volume Imaging* allows high resolution and contrast-enhanced images The strength of this technology is the easiness in obtaining real-time images of the heart, the high volumetric frame rate and the opportunity to obtain scanning planes with the same axial and lateral resolution. These features improve the overall understanding of anatomical structure arrangement. Matrix technology could be very useful in congenital cardiac clinical applications: real-time 3D echocardiography shows instantaneous rendered images of the beating fetal heart with complex pathologies in one complete heart cycle, and application of this modality allows its spatial location in the heart and its temporal location in the cardiac cycle.

Key Words: 3D Ultrasound, Fetal Echocardiography, Live Echocardiography, Matrix Probes.

INTRODUCTION

Real-time four-dimensional (4D) echocardiography is the examination of the fetal heart in the three spatial dimensions plus motion. In order to produce real-time 4D ultrasonographic images, volume datasets need to be acquired and displayed faster than the capacity of the human eye to retain a visual impression, which is estimated as one tenth to one thirtieth of a second. However, because of the difficulty in obtaining a fetal electrocardiogram to gate the heart, real time fetal echocardiography has been limited [1-14]. Different 3D echocardiographic methods have been employed in fetal echocardiography, including multiplanar, surface rendering, power and color Doppler methods or spatiotemporal image correlation. These techniques are limited by the use of off-line system, increasing reconstruction-time. With the advent of a new matrix array probe that allows real-time 4D data acquisition and image rendering, many of the above limitations could be circumvented.

The matrix probe's technology is capable of direct volume scanning. Direct volume scanning is a term proposed by Deng in 2003, to describe 3D/4D systems capable of scanning a volume of interest (1) in its totality, (2) within a time in which movement is negligible (in an instant), and (3) with sufficient spatial resolution. Since in the case of mechanical transducers the totality of the volume of interest is not scanned in an instant, the term "indirect volume scanning" applies to 3D/4D ultrasound systems that employ this technology. This has considerable implications for the examination of the moving fetus and, specially, the fetal heart, since motion artifacts can easily interfere with the quality of the images obtained if the structure of interest moves faster than the speed at which the volume dataset is being acquired. In contrast, matrix array transducers allow direct volume scanning by electronically interrogation of a region of interest and acquisition of a pyramidal volume of ultrasonographic data. This technology has the potential to minimize motion artifacts associated with 3D/4D ultrasonography and, giving a satisfactory spatial resolution, has become an attractive alternative to examine fetal heart.

THE TECHNOLOGY

xMATRIX transducers are made by a double array of piezoelectrics elements that creates a matrix area of pulsing. This transducer's technology is based on a special laser used to cut the piezoelectric crystal into many equal-sized square elements, forming an xMATRIX element (Fig. **1**).

***Address correspondence to Fabrizio Taddei:** Dept. Obstet. Gynecol. Azienda Ospedaliera "C.Poma" -Mantova-Italy; E-mail: taddei.fabrizio@tiscali.it

Giuseppe Rizzo and Domenico Arduini (Eds)

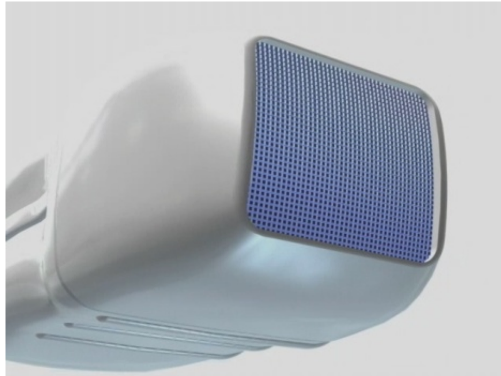

Figure 1: Surface of xMatrix probe.

These elements are directly connected with the beamformer in one way and with the surface of the transducer on the other hand. The beamformer permits to electronically drive these elements to fire the ultrasound beam in any direction in the space. The xMATRIX array transducer produces pyramidal volumetric ultrasound beam, composed by the beams emitted by each single element (Fig. **2**).

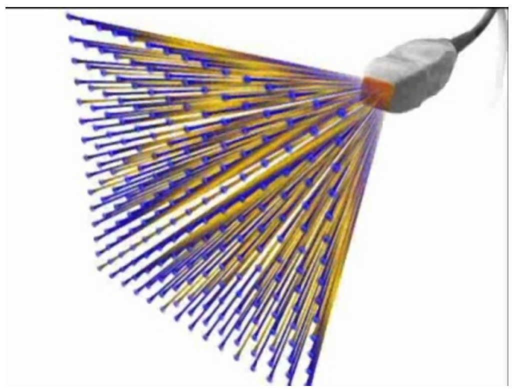

Figure 2: Pyramidal ultrasound beam electronically produced by xMatrix transducer.

This pulsing technique permits to create new imaging modes, other than standard 2D ultrasound image obtained by arranging the pulsing elements in a linear way.

The system allows beam steering and focusing in the 3D volume dataset, making it possible to simultaneously examine two different planes of section of the same structure, in real-time, without resolution loss (Live xPlane imaging). In this modality, images are shown on a screen divided into two parts: the original plane is on the left-hand side, while the right-hand side shows one of the different scanning planes that the sonographer can visualize using a different orientation of the ultrasound beam in the space.

This second plane can be perpendicular to the main scanning plane, but it can also be parallel or oblique. In this way, starting, for example, from an axial view of the fetal thorax showing the four chambers, and orientating the second plane (simultaneously shown on the right-hand side of the screen) in different directions, the main structures of the fetal heart can be visualized

The strength of the xMATRIX array approach for examination of fetal structures lies in the possibility of directly acquiring a pyramidal volume of ultrasonographic data, creating a new imaging mode called Live 3D Volume Imaging. By appropriately defining the ultrasound beam for each single element, it is possible to build up a pyramidal volumetric ultrasound beam, with an opening angle between 6 and 110 degrees). This volumetric ultrasound beam allows a real-time three-dimensional moving imaging (live volume imaging) without the use of software-reconstructed section planes. In other words, the volume is not created from single planes, but from a number of planes simultaneously close one to each other. This makes the voxels to have the same resolution along all the three directions of the beam (isovoxel resolution). Two orthogonal reference planes are used to localize the structures within the volume. This kind of imaging can give us the classic multiplanar view with visualization of the three orthogonal planes in the same time, or the rendering view. Rendering is subjected to all the parameters that allow this algorithm to selectively display surface of the structures, hyperechoic or hypoechoic structures. These parameters should be set-up every time in order to create a good visualization of the rendered image.

By acquiring a high-resolution volume image even combined with Doppler techniques (color or power) a new imaging option is obtained from the xMATRIX technology: Full Volume 3D imaging. This acquisition mode gives both functional and structural data for a complete analysis (Fig. **3**).

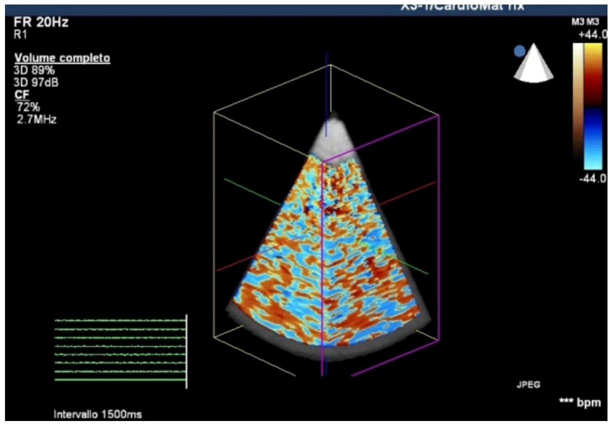

Figure 3: Full Volume 3D Imaging combined with Color-Doppler. This technique gives both structural and functional data for exaustive analysis of fetal heart.

A brand new imaging modality is the Thick Slice Live Volume Imaging: the beamformer sets the acquisition angle into a low value (6-20 degrees) and increases the line density to the maximum. In this way, the image produced by thousand elements is condensed into a "thick" slice and visualized using the rendering modes. This kind of technique allows high resolution and contrast-enhanced images (Fig. **4**).

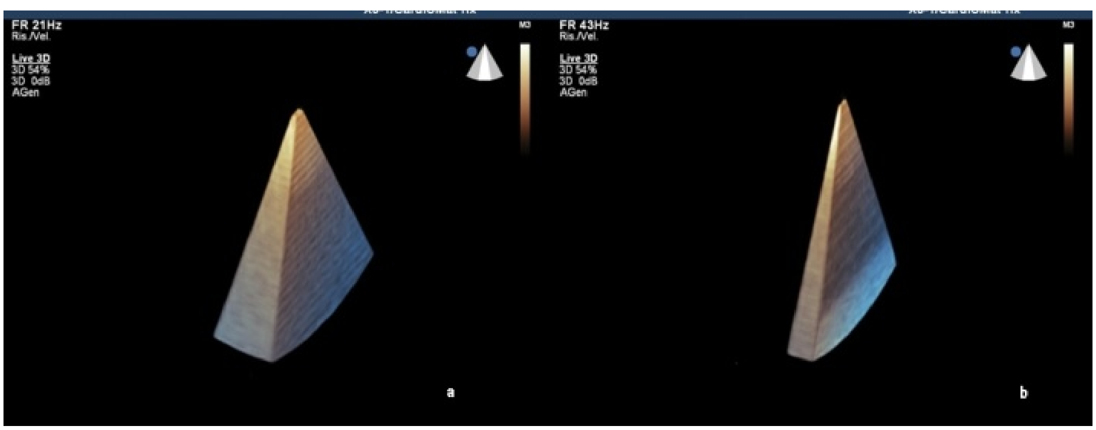

Figure 4: Comparison between Live 3D Imaging (a) and Thick Slice Imaging (b). Thick slice imaging has lower acquisition angle and more line density, allowing higher frame rates and better resolution.

THE CLINICAL APPLICATION.

Two-dimensional (2D) echocardiography is an accurate and reliable technique used to evaluate normal fetal heart and congenital heart diseases. Since 2D echocardiography approaches the heart from multiple orthogonal planes, it requires the user to form a mental anatomic reconstruction to comprehend the relationship between the cardiac structural defects and the surrounding rims.

Three-dimensional echocardiography offers new insights into the anatomy of the heart valves and the septa. A complete evaluation of fetal heart in real time (three spatial dimensions plus temporal dimension) is offered by matrix arrays,that have been extensively used in clinical practice for the examination of adult and pediatric heart and, more recently, for fetal echocardiography.

Assessment of Normal Fetal Heart Anatomy

In the Live 3D Volume imaging, the system acquires the volume dataset using a pyramidal imaging volume. Two orthogonal reference plans are used to localize cardiac structure in the volume (Fig. **5**).

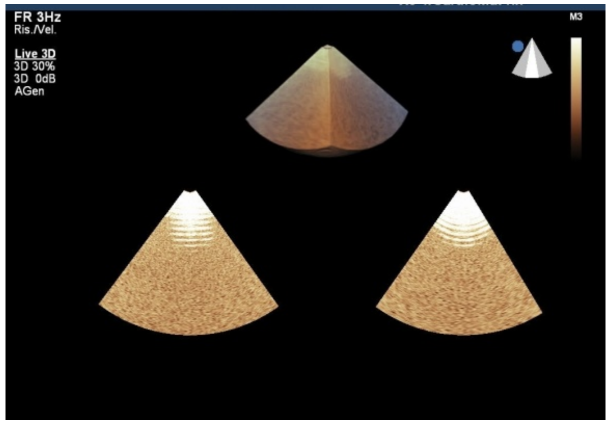

Figure 5: Live 3D Volume Imaging: in the lower part of the image the two reference planes used to localize the region of interest displayed by a surface rendering mode in the upper part of the image.

The software is used for navigation and cropping, and for calculation and visualization of 3D structures. For example, in fetal cardiac application navigation by cropping the volume allows surface rendered views of the intracardiac structures (en face views of the valves (Fig. **6**, Video 1) and entire structure of the septa (Fig. **7**).

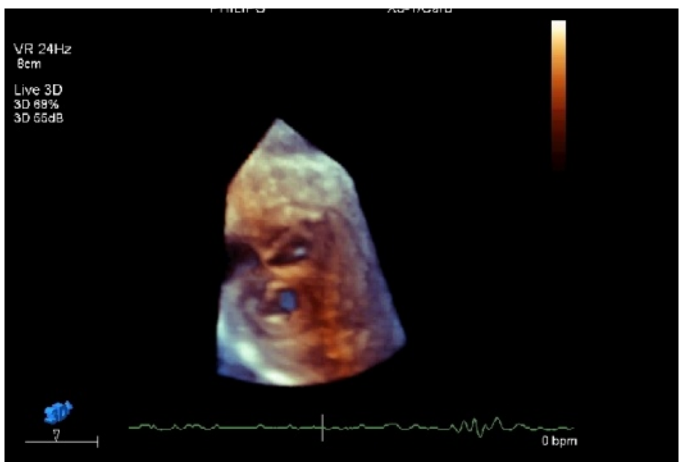

Figure 6: En-face surface rendering view of the atrio-ventricular valves.

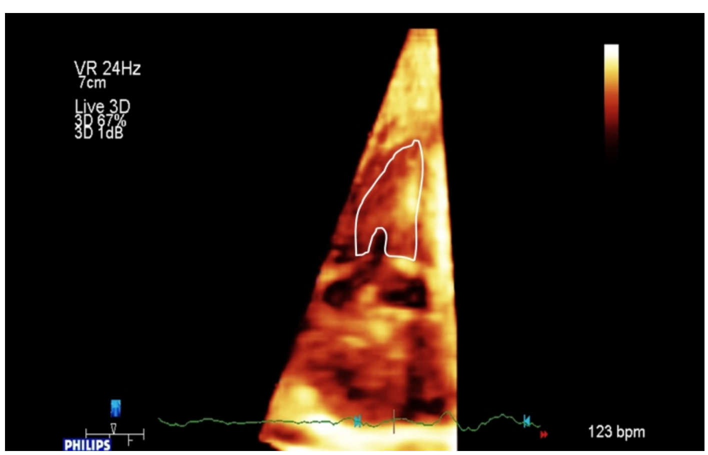

Figure 7: Surface rendering of the entire inter-ventricular septum and the left ventricular outflow tract.

Moreover, by using a systematic method of manipulation (cropping and rotation) of the three-dimensional pyramid it is possible to visualize, from a single volume dataset, the ascending aorta and the pulmonary trunk (Fig. **8**).

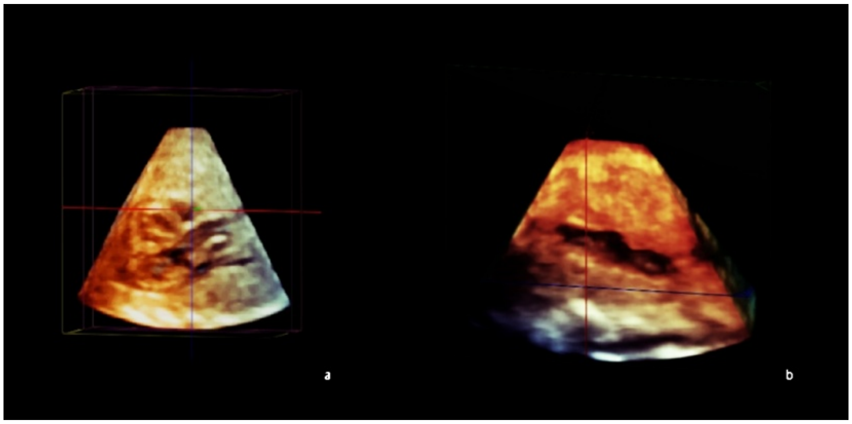

Figure 8: Imaging of renderd ascending aorta (a) and pulmonary trunk (b) obtained by cropping and rotating a 3D Full Volume Dataset.

Using this system, it's possible to perform real time 4D observations of the fetal heart, and to obtain instantaneous rendered 3D images of the beating fetal heart. Rendered displays of volume data allow surgeon's eye views of important and unique fetal cardiac anatomic structures, not easily visualized or understood on conventional two-dimensional (2D) imaging (Video 2).

X-plane imaging allows the scanning of two image planes of the fetal heart at different angles. Situs visceralis, four-chambers, great vessels, three vessels and arches views are obtained simultaneously without moving the transducer (Fig. **9**).

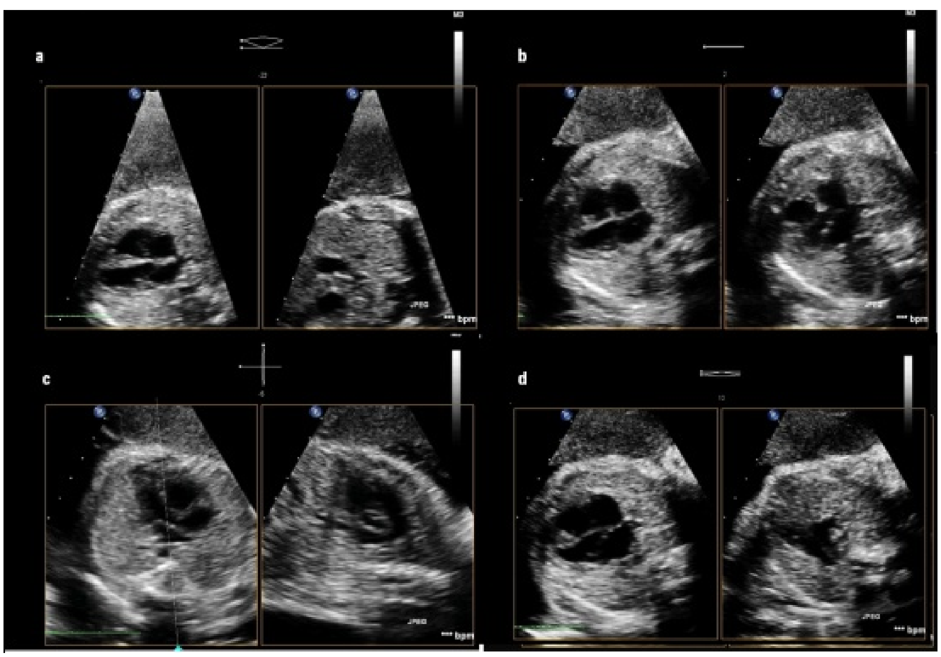

Figure 9: X-planes imaging displaying standard views of fetal heart examination: each image shows 4 chamber view simultaneously with stomach (a), aorta (b), pulmonary trunk (c) and three vessel view (d).

Using rotation, lateral and vertical tilts, all normal cardiac structures are identified from a unique reference image plane: atrial cavity and septum, atrioventricular valves, ventricular cavity and septum, left and right ventricular outflow tracts, ascending aorta and main pulmonary artery and its bifurcation.

In order to increase temporal resolution, thick slice volume imaging can be used (Fig. **10**, Video 3).

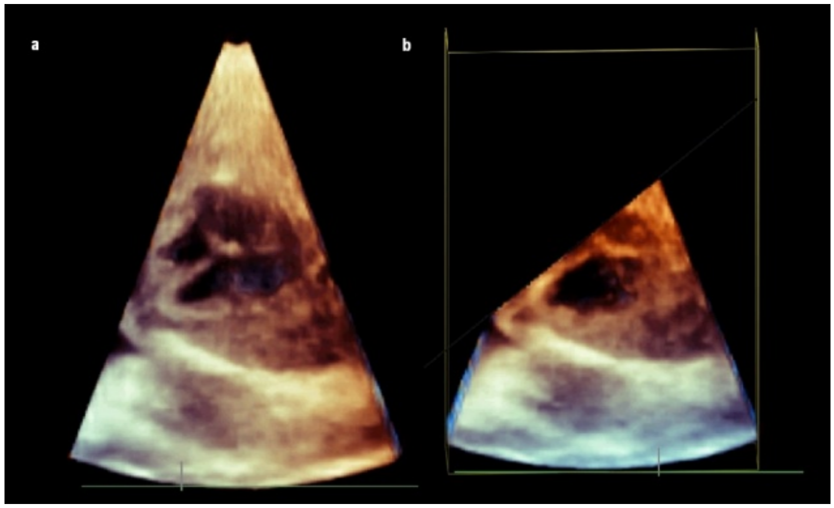

Figure 10: Thick Slice imaging showing the cropping technique applied for inter-ventricular septum visualization.

Diagnosis of Congenital Heart Defects

Real time echocardiography can enable improved understanding of congenital heart disease anatomy.

Several reports have been published describing the feasibility and clinical utility of this modality in prenatal diagnosis of congenital heart defects.

In 1999, Sklansky *et al* reported preliminary observations on real-time examination of the fetal heart in 10 fetuses between 21 and 36 weeks of gestation, four of which had congenital heart disease diagnosed by 2D ultrasonography. Fair to good image quality was achieved in 11 of 12 examinations and, in 70% of the cases basic cardiac views could be adequately visualized. In 2000, Scharf *et al*. obtained images of at least satisfactory quality in 13 fetuses examined with a 2D matrix array transducer between 20 and 24 weeks of gestation. Deng et al. described optimal imaging windows to examine the fetal heart using this technology. Maulik *et al.* [8] reported that a comprehensive assessment of cardiac valves, atrial and ventricular chambers, and outflow tracts was possible in a group of 12 fetuses examined between 16 and 37 weeks of gestation by either real-time direct 4D ultrasonography or full volume 4D ultrasonography acquisitions triggered by an external ECG simulator device. Sklansky *et al* [11] used full volume 3D acquisitions to image fetal cardiac structures, and were able to successfully visualize a wide range of cardiac anomalies (hypoplastic left heart syndrome, atrioventricular canal, double inlet single ventricle, double outlet right ventricle and transposition of the great arteries) but not small ventricular septal defects. More recently, Acar *et al.* [1-2] reported successful visualization of fetal cardiac structures in 56 of 60 fetuses examined with either real-time direct 4D ultrasonography or live xPlane imaging.

This novel imaging technology could be very useful in a wide variety of congenital cardiac clinical applications. In fact, real-time 3D fetal echocardiography shows instantaneous rendered images of the beating fetal heart with complex pathologies in one complete heart cycle, and application of this modality allows its spatial location in the heart and its temporal location in the cardiac cycle. These observations can be made from any direction. It's also possible to navigate through the volume of data containing images of the heart in order to find the abnormal structures of interest.

The en face imaging of the septa allow for views of atrial and ventricular septal defects and their relation with both ventricles and with adjacent structures. The size of a defect and its position are crucial parameters when counceling about associated chromosomal abnormalities and evaluating postnatal follow up, whether to pursue and planning transcatheter closure treatment.

Real time imaging also enhances the comprehension of valve anatomy. Precise description of the valve anatomy can be difficult from 2D planes alone, and the surface of the leaflets and commissures are better rendered by live imaging. Additionally, congenital valve diseases are precisely revealed by 3D views, which depict the mechanism of regurgitation or obstruction. Thus, real time 3DE offers improves insight for diagnosing valve defects and predicting the success of surgical valve repair.

The real-time fetal echocardiography provides excellent depiction of pathologies such as ventricular outflow tracts in the case of double-outlet right ventricle (DORV) (Fig. **11**, Video 4), transposition of the great arteries (TGA) (Fig. **12**, Video 5) or tetralogy of Fallot (TOF) (Video 6). In these cases real time 4D echocardiography may assist in the evaluation of fetal cardiac anatomy and hemodynamics, and offer potential advantages relative to conventional 2D fetal echocardiography.

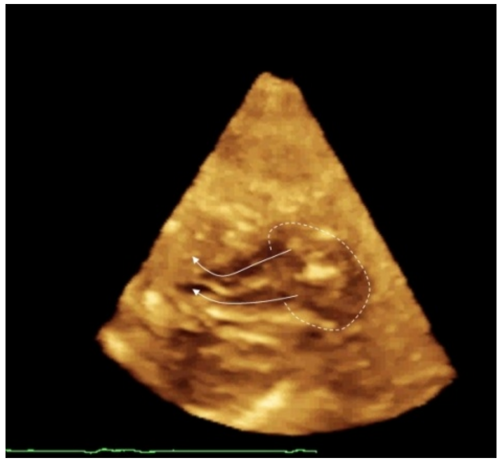

Figure 11: Surface rendering view from a a Live 3D image of outflow tracts (arrows) in double outlet right ventricle (DORV).

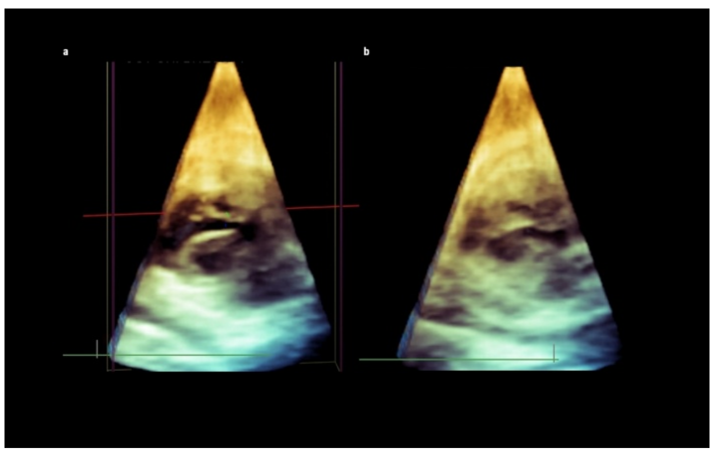

Figure 12: Visualization of the discordant origin of the outflow tracts from each ventricle in TGA, using planes obtained by a Live Thick Slice Live Volume dataset

In a case of congenital absence of ductus venosus [14] it has been described the usefulness of biplane and real time imaging: these imaging modalities depicted the anatomy of the systemic venous return, displaying the abnormal connection of the umbilical vein to the right atrium and the features of the systemic venous drainage. (Video 7, Video 8).

There have been a few reports on real-time 3D color Doppler echocardiographic imaging of the fetal heart in the normal fetus and congenital heart disease during pregnancy. This technology allows for the depiction of the shape, direction and propagation of color flow jets in three-dimensions for analysis of ventricular septal defects, valvar and subvalvar stenosis, regurgitant jets and so forth. In certain cases real-time 3D color Doppler echocardiography also provides additional useful information to conventional 2D and 2D color flow Doppler for the correct prenatal diagnosis.

CONCLUSIONS

Several studies have shown the feasibility of examining fetal structures, including the fetal heart, by 2D matrix array technology. However, substantial obstacles still remain and 2D matrix array transducers are not yet widely accepted in clinical practice.

One of the current limitations for fetal heart volumetric imaging includes lower image resolution, due to lower transducer frequencies in the 2D matrix array probe (1 to 7 MHz) when compared to commercially available mechanical volumetric transducers. Lower image resolution may result in distortion of fetal heart anatomy when compared to images obtained by the latest generation of mechanical volumetric transducers.

Another limitation is the low lateral resolution, in particular at deepest planes.

Practical clinical applications will depend on several technical factors, including the development of satisfactory image resolution and reliable maintenance of fast volume data acquisition rates.

The strength of this technology is the easiness in obtaining real-time images of the heart, the high volumetric frame rate and the opportunity to obtain scanning planes with the same axial and lateral resolution. These features improve the overall understanding of anatomical structure arrangement. Moreover, the cropping software gives a "cutting" plane that can be easily moved and placed in the volume, even on live imaging, in order to visualize planes not obtainable with conventional 2D, and with a better resolution than the classic 3D/4D imaging.

The present and future application of real-time 4D fetal echocardiography to the prenatal diagnosis of fetuses with congenital heart disease might be promising. However, this is not to imply that real-time 4D fetal echocardiography will replace conventional 2D fetal echocardiography. This novel technique may assist in the prenatal diagnosis of fetal cardiac anomalies, and offer the potential advantages relative to conventional 2D fetal echocardiography and color Doppler flow mapping. Moreover, the correct prenatal diagnosis of congenital heart disease may improve the prognosis of the infant after birth.

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