CHAPTER 9

Automated Echocardiography

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Abstract: The recent introduction of 3D/4D ultrasonography to clinical practice presents an important milestone in imaging technology. In this chapter, we will present the basic principles of 3D automated sonography as it relates to the examination of the fetal heart. This approach holds great promise for simplifying the fetal cardiac examination that may translate to increased prenatal detection of congenital heart disease.

Key Words: 3D Sonography, Fetal Echocardiography, Automated Multiplanar Imaging, Diagnostic Cardiac Planes.

THE MAIN CONCEPT OF 3D-AUTOMATED FETAL ECHOCARDIOGRAPHY

Mounting evidence suggests that the performance of obstetric sonography with regard to the detection of fetal abnormalities has been suboptimal [1-4]. A study addressing the value of ultrasound accreditation noted that more than 40% of practices seeking accreditation by the American Institute of Ultrasound in Medicine were operating below the minimum established professional standards for the performance of obstetric sonography [5]. Several studies have documented that the efficacy of obstetric sonography is dependent on the expertise of the operator, and a significant difference has been reported between tertiary and nontertiary centers in the detection of fetal abnormalities [1-4]. Probably because of the difficulty inherent in the anatomical evaluation of the fetal heart, population-based studies have confirmed low detection rates, with more than 50% of congenital heart abnormalities remaining undetected on routine second-trimester fetal ultrasound examination [6-8]. Enhancing the detection of fetal congenital heart abnormalities, especially ductal-dependent lesions, should result in reduced morbidity and mortality of affected neonates [9-11].

One of the reasons for the suboptimal performance of obstetric sonography is related to the inherent limitations of ultrasound technology, which is operator-dependent and therefore lacking in consistency, standardization and reproducibility, especially when compared with other imaging modalities, such as computed tomography and magnetic resonance imaging. This limitation of ultrasound technology is compounded by a constantly moving target, the fetus, which adds technical difficulty to the examination.

The recent introduction of 3-dimensional (3D) ultrasonography to clinical practice provided an important advance in imaging technology. With 3D ultrasonography, an infinite number of 2D planes of a target volume are acquired. The volume acquired by 3D ultrasonography can be displayed on a monitor in 3 orthogonal planes, representing the sagittal, transverse, and coronal planes of a representative 2D plane within this volume. Such a display of 3 orthogonal planes from a 3D volume acquisition is termed a *multiplanar display*. The multiplanar display of 3D ultrasonographic volumes enables an operator to manipulate the acquired target volume to create and display reconstructed planes within this volume. Despite these recent advances in ultrasonographic imaging, the acquisition, display, and manipulation of 3D volumes is a technique that requires a substantial learning curve. Even for well-trained personnel, 3D volume manipulation can be difficult to perform, particularly when the volume involves relatively complex anatomic organs such as the fetal heart. On the other hand, these manual rotations are still dependent on the operator expertise and due to several inherent variations, like fetal position and orientation, are extremely difficult to reproduce.

Two important concepts of 3D multiplanar display need to be highlighted given its relevance to the discussion at hand. First, the acquired volume of a particular anatomic structure by 3D ultrasonography, such as a volume of the fetal heart, contains all the anatomic 2D planes for a complete anatomic evaluation of this structure. Second, for every human organ, these 2D planes that are required for a complete anatomic evaluation of that particular organ are organized in a constant anatomic relationship to each other. It is therefore theoretically possible to obtain a volume of a specific organ, such as the fetal heart, and to allow an automated program to display out of this volume all the 2D planes that are required for a complete anatomic evaluation of this organ. We termed this concept a*utomated multiplanar imaging* (AMI) [12].

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Automated sonography is based on a software program that, for various organs, relates all the standardized planes that are required for a complete anatomic evaluation of a particular organ based on the respective spatial relationship of these planes within a 3D volume. This spatial relationship between standardized planes, which can be mathematically defined by the x-, y-, and z-axis, is constant for each organ. In practical terms, the spatial relationships of the standardized 2D planes of the fetal heart are predetermined, and their respective formulas are entered into a software program. Once a 3D volume of the fetal heart is obtained from the level of a standardized plane, such as the 4-chamber view, for instance, AMI will automatically generate all other standardized planes from the acquired volume in an operator-independent method. The constant anatomic relationship of these standardized planes to each other will allow an excellent reproducibility of AMI-generated ultrasonographic images. Automated multiplanar imaging will thus allow a complete evaluation of anatomically complex organs with a standardized and operator-independent approach.

VOLUME STANDARDIZATION

3D sonography needs to be applied at the level of volume *acquisition* and *display*. These are required first steps in the automated process [13]. Standardized acquisition parameters for specific anatomic regions will ensure that the fastest and most uniform acquisition is obtained, thus minimizing artifacts especially when dealing with fetal movement or motion within an organ such as the fetal heart. Standardization in acquisition of volumes should address the reference plane of acquisition, the size of the acquisition box, and the angle of acquisition of a specific target anatomic region. For instance, the acquisition of a volume of the fetal chest can be standardized if the acquisition reference plane is set at the level of the 4-chamber view, the borders of the acquisition box placed just outside the fetal skin and the angle of acquisition wide enough to ensure inclusion of the stomach inferiorly and the lower neck superiorly. In the mid second trimester the acquisition angel should be 35-45 degrees (Fig. **1**).

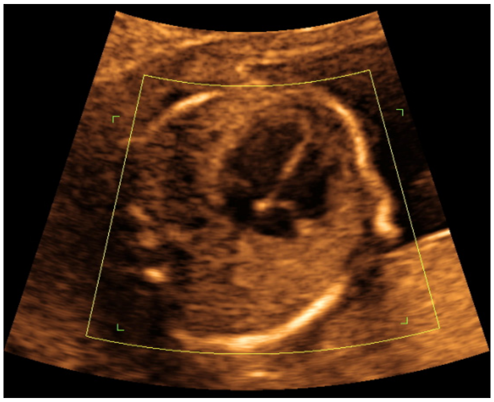

Figure 1: Standardization of volumes acquisition**.**

To standardize the display of 3D volumes, volumes need to be displayed in the multiplanar format. The multiplanar display of 3D volumes will show the reference plane (plane of acquisition) in the left upper plane (plane A) and the 2 orthogonal planes to the reference plane in the right upper plane (plane B) and left lower plane (plane C), respectively (Fig. **2**).

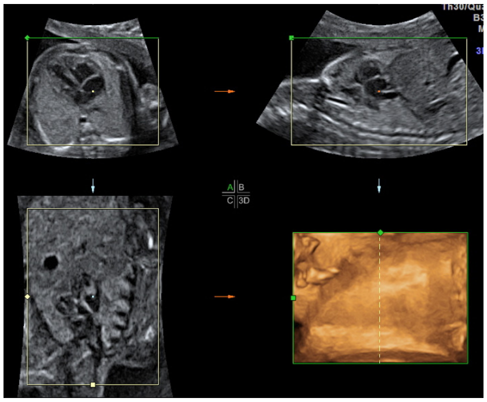

Figure 2: Initial multiplanar view of a 3-D sonographic volume of the fetal chest.

Standardization of display of 3D volumes needs to be applied in the A, B, and C planes to ensure uniformity of orientation in 3 dimensions. For volumes involving the chest of the fetus, standardization is best achieved by ensuring a uniform orientation of the spine in planes A, B, and C, respectively. For fetuses in cephalic presentations, this is accomplished by rotating plane A along the z-axis (z rotation) to place the spine at the 6-o'clock position and the apex of the heart in the left upper chest (Fig. **3**).

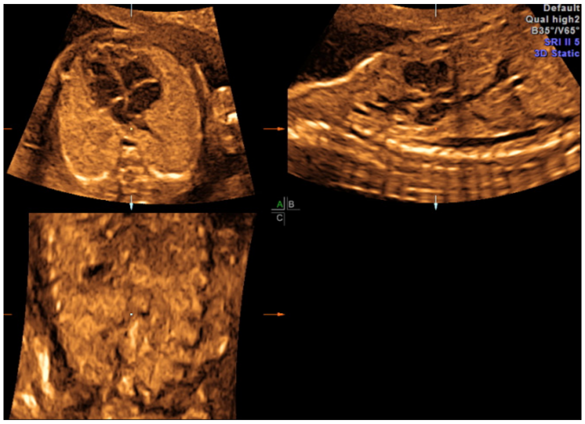

Figure 3: Standardization of volumes display. Plane A is rotated (four-chamber view) along the *z*-axis until the spine was at the 6-o'clock position.

When the reference point is placed on the fetal spine in plane A, a longitudinal view of the spine is displayed in planes B and C (Fig. **4**).

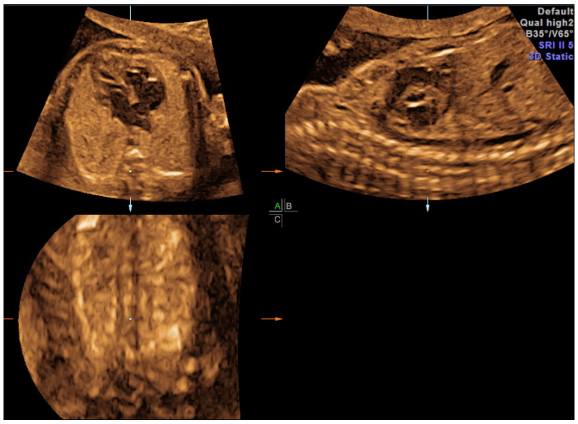

Figure 4: Standardization of volumes display. Reference/rotational point is placed in the fetal spine in plane A.

Standardization in planes B and C is achieved when the spine is aligned horizontally and vertically in planes B and C, respectively (z rotation in each plane). To complete the standardization, the reference point is then placed at the crux of the heart in plane A for volumes of the fetal chest (Fig. **5**). For breech presentations, start by rotating the 3D volumes 180° along the y-axis, and then follow the steps above. Table **1** details standardization steps for 3D volumes obtained at the level of the fetal chest. Achieving standardization in fetal 3D imaging will result in uniformity in retrieval of diagnostic 2D planes out of 3D volumes and a simplified approach to training. Finally, with standardization, the diagnostic capabilities of volume sonography in obstetrics are enhanced.

Table 1: Standardization of 3D Volumes of the Fetal Chest (Cephalic Presentations*)

Volume acquisition	
Reference plane	Obtain an axial view of the chest at the level of the 4-chamber view; ensure that you have 1 full rib on each side
Acquisition box	Open the acquisition box wide enough to ensure that the fetal chest is contained within the box; the box boundaries should be placed just outside the fetal skin
Acquisition angle	Use an acquisition angle that is wide enough to include the stomach inferiorly and the lower neck superiorly

Table 1: cont….

Volume display	
Step 1	Rotate image in plane A (4-chamber view) along the z-axis until the spine is at the 6-o'clock position and the apex of the heart is in the left upper chest
Step 2	Move the reference point in plane A to the spine (body of vertebra); this will bring a longitudinal view of the spine in planes B and C.
Step 3	Rotate image in plane C (coronal view) along the z-axis until the section of the midthoracic spine is aligned vertically
Step 4	Rotate image in plane B (sagittal view) along the z-axis until the section of the midthoracic spine (posterior to the heart) is aligned horizontally
Step 5	Place the reference point in plane A at the crux of the heart, at the level of the insertion of the medial leaflet of the tricuspid valve into the septum

Spatial Relationships of the Standard Diagnostic Fetal Cardiac Planes

The initial required step in the automation process is to define the spatial relationships of the standard diagnostic 2D planes to a reference plane of the target organ [14]. More recently the spatial relationships to the 4-chamber view plane of 6 diagnostic cardiac planes in the second trimester of pregnancy (between 18 and 23 weeks' gestation) has been identified [15-17]. Based upon these data special software was developed. The six standard diagnostic cardiac planes include the left ventricular outflow plane (Cardiac plane 1: five-chamber view, aorta), the right ventricular outflow plane (Cardiac plane 2: pulmonary artery), the abdominal circumference plane (Cardiac plane 3: abdominal circumference, stomach), the ductal arch (Cardiac plane 4), the right atria inflow (Cardiac plane 5: vena cava inferior and superior to the right atrium) and the aortic arch (Cardiac plane 6) – Figs 6-11. In order to enhance the accuracy of the software and to account for gestational age and individual variations between fetuses, tomographic ultrasound imaging (TUI) was added to the display of each diagnostic plane. TUI was set to display seven images for each diagnostic plane. Characteristics of software and the TUI image-to-image distances are reported in Table **2**.

Table 2: Software characteristics: spatial relationship of Cardiac planes 1-6 to the four-chamber view (4CV) reference plane and tomographic ultrasound imaging (TUI) display

Cardiac plane	Spatial relationship to 4CV	TUI image-to-image distance (mm)
1	*Parallel shift: -3.84 mm; Y rotation: 26.5*	0.56
2	*Parallel shift: -9.00 mm*	1
3	*Parallel shift: +14.0 mm*	2
4	*Y rotation: 90*	0.66
5	*Parallel shift: +5.98 mm; Y rotation: 90*	0.80
6	*Parallel shift: +3 mm; X rotation: 14; Y rotation: -2; Z rotation: -6*	1

Automated Retrieval of Standard Diagnostic Cardiac Planes

Prospective studies were done to evaluate the ability of software to retrieve six diagnostic cardiac planes from static 3D-volumes of the normal fetal heart, in the 2nd trimester of pregnancy [15-17]. It has been reported that this software demonstrated an excellent display of all six cardiac views with appropriate quality of images in most cases. Each target cardiac plane was displayed in at least one TUI image in more than 90% of volumes. Therefore all 6 diagnostic planes were retrieved from a single 3D volume in more than 75% of cases. The software performed equally well at each gestational age between 18 and 23 weeks.

The potential clinical usefulness of automated multiplanar echocardiography was recently proved a study by Rizzo *et. al* [18]. This technique allowed successfully retrieve of outflow tracts planes from 4D volumes obtained at the level of four-chamber view and confirm discordant ventricular-arterial connection in fetuses with complete transposition of great arteries as well as with corrected TGA.

Limitations of the Technique

The detailed analysis of the impact of different factors on the ability of the automated software to retrieve diagnostic planes, from 3D cardiac volume datasets has showed that besides artifacts, which are typical for 3D volume acquisition such as fetal activity (body or breathing movements), there are limitations typical for AMI technology only. The quality of 3D volume plays a critical role in the resolution of the retrieved planes. Given that the software is dependent, for its optimum performance, on adequate 3D volumes, its performance in difficult-to-image patients remains to be determined. Therefore it was reported if the initial acquisition of the 4-chamber view required z-rotation more than 90 degrees, the ability of software to display diagnostic cardiac plane 4-6 was affected. To avoid this problem the examiner should angle the transducer to obtain a better cardiac plane.

The main limitation specifically related to the performance of the software and may be difficult to avoid, is a heart position in the chest. It was demonstrated that cardiac axis less then 35 or greater then 55 degrees caused the inability to obtain left and right ventricular outflow planes [19]. This aspect should be considered in future studies. We hope that future improvement in AMI technology will help to minimize this effect.

Furthermore, most studies focused on gestational ages of 18–23 weeks, because most fetal anatomical surveys and echocardiograms are performed within this window. The performance of this software in fetuses at other gestational ages and in those with different congenital heart disease remains to be determined.

CONCLUSION

Our results validate the concept of automated sonography and its clinical applicability. By standardizing the approachto image acquisition and display and by substantially reducing the possibility of human error, automated sonography will improve the diagnostic acumen of ultrasound imaging and thus prove advantageous to clinical practice. Automated sonography also has the potential for improving the efficiency of ultrasound imaging by reducing the time needed to complete an ultrasound examination, thereby resulting in increased throughput of ultrasound laboratories.

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