CHAPTER 6

Analysis of Acquired Volumes: Methodological Approach

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Abstract: The purpose of this paper is to review how 3D/4D echocardiographic images can be manipulated to maximize the information regarding cardiac structure to improve the diagnostic yield of congenital heart defects. The following topics are discussed: (1) the differences between 3D and 4D ultrasound; (2) basic imaging principles of four-dimensional ultrasound when using spatial-temporal image correlation, real-time volume display, and matrix array technology; (3) analysis of acquired volumes using X,Y and Z rotation, the transverse sweep, the spin technique, tomographic imaging, rendering, inversion, and B-flow. The conclusion is that while the 3D and 4D volumes are easy to acquire, the user must understand the number of tools available to enhance the examination of the fetal heart.

Key Words: 4D ultrasound, Fetal echocardiography, Cardiac volumes, Methodology.

INTRODUCTION

Fetal echocardiography was introduced to clinical medicine in the early 1980's when the first studies reported its use for evaluation of cardiac arrhythmias as well as basic cardiac anatomy using M-mode, M-Mode-directed real-time, and real-time ultrasound [1-21]. In the late 1980's color and pulsed Doppler ultrasound were added to the armamentarium so that blood flow could be evaluated. [22-29]. These diagnostic tools allowed the fetal examiner utilize tools that were the standard for pediatric and adult echocardiography [30].

During the past seven years a new imaging modality, 3D/4D ultrasound, has emerged as an important adjunct to cardiac imaging [31-72]. This modality has allowed the examiner to review cardiac anatomical relationships in a manner that has not been available in the past. After acquiring 3D/4D fetal cardiac volume datasets the examiner must use sophisticated online and/or offline computer programs to analyze the fetal heart. For many physicians who are only familiar with acquiring and interpreting 2D images (B-mode, color Doppler, pulsed Doppler) the concept of manipulating a 3D/4D dataset may be a daunting task. The purpose of this paper is to review how 3D/4D echocardiographic images can be manipulated to maximize the information regarding cardiac structure for improved diagnostic yield. This paper will include a description of each technique, a cine clip illustrating the technique, a link to a free downloadable program used for volume manipulation, and sample volumes the user can download and evaluate.

DIFFERENCES BETWEEN 3D AND 4D ULTRASOUND

When three-dimensional (3D) ultrasound was introduced to the imaging community as a commercial product it consisted of multiple 2D images that were stacked one behind another during a manual or automated sweep of the transducer beam through an area of interest (Fig. **1**).

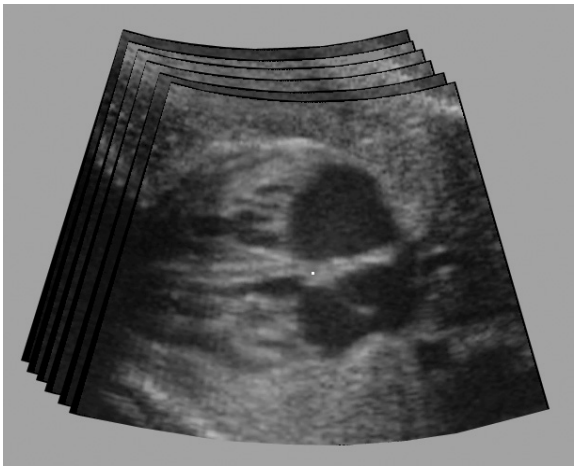

Figure 1: This illustrates the acquisition of multiple 2D images obtained during the sweep of the transducer beam through the

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fetal chest. These images are used to create a dataset of voxels that are used to reconstruct 3D and 4D images of the fetal heart. This technique is used with mechanical transducers in non-pediatric 3D and 4D ultrasound machines.

Imaging of the heart proceeded without regard to changes in diastolic and systolic cardiac configuration that occur during the cardiac cycle. The ''non-gated'' approach to reconstructive 3D imaging results in a ''static'' image display of non-cardiovascular and cardiovascular anatomy that can be examined simultaneously in three planes (X, Y and Z) that are perpendicular to each other (Fig. **2**).

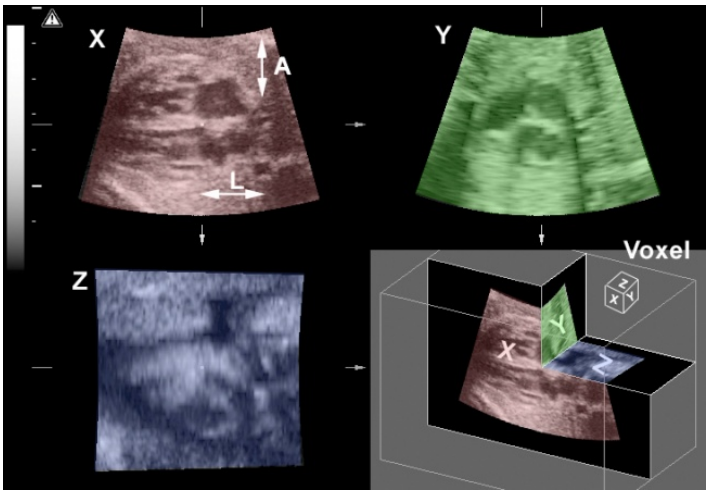

Figure 2: Following the acquisition of sequential, parallel 2D images, the volume dataset is created containing voxels. Each voxel consist of a volume of image pixels that have an X, Y, and Z component. The X plane image is obtained during the initial acquisition and has the characteristics of axial (A) and lateral (L) resolution of the 2D image which is a function of the characteristics of the transducer beam. The Y and Z planes also have axial and lateral resolution. However, the resolution in these planes is a function of the transducer beam as well as the size of the voxel that is created from the original volume dataset. For this reason, the Y and Z images are of lower resolution than the image in the X plane.

The X plane image has the highest resolution and is equivalent to the 2D image displayed during the 3D volume acquisition (Fig. **2**). The X plane image consists of pixels that have the properties of axial and lateral resolution, identical to a typical 2D image. Axial resolution provides the greatest detail for imaging tissue structures in the plane of the ultrasound beam, while lateral resolution provides less detail because it displays structures lateral to the ultrasound beam (Fig. **2**). Therefore, the X plane image would be equivalent to a 2D image displayed during a non-3D examination of the fetus. As the two-dimensional images acquired during the 3D volume acquisition are stacked one behind another, a voxel is created which has X, Y, and Z components (Fig. **2**). The size of the voxel determines the resolution of the images in the Y and Z planes (Fig. **2**). The 3D Y plane displays an image perpendicular to the X plane, in a vertical orientation (Fig. **2**). This image has less detail than the X plane image because it is reconstructed from voxels within the volume dataset. Although the Y plane image has less detail than the X plane image, it has more detail than the Z plane image. The Z plane image is perpendicular and horizontal to the X plane (Fig. **2**).

While the ability to examine cardiac structures in three perpendicular planes is a new approach not available with conventional 2D imaging, there are two limitations when comparing this to a 2D real-time image display of the fetal heart. The first is that the image is ''static'', thus not displaying a real-time image of cardiac structures, i.e. wall motion and opening and closing of valves. This would be equivalent to a freeze frame image obtained by pausing a video tape player, or freezing a still image while performing a live 2D real-time examination. The second limitation is the speed at which the volume dataset is acquired. All 3D ultrasound machines allow the examiner to control the sweep speed during image acquisition. The slower the sweep speed, the higher the resolution of the images displayed in the Y and Z planes. However, at slower sweep speeds artifact is introduced in the Y and Z planes as the result of fetal somatic and cardiac motion (Fig. **3**), thus negating the benefit of the 3D volume dataset. Conversely, the faster the sweep speed the lower the resolution in the Y and Z planes. However, with a faster sweep speed there is less of a chance of artifact introduced from cardiac motion (Fig. **3**).

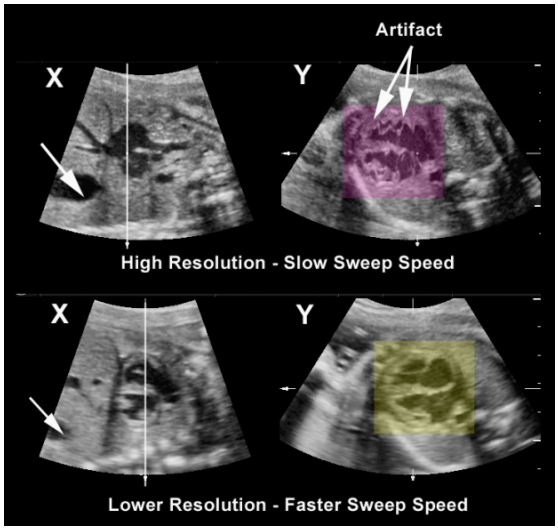

Figure 3: This is a static 3D sweep through the fetal chest containing cardiac structures. This image acquisition was sagittal, from left to right. The Y plane illustrates the reconstructed four-chamber view of the heart. The upper panel demonstrates the X and Y planes in which the sweep speed is set at a slow rate to acquire a greater number of 2D images to construct the 3D dataset. Using this technique increases the image resolution in the X plane. However, because of the decreased sweep speed, there is artifact in the Y plane resulting from contraction of the fetal heart during the image acquisition. The lower panel demonstrates a similar sweep at a lower speed. The Y plane does not demonstrate artifact, however, the image resolution of the four-chamber view is less.

Because the 3D static sweep captures cardiac structures randomly within the cardiac cycle, measurements of chamber and outflow tract dimensions at end-diastole or end-systole cannot be made. Therefore, when the examiner acquires a 3D static volume dataset of the fetal heart it is desirable to determine the transducer sweep speed that optimizes image resolution without introducing movement artifact in the Y and Z planes.

Basic Imaging Principles of Four-Dimensional Ultrasound

The question often asked is "what is four-dimensional (4D) ultrasound?" The fourth dimension is time, i.e. rapidly displaying 3D datasets so that the structures displayed on the screen appear to be moving. This gives the impression of motion such as a smiling face, movement of extremities, and contraction of the heart. This is similar to real-time ultrasound in which static 2D images are displayed on the screen at a rapid rate (frequency) giving the illusion of movement. Currently, there are several 4D technologies that are commercially available that will be discussed in this section.

Mechanical Array Transducer

Spatial–Temporal Image Correlation (STIC)

Initially the reconstruction of image datasets was time consuming and could only be performed with computerized offline data analysis and rendering. This prevented the clinical use of this technology on a widespread basis. In 2002 GE-Kretz (Voluson 730 Expert, Zipf, Austria) introduced the first clinical ultrasound machine that reconstructed 3-dimensional datasets of the fetal heart and displayed a cine loop of a single cardiac cycle [48]. The technology that was used is called spatial–temporal image correlation (STIC). After the introduction of B-mode STIC in 2002, STIC color and power Doppler were introduced in 2003 [44]. Since the first introduction of STIC, additional manufacturers have introduced similar technologies. The STIC volume display consists of thousands of 2D images acquired through the area of interest during a single sweep that lasts between 7.5 and 15 seconds. The images are then analyzed and multiple volumes are correlated with end-systole and end-diastole to create a cine loop of a single cardiac cycle. This allows the examiner to evaluate the volume dataset, identical to what is accomplished with the 3D static volume, with the only difference being that cardiac structures are viewed as a cine loop of a single cardiac cycle. STIC technology can display the data as either a B-mode image, B-mode with color Doppler, B-mode with Power Doppler, color Doppler, power Doppler, and B-flow (Fig. **4**).

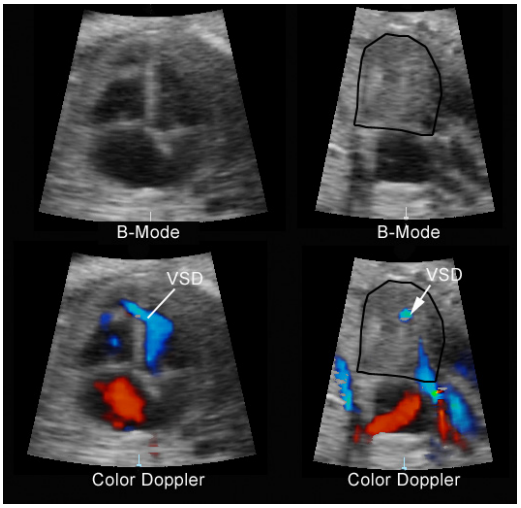

Figure 4: This is a STIC acquisition of the four-chamber view. The upper and lower panels are identical images, except for display of the color Doppler in the lower panel. The upper panel demonstrates the four-chamber view in the X plane and an "enface" view (outlined by black line) of the ventricular septum in the Y plane. Careful examination does not suggest any pathology of the interventricular septum. The lower panel, with color Doppler activated, demonstrates a shunting ventricular septal defect near the apex in the X plane. The size and location of the septal defect is clearly identified in the "enface" view of the Y plane.

The only limitation of the STIC volume data acquisition is that fetal movement may occur during the volume acquisition. Depending upon the type of movement (fetal breathing, gross body movement, maternal breathing) the images in the X, Y and Z planes may be minimally altered, or may become non-interpretable. Like the static 3D volume data acquisition, the resolution of the images in the X, Y, and Z planes are a function of how the user acquires the volume dataset. The volume sweep speed can be selected between 7.5 and 15 seconds and the angle of the sweep between 15 and 40 degrees. The angle of the sweep is equivalent to the distance covered during the sweep; a shorter distance is equivalent to a smaller angle; a larger distance is equivalent to a larger angle

For example, if the selected time is 7.5 seconds, a fixed number of images will be acquired whether the angle is 15 or 40 degrees. Therefore, the image resolution will be higher when the angle is 15 degrees than if it were 40 degrees. The reason for this is that although the same number of images are acquired during the 7.5 seconds, there is a greater distance between the images than when the angle is smaller. This results in lower resolution images in the Y and Z planes in the 40 degree sweep than in the 15 degree sweep. The advantages of STIC technology are the following: (1) looped cardiac cycle that simultaneously displays cardiac anatomy in the X, Y and Z planes (Fig. **5**),

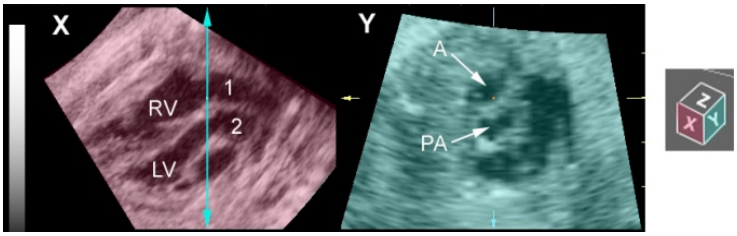

Figure 5: Using STIC technology, the outflow tracts are imaged cephalad to the four-chamber view demonstrating two outflow tracts (1 and 2) parallel to each other as they exit their respective ventricles. By rotating the image so that the outflow tracts are perpendicular to a horizontal plane, the outflow tracts are viewed in the short axis in the Y plane, demonstrating both to be adjacent to each other. This fetus had d-transposition of the great arteries.

(2) depending upon the settings selected (maximal time acquisition, minimal angle volume to image the cardiac structures) the image resolution is improved when compared to the 3D static volume sweep, (3) a single cardiac cycle is displayed allowing the examiner to examine cardiac anatomy frame-by-frame or in the cine-loop mode, (4) color Doppler and power Doppler flow dynamics can be examined simultaneously in the X, Y and Z planes (Fig. **4**), (5) end-diastole and end-systole can be determined and cardiac measurements can be made from the B-mode images in the X, Y and Z planes. (Fig. **6**).

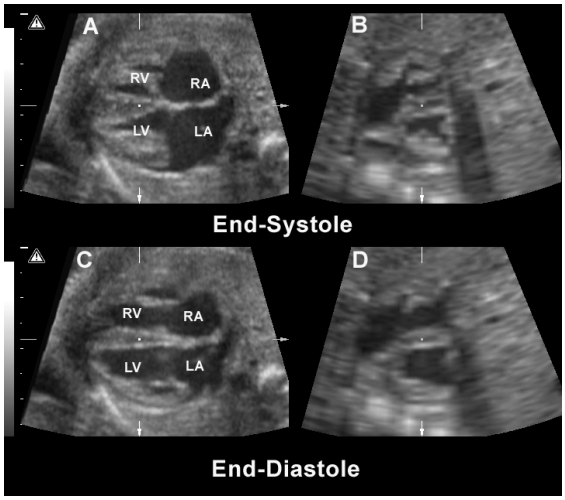

Figure 6: Isolation of end-systole and end-diastole from a STIC volume from which measurements of atrial and ventricular chambers can be made from the four-chamber view (A and C). Using this approach facilitates cardiac measurements because the examiner and align the heart in the short axis view (B and D) so that the widest and smallest dimension of the ventricular or atrial chambers are measured accurately. RA=right atrium, LA=left atrium, RV=right ventricle, LV=left ventricle.

Real-Time Volume Display

Using a mechanical array probe (GE-Kretz Voluson 730 Expert, Zipf, Austria; Philips HD 11, Bothel, WA, USA) multiple sequential volumes are acquired and displayed continuously on the screen. This results in an image sequence similar to 2D real-time imaging. Because of limitations of computer processing of volume datasets, the quality of the image is markedly decreased when compared to a 2D real-time image, static 3D image, or a 4D STIC image (Fig. **7**).

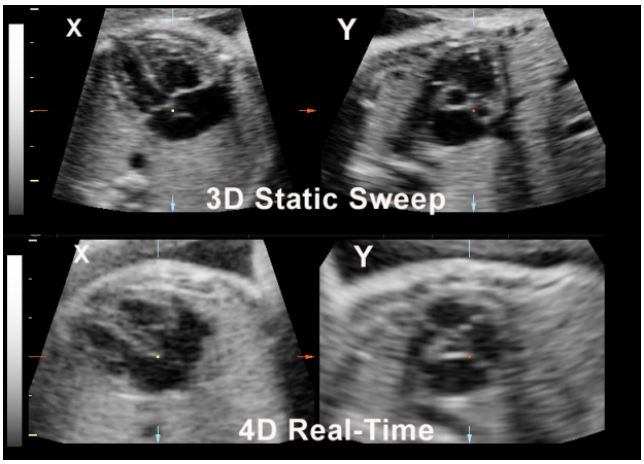

Figure 7: This compares images acquired using the 3D static sweep and the 4D real-time obtained with a mechanical array probe. The 4D real-time image was acquired at a volume rate of 6 Hz. To accomplish this requires a rapid sweep speed, thus resulting in a lower resolution image compared to the 3D static sweep in the upper panel. The only benefit of the 4D real-time display is that the examiner can visualize the contracting heart, although the frame rate is 6 Hz.

However, if the examiner is desirous of evaluating the heart in the Y and Z planes, this can be accomplished without introducing artifact, as is the case with the static or STIC acquisition, described above.

Matrix Array Transducer

In 2002 Philips Ultrasound (Bothel, WA, USA) introduced the matrix array probe to adult cardiology in which all elements of the probe are fired simultaneously in a 3- dimensional matrix, generating a truncated pyramidal volume of ultrasound virtually instantaneously. This is in contrast to 3D/4D imaging described above which reconstructs volumes from a series of 2D images acquired over time. For this reason, ‘‘real-time’’ 3D technology, unlike reconstructive 3D technology, does not require cardiac gating to capture cardiac motion. Because of the faster frame

rate achieved with this technology than with the mechanical array probe, there is no movement artifact introduced into the Y and Z planes of the volume dataset (Fig. **8**).

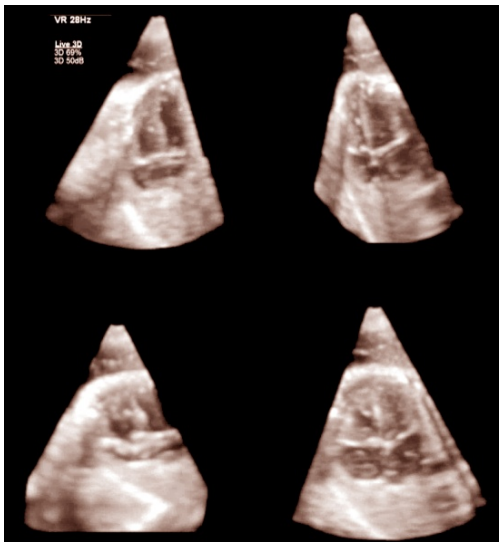

Figure 8: This is a real-time 4D volume examination of the fetal heart using the maxtrix array 4D probe. The images are of the fetal heart taken using different orientations of the cut plane as it passes through the four-chamber view. Because the ultrasound volume dataset is acquired simultaneously in all planes (X, Y, and Z), the volume rate is higher (28 volumes/second) than when using the mechanical array probe (6 volumes/second).

One of the limitations of the current technology is that the size of the acquired volume dataset is smaller than what can be acquired using STIC technology, which limits its use in the third trimester of pregnancy. However, a novel approach has recently been described to address this problem [66]. Because of lower transmitted ultrasound frequencies using the matrix array, the volume dataset acquired with the STIC technique provides the highest image resolution.

ANALYSIS OF THE ACQUIRED VOLUMES

Although we have reviewed the different image acquisition techniques, the analysis of acquired volumes will focus on 3D and 4D STIC volume datasets. To illustrate the principles for each of the following topics a descriptive cine clip can be viewed that illustrates each step-by-step technique. A free copy of 4D View (GE-Kretz Voluson 730 Expert, Zipf, Austria) can be downloaded from the following Internet link: http://www.volusonclub.net/4dview. After downloading this program select the *Free Unlimited De-Featured Version* during the installation process. This will provide you with the basic elements for our discussion. Download two volume datasets that can be opened and analyzed with 4D View. The first volume is a B-Mode volume from a normal fetal heart.. The second is a normal color Doppler volume from a normal fetal heart.

Rotating the XYZ Planes

Once the 3D/4D volume has been acquired, the examiner often chooses to rotate the XYZ planes to view cardiac anatomy from the A, B, or C reference images. To accomplish this there are two approaches. The rotation buttons can be used for each of the XYZ planes. However, this may be confusing to the examiner, depending upon which reference image is selected, A, B or C. The approach that I prefer uses the right and left buttons of the mouse. Click the following link to review the instructional cine entitled, "ROTATION

Transverse Sweep

The transverse sweep is a technique that has been used to evaluate the four-chamber, five-chamber, three-vessel and the tracheal views. If the examiner can demonstrate these views to be normal, then major structural abnormalities of the fetal heart can be excluded (Fig. **9**). (74-76)

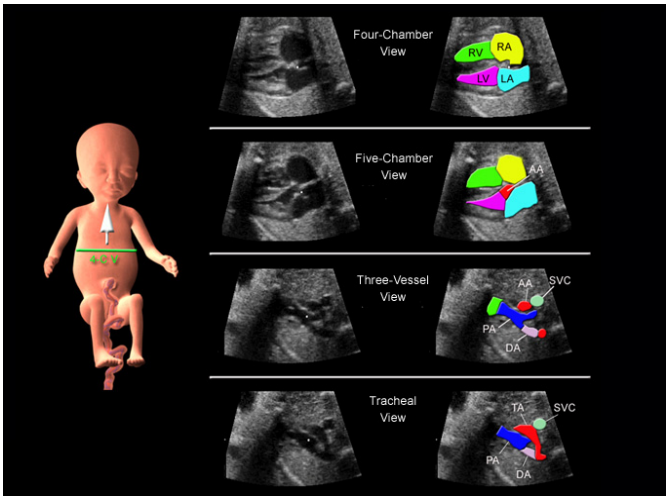

Figure 9: The views can be obtained by directing the ultrasound beam from the four-chamber view to the upper thorax in a transverse plane. The views that are observed in sequential order are the four-chamber view, the five-chamber view, the three-vessel view, and the tracheal view. If all of these views are normal, then major congenital heart defects can be eliminated. RA=right atrium, LA=left atrium, RV=right ventricle, LV=left ventricle, AA=ascending aorta, PA=pulmonary artery, SVC=superior vena cava, DA=ductus arteriosus, TA=transverse aortic arch.

These views can be examined from the 3D/4D volume by a simple technique of moving the reference dot through the B reference image, resulting in imaging of the above views in reference image A. Click the following link to review the instructional cine entitled, "SWEEP."

Spin Technique

This technique utilizes the concept of rotation, described above, to systematically identify the left outflow tract, the aortic arch, and the main pulmonary artery and its bifurcation (Fig. **10**) [47].

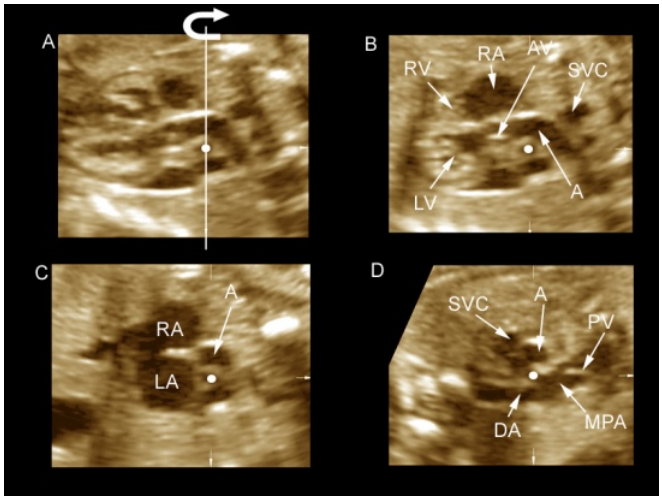

Figure 10: Panel A is the five-chamber view. The reference dot (white circle) is placed within the vessel inferior to the ascending aorta which should be the right pulmonary artery (A). The volume dataset is then turned around the Y axis (Panels B, C, and D) until the right pulmonary artery is elongated and demonstrated to exit the main pulmonary artery (Panel D). The "spin technique" can be used to identify any vessel in the cardiovascular system. These views are complimentary and additive to the transverse sweep, described above. Click the following link to review the instructional cine entitled, "SPIN."

Tomographic Imaging

Tomographic imaging displays multiple, simultaneous views of the heart from either a static or STIC volume [77] (Fig. **11**).

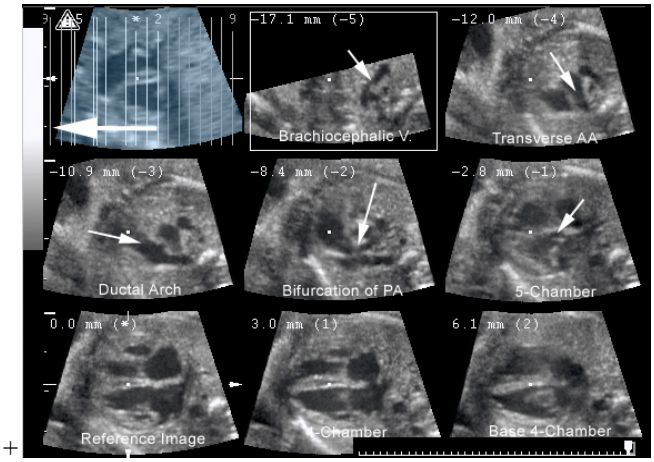

Figure 11: These images are from a STIC acquisition. The panel of 9 images are displayed at exactly the same point in the cardiac cycle. The upper left image has parallel lines that represent the labeled images that are perpendicular to this image. The reference image is indicated by an *. From this point images to the right are indicated by + mm, while images to the left are indicated by – mm. For identification purposes, the + and – millimeters indicators are not useful, but the absolute value is. For example, the base of the four-chamber view is 6.1 mm below the reference image, the five-chamber view is 2.8 mm above the reference image, the bifurcation of the pulmonary artery is 8.4 mm above the reference image, and the transverse aortic arch is 12 mm above the reference image.

The benefit of this technique is that the examiner can view the necessary transverse views (4-chamber, 5-chamber, 3-vessel, and tracheal) used to screen for congenital heart defects. Click the link to review the instructional cine entitled, "TUI."

Rendering

Another benefit of static and STIC volume acquisitions is that the 2D images contained within each volume can be compiled to create a 3-dimensional model of the heart. For example, the typical 2-dimensional four-chamber view can be rendered to provide a 3-dimensional structure that demonstrates depth. Fig. **12** illustrates a 3-dimensional rendered image that demonstrates and inferior vena cava in the back wall of the right atrium.

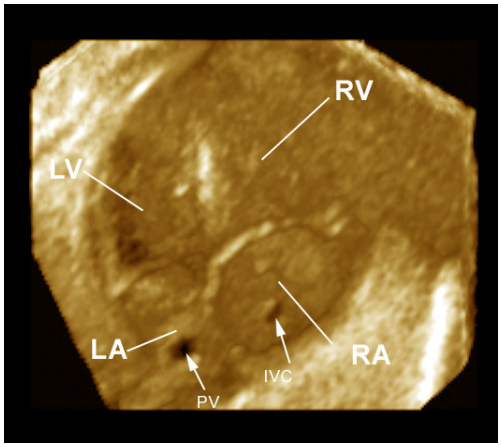

Figure 12: This is a 3D rendered four-chamber view of the fetal heart. While the image has the appearance of a 2D image, the rendering provides depth so that the back walls of the atrial and ventricular chambers can be identified. The right atrium demonstrates the opening of the inferior vena cava (IVC) and the left atrium the opening of one of the pulmonary veins (PV). RA=right atrium, LA=left atrium, RV=right ventricle, LV=left ventricle.

Click the link to review the instructional cine entitled, "RENDERING."

Invert

Another method utilized for creating a 3-dimensional image of the heart is the inversion mode. This technique requires the examiner to render the 3-dimensional heart (see above, Rendering) and then invert the colors. This

creates an image that has the appearance of a mold of the heart (Fig. **13**). Click the link to review the instructional cine entitled, "INVERT"

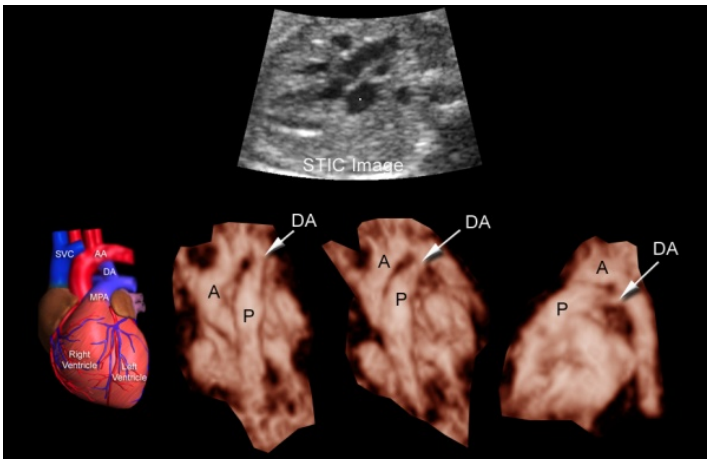

Figure 13: The STIC B-mode image is of the left outflow tract as it exits the left ventricle. The rendered inverted images demonstrate the crossing of the main pulmonary artery (P) and the aorta (A) as well as the ductus arteriosus (DA).

Examination of the Interventricular Septum

Evaluation of the ventricular septum is usually performed at the level of the four-chamber view. Unfortunately, this view represents only a portion of the septum. Using 3D/4D STIC acquisitions the entire septum can be examined for evidence of defects that are not in plane of the four-chamber view [18] (Fig. **4**). Click the link to review the instructional cine entitled, "SEPTUM."

Identification of the Aortic and Ductal Arches

Many examiners have difficulty identifying the aortic and ductal arches witought using a systematic approach (Fig. **14**).

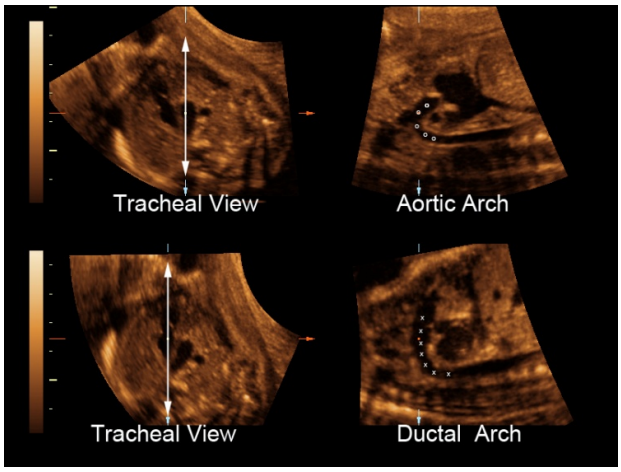

Figure 14: The aortic and ductal arches can be identified by aligning their respective vessels at the level of the tracheal view. After aligning each vessel in the vertical plane, the perpendicular image reveals the aortic and ductal arches, respectively.

sing 3D/4D STIC acquisitions, a systematic approach can be used to identify these vessels. The cine clip entitled "ARCHES" will illustrate two techniques for identification of the aortic arch and one technique for identification of the ductal arch. Click the link "ARCHES" to review the instructional cine.

Rendered B-Flow

B-mode ultrasound identifies soft tissue and the blood pool when examining fetal cardiovascular structures. However, it does not identify the flow of blood. In order for most examiners to identify blood flow color Doppler or

Power Doppler is used. One of the problems with the rendered color Doppler image is that the borders are not as well defined between the blood pool and the chamber walls. However, B-flow is a technique in which moving red blood cells are identified from the B-mode image (Fig. **15**).

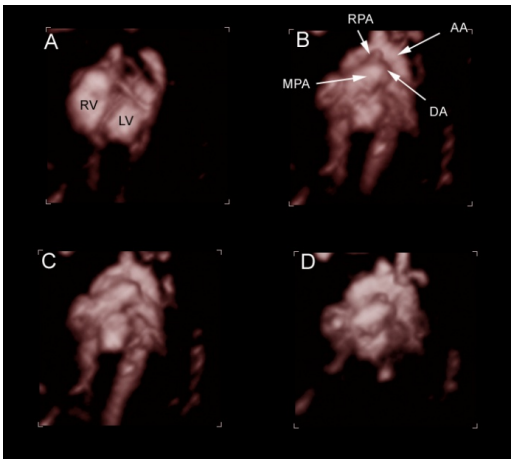

Figure 15: This is a B-flow image sequence from a 17 week fetus. Panel A represents filling of the right (RV) and left (LV) ventricular chambers during diastole. Panel B demonstrates ventricular systole after the ventricles have emptied. This image demonstrates the relationships of the main pulmonary artery (MPA), right pulmonary artery going beneath the aortic arch (AA) and the ductus arteriosus (DA) emptying into the thoracic aorta. Panel C is similar to panel B except later in the systolic cycle. Panel D is the same image as panel C except the volume has been rotated to show the perpendicular relationship of the MPA and the AA.

This technology does not utilize Doppler principles to display blood flow. Once the B-flow image is acquired, it can be rendered to provide a 3-dimensional structure of the fetal cardiovascular system that resembles an angiogram. Click the link to view the instructional cine entitled, "BFLOW."

Color Doppler

When a STIC acquisition includes color Doppler, the examiner can adjust the color settings so that the color does not override the vessel or chamber walls. Click the link to view the instructional cine entitled "COLOR".

CONCLUSION

This communication has attempted to provide an overview of 3D/4D examination of the fetal heart. Although the 3D static and 4D STIC volume datasets are easy to acquire, the difficulty occurs when the volumes are analyzed. As this paper illustrates, there are a number of tools the examiner can use to evaluate acquired volumes of the fetal heart. Understanding how to use the tools enhances the evaluation of the fetal heart, especially when pathology is suspected.

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