CHAPTER 5

Rendering Cardiac Volumes in Three and Four-Dimensional Ultrasonography

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Abstract: This chapter summarizes different approaches currently used to examine the fetal heart using three and four-dimensional ultrasonography with a particular emphasis on multiplanar display and novel rendering modalities. These new imaging modalities provide important insight into the normal and abnormal fetal cardiac anatomy and function and have the potential to reduce the operator dependency that characterizes two-dimensional ultrasound.

Key Words: Fetal Echocardiography, 4D Fetal Echocardiography, Volume Rendering.

INTRODUCTION

A growing body of evidence indicates that four-dimensional (4D) ultrasound imaging with spatiotemporal image correlation (STIC) facilitates examination of the fetal heart [1-45]. Thus, 4D fetal echocardiography have the potential to reduce the operator dependency that characterize two-dimensional ultrasonography and may increase the detection rate of congenital heart defects (CHDs). Volume datasets obtained with 4D sonography can be compared with blocks of pathological specimens, where all the anatomical information is contained in the block and the information displayed depends on the level at which the block is cut, with the additional advantages that these planes can be assessed in a virtual beating heart and that rendering techniques can be used to gain additional insight into the structure and function of the fetal heart. Prenatal diagnosis of congenital heart defects is challenging because of the structural complexity of the heart and the expertise required to master the use of standard planes for fetal echocardiography. In addition fetal and/or maternal motion, maternal body mass index, gestational age, adequacy of the amniotic fluid volume and fetal position are important factors that can affect image quality. Prenatal diagnosis of CHDs is desirable because unrecognized congenital heart defects may be associated with worse neonatal outcome. 4D ultrasonography with spatiotemporal image correlation (STIC) allows the acquisition and storage of volume data sets of the fetal heart using which can be resliced to obtain the standard planes for fetal echocardiography, as well as novel planes. In addition to this anatomic information, functional information of the fetal heart can also be obtained including the direction of blood flow if the volume dataset was obtained color Doppler or high dimensional (HD) power Doppler

The image quality contained in a STIC volume dataset can be substantially improved by optimizing the settings before acquisition. This can be achieved by adjusting the two-dimensional grayscale and color Doppler parameters. Our preference is to use low persistence, high contrast, and high frame rate settings. Typical acquisition time ranges from 5 to 15 seconds. Shorter acquisition times can be used to minimize motion artifacts but this reduces the image spatial resolution. At the time of volume acquisition, transverse sweeps of the fetal thorax can yield better images of four-chamber, five-chamber, and three-vessel and trachea views. In contrast, sagittal sweeps through the fetal thorax can yield better images of the aortic and ductal arches as well as the venous connections to the fetal heart

Evaluation of the Fetal Heart Using 3D and 4D Ultrasonography

Two-dimensional (2D) ultrasonography relies on standard anatomic planes for the examination of the fetal heart, including the four-chamber view, three-vessel and trachea view, the left and right outflow tracts [46-51]. However, visualization of vascular connections to the fetal heart with two-dimensional (2D) ultrasonography requires the examiner to scan these vascular structures in multiple scanning planes to obtain a mental reconstruction of their spatial relationships. This process can be facilitated using different display modalities used in 3D and 4D ultrasonography including power Doppler reconstruction 3D and 4D volume datasets, [52-56] minimum projection mode, [39] inversion mode, [40, 42, 57] and B-flow. [58-60]

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Multiplanar Display

Multiplanar display is a unique modality available in 3D and 4D ultrasonography that allows for the simultaneous visualization of three anatomic planes which are orthogonal to each other: the transverse, sagittal and coronal planes (Fig. **1**).

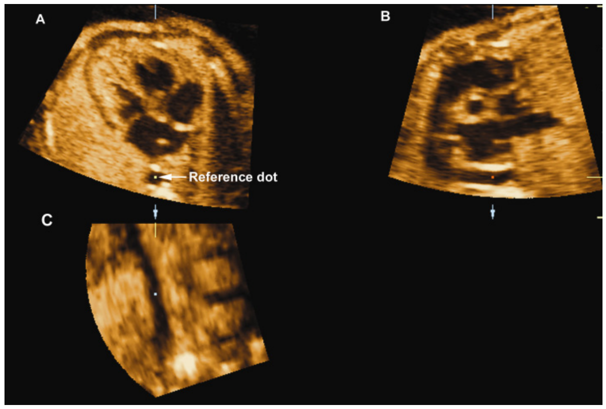

Figure 1: Volume datasets were adjusted to display the four chamber view in panel A, where the fetal aorta was aligned with the crux of the heart in the vertical plane. The reference dot was positioned in the aorta allowing the visualization of the coronal view of the descending aorta in panel C.

Moreover, an imaging tool referred as the reference dot allows for the identification of anatomic structures in these three orthogonal planes. This display modality can also be used to scroll through the volume data set to visualize the transverse view of the upper abdomen, four-chamber view, five-chamber view and the three-vessel view.

A central feature of this display modality is the ability to focus on a specific anatomic structure in panel A by placing the reference dot in the structure and visualizing the same structure in two perpendicular planes displayed in panels B and C (Fig. **1**). Using this approach we demonstrated that the simultaneous display of orthogonal planes of abnormal vascular connections to the fetal heart facilitated the identification of the nature of the abnormal vessel and the visualization of its spatial relationships with other vascular structures. Indeed, the multiplanar view allowed for the visualization of the drainage of a dilated azygos/vein into the SVC (Fig. **2**) in a fetus with interrupted IVC with hemiazygos vein continuation.

This technique involves the visualization of standard views used in fetal echocardiography in panel A and the subsequent placement of the reference dot in the abnormal vascular structure to identify the nature of the vessel and its connections which where displayed using the sagittal and coronal planes in panels B and C, respectively. This technique can be improved by adding the spin technique [61] (see below).

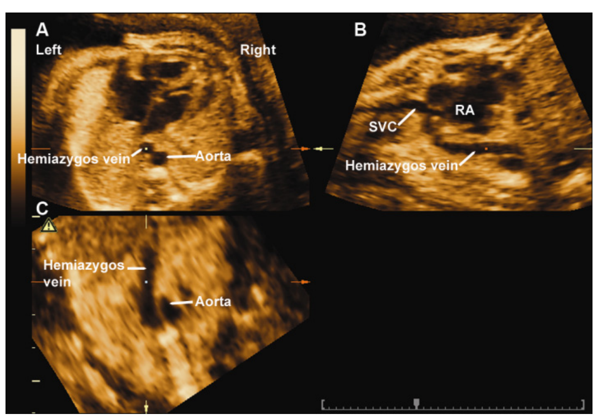

Figure 2: Multiplanar display of a dilated hemiazygos vein in a fetus with interrupted inferior vena cava and dextrocardia. The reference dot was placed in the dilated hemiazygos vein in the four chamber view of the heart in panel A. This allowed for both the visualization of the sagittal view of the hemiazygos vein in panel B and the coronal view of the dilated hemiazygos vein in panel C. The rotation of the coronal view to a vertical position on panel C allowed for the visualization of the dilated hemiazygos vein draining into the SVC. SVC: superior vena cava; RA: right atrium

Several algorithms using the multiplanar display have been proposed for simultaneous display of both outflow tracts [25], to visualize the aortic and ductal arches [62], (Video 1) and to determine the nature of vascular connections to the fetal heart using the spin technique [38]. The later involves positioning the reference dot in the center of the structure and 'spinning ' the volume data set around the *y* axis to determine its spatial relationship with the heart and other vascular structures and to identify its nature

A detailed examination of the fetal heart has been proposed to include a long-axis view of the arterial duct [51] (sagittal view of the ductal arch). This sonographic plane allows visualization of the right ventricle in continuity with the main pulmonary artery, pulmonary valve, ductus arteriosus, and descending aorta, as well as a transverse view of the ascending aorta (Fig. **3**).

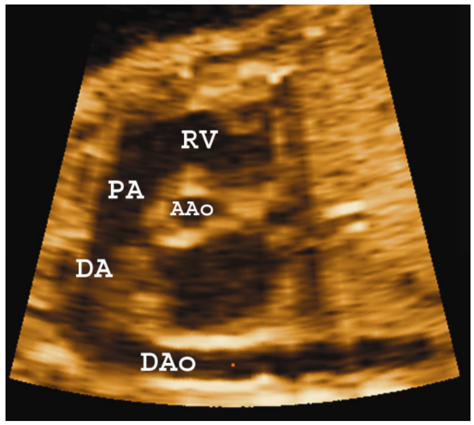

Figure 3: The components of the sagittal view of the ductal arch (Fig. **1a**) as determined by the multiplanar display are displayed in Fig. **1b**, including: right ventricular outlet (RV), main pulmonary artery (PA), ductus arteriosus (DA), descending aorta (DAo), and a cross-section of the ascending aorta (AAo).

The sagittal view of the ductal arch can be easily obtained using 4D volume datasets of the fetal heart acquired with STIC by following the first two steps of a reported algorithm [63]. Briefly:

1. The volume datasets are adjusted to display the four-chamber view in panel A, where the fetal aorta was aligned with the crux of the heart in the vertical plane. The reference dot is positioned in the aorta, allowing the visualization of the coronal view of the descending aorta in panel C (Fig. **1**).
2. In panel C, the image is rotated to display the aorta in a vertical position. This allowed for the visualization of the sagittal view of the ductal arch in panel B and the four chamber view in panel A (Fig. **4**).

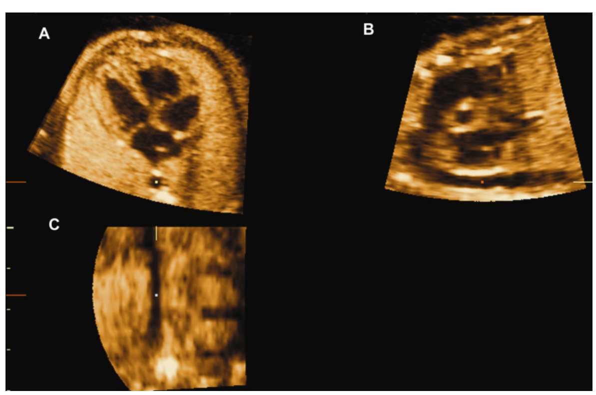

Figure 4: In panel C, the image was rotated to display the aorta in a vertical position, when necessary. This allowed for the visualization of the longitudinal view of the ductal arch in panel B.

Video 2 illustrates the simplicity of these steps. A retrospective study using this approach [63] reported that the visualization rate of the sagittal view of the ductal arch was significantly lower in fetuses with conotruncal anomalies 5.6% (1/18), than among normal fetuses [93.1% (108/116)] and those with other CHDs [79.4% (27/34); p<0.01]. The authors concluded that the inability to visualize the ductal arch using the proposed algorithm should raise the possibility of conotruncal anomalies because it is associated with a nine-fold increase in the risk for a conotruncal anomaly [64]. However, prospective studies are required to determine the value of the proposed approach in the screening for conotruncal anomalies

Rendering techniques can also be applied to the visualization of vascular connections to the fetal heart to obtain a depth perspective using a "thick slice".[64] (Fig. **5**)

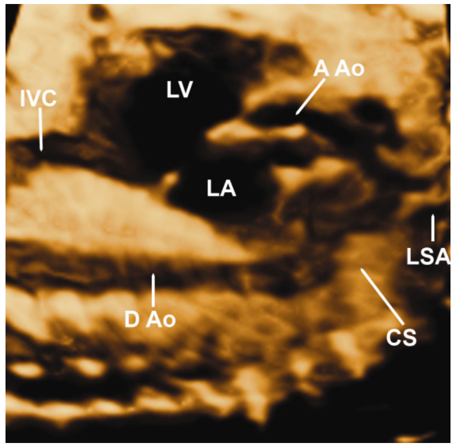

Figure 5: "thick slice" rendering of an aortic arch in a patient with aortic coarctation. Contraductal shelf (CS), descending aorta (D Ao), inferior vena cava (IVC), left ventricle (LV), left atrium (LA), ascending aorta (A Ao), left subclavian artery (LSA)

Automated Display of Multiple Slices

Several ultrasound manufacturers provide software to automatically slice 3D and 4D volume data sets (Multislice View ™ ; Accuvix, Medison, Seoul, Korea; Tomographic Ultrasound Imaging; GE Healthcare, Milwaukee, WI; iSlice; Philips Medical Systems, Bothell, WA; Multi-Slice View; Siemens Medical Solutions, Malvern, PA). This technology allows an examiner to automatically display several slices that are parallel to each other on a single screen

TUI has been introduced as a new display technology for 3DUS and 4DUS. This modality allows for the simultaneous display of up to eight parallel planes whose distance can be adjusted for a better visualization of anatomic planes. Thus, TUI allows the visualization of multiple sections of a beating heart at the same time. An "overview image" is shown on the upper left corner. This view shows a plane orthogonal to the slices, and parallel lines demarcate the position of the slices within the volume dataset (Fig. **6**).

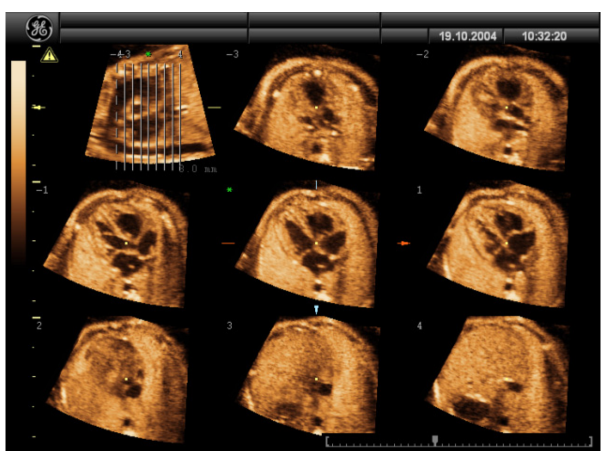

Figure 6: An "overview image" is shown on the upper left corner. The parallel lines determine the position of the eight orthogonal planes to the plane containing the "overview image"

The user can adjust the number and position of the slices with specific software controls. TUI has been used for the examination of the fetal heart [65-68]. and other fetal organs [69]. However, the simple use of parallel planes to the four-chamber view of the heart does not allow for the visualization of the long axis view of the left outflow tract and the short axis view of the aorta, which are considered part of an integral examination of the fetal heart [49-51, 70].

Moreover, the untargeted use of TUI allows for the simultaneous display of anatomic planes with and without diagnostic value. In order to determine the minimum number of images required for a comprehensive examination of the fetal heart we developed an algorithm using TUI and STIC [71]. This algorithm allows for the simultaneous visualization of the standard planes for fetal echocardiography including the four-chamber view, three-vessel view, left outflow tract and short axis (right outflow tract), in most fetuses without CHDs [71]. With the use of this algorithm a normal four-chamber view, five-chamber view, longitudinal view of the ductal arch, three-vessel and trachea view, left outflow tract and short axis were visualized in 99%, 96.9% , 98.5 % , 88.2%, 93.3%, and 87.2% of the volume datasets, respectively.

Similar results were recently reported by Rizzo et al [72]. using STIC and a simplified method referred to as the "three-steps technique."

The former algorithm involves the steps that are displayed in Video 3 and include:

Step 1: Placement of the reference dot in the crux of the heart and alignment of the aorta in the midline on panel A (Fig. **7**)

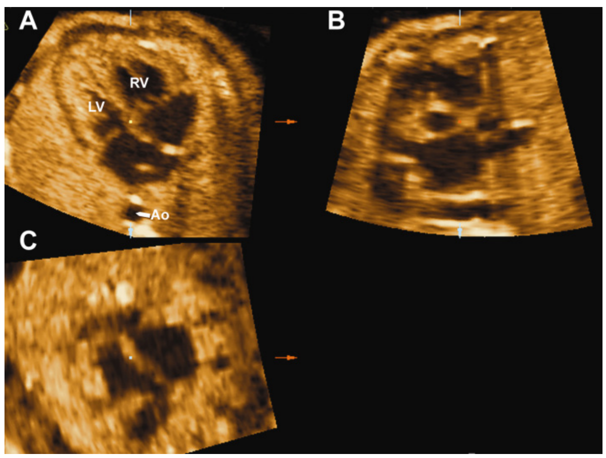

Figure 7: Volume datasets were adjusted to display the four chamber view in panel A, where the fetal aorta was aligned with the crux of the heart in the vertical plane. RV: right ventricle; LV: left ventricle; Ao: aorta

Step 2: Placement of the reference dot on the aorta in panel A to visualize the coronal view of the aorta in Panel C (Fig. **8**)

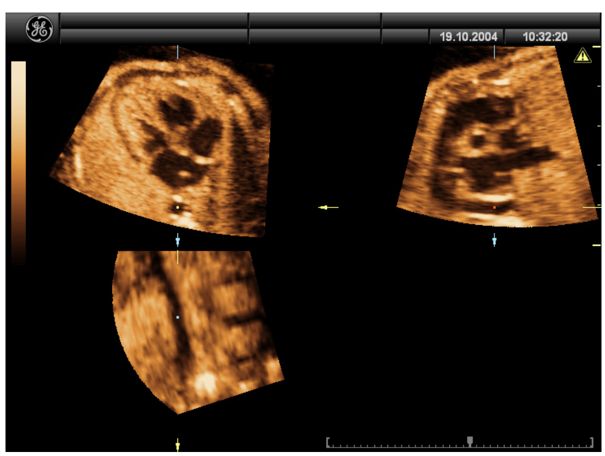

Figure 8: The reference dot was positioned on the aorta in panel A allowing the visualization of the coronal view of the descending aorta in panel C.

Step 3: On panel C, rotate the aorta until it is in a vertical position. This allows the visualization of the sagittal view of the ductal arch in panel B (Fig. **9**)

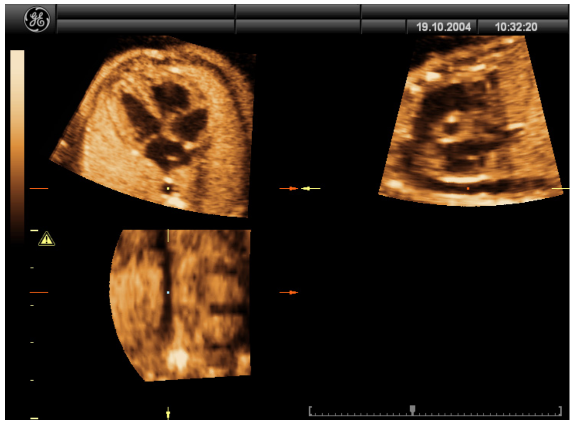

Figure 9: In panel C the image was rotated to display the aorta in a vertical position. This allowed for the visualization

Step 4: Move the reference dot back to crux of the heart in panel A, in preparation for TUI activation

Step 5: Activate Tomographic Ultrasound Imaging

Step 6: Reduce the number of slices to 3 and change the display format to four planes. This will automatically enlarge the images displayed (Fig. **10**)

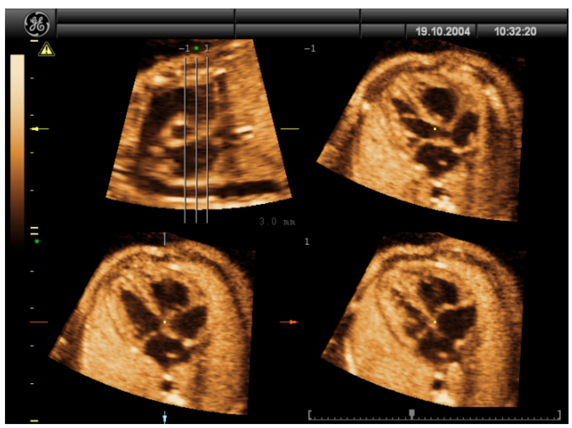

Fig 10: see text

Step 7: Right click on panel A and move the image to place reference dot in the aorta. This step allowed the visualization of the five-chamber view on panel C which corresponds to the slice marked with an asterisk in the "overview image" (Fig. **11**)

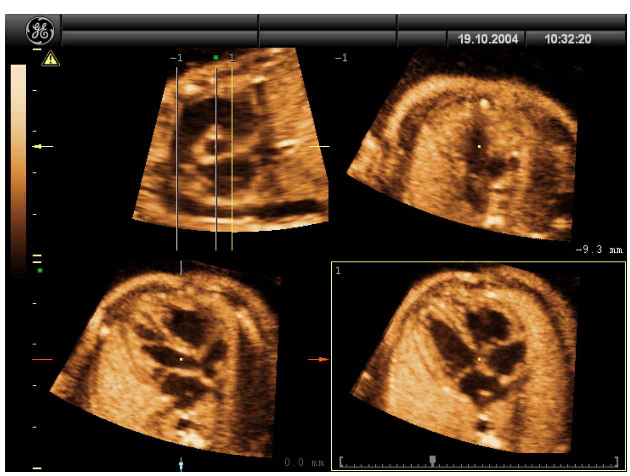

Figure 11: see text

Step 8: Click on the "adjust" option and right click on panel B to display a horizontal arrow. Move this arrow to the left until the upper line (-1) on panel A coincides with the ductal arch. (Fig. **11**)

Step 9: Right click on panel D to display the horizontal arrow. Move this arrow to the left until the lower line (1) on panel A coincides with the edge of the aorta. This allowed the visualization of the four-chamber view on panel D in 99% (193/195) of fetuses without heart defects (Fig. **11**)

Step 10: Left click on panel C and on "Rotation Y". Scroll the bar on the "Rotation Y" to the right until the left outflow tract is visualized on panel C. This is generally accomplished with a right sided rotation between 8 to 22 degrees depending on the gestational age at which the volume dataset was obtained. This step allows the visualization of the left outflow tract in panel C and the short axis of the aorta in panel A. In about one third of fetuses the reference dot in panel C need to be placed above the aortic valve to visualize the short axis of the aorta in panel A. (Fig. **12**)

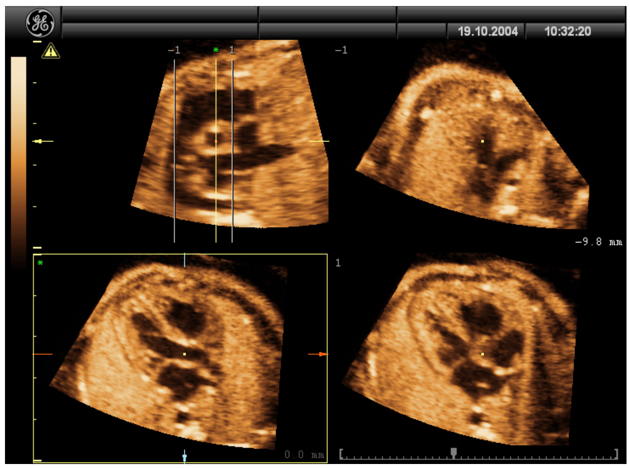

Figure 12: see text

Rendering Techniques

Several rendering algorithms have been described for visualization of the three-dimensional structure and spatial relationships of great vessels and venous return to the heart. These images can be obtained by acquiring volume data sets with gray-scale, color Doppler, power Doppler or B-flow imaging

Inversion Mode

The "inversion mode" is a new rendering algorithm that transforms echolucent structures into solid vowels. Thus, anechoic structures such as the heart chambers, lumen of the great vessels, stomach and bladder appear echogenic on the rendered image, whereas structures that are normally echogenic prior to gray-scale inversion become anechoic. Post processing adjustments are performed as necessary, including adjustments of the gamma curve, threshold and transparency to improve image quality. The technique allows examiners to obtain 4D rendered images of cardiovascular structures from volume data sets acquired with gray-scale only, without the need for color Doppler, power Doppler, or B-flow imaging. We have previously demonstrated the value of the display technique in the visualization of dilated azygos or hemiazygos veins and their spatial relationships with the descending aorta, the aortic arch, the SVC, the right atrium, and the fetal spine in cases of interrupted IVC associated with and without heterodoxy syndromes (Fig. **13**).

As mentioned above, volume datasets obtained with a sagittal sweep of the fetal chest are preferred over those obtained using a transverse sweep when evaluating the normal or abnormal vascular connection to the fetal heart. Once a sagittal view of the heart is visualized in Panel A, the region of interest was selected in panel B, reducing the rendering box height and width to display only the fetal spine, fetal heart and its vascular connections. Next the direction of view (green dotted line) was set to display the sagittal view of the heart in the anteroposterior projection and finally the "inversion mode" rendering algorithm was selected in the ultrasound equipment with the threshold filter set between 70 and 90.

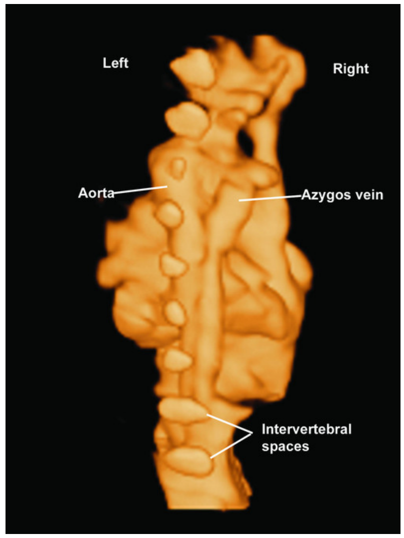

Figure 13: Three-dimensional images of a fetal heart rendered with the "inversion mode" in case of interrupted IVC with azygos vein continuation. RA: right atrium; SVC: superior vena cava. A posterior view of the fetal heart shows a dilated azygos vein located to the right of the descending aorta. The arch of this vein forms a Y image with the aortic arch before joining the SVC

Transparence Modes

The minimum projection mode (MPM) is another volume-rendering tool that allows preferential display of minimum gray values within a volume dataset. This algorithm can be useful for displaying vascular structures and fluid-filled organs [73-74]. The MPM can provide important insight into the spatial relationships of abnormal vascular connections to the fetal heart in the upper mediastinum and could potentially be useful in the determination of atria morphology in cases of left and right isomerism.[39] (Fig. **14**)

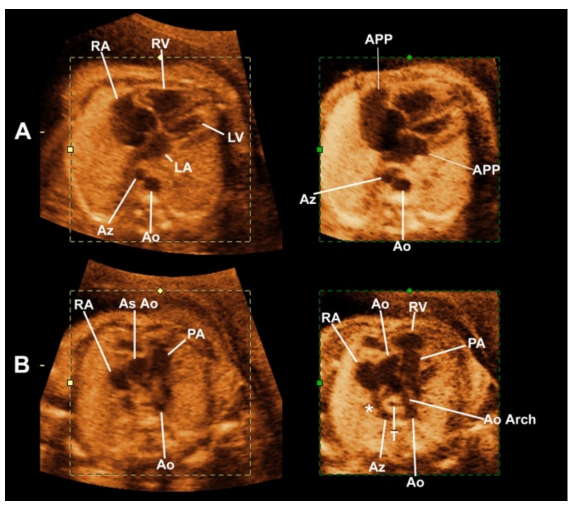

Figure 14: Comparison of minimum projection mode (MPM) images, on the right, with their corresponding two-dimensional images, on the left, in a case of left isomerism with interrupted IVC and azygos continuation. A) The four-chamber view shows a two-vessel sign; the MPM image shows that both atria appendages (APP) are morphologically left; B) Three-vessel view. In the MPM image, the azygos vein drains into the superior vena cava (SVC) and the right atrium, whereas the two-dimensional ultrasound image shows only the ascending aorta, the pulmonary artery and the dilated right atrium. RA: right atrium, RV: right ventricle; LV: left ventricle; LA left atrium, Ao: aorta; AZ: Azygos vein; PA: pulmonary artery; Ao Arch: aortic arch, T: trachea, *: Azygos' arch

B-flow

B-flow is a new display modality in 4D ultrasound that digitally enhances signals from weak blood reflectors from vessels and, at the same time, suppresses strong signals from surrounding tissues [75-77]. Because this technology does not rely on Doppler methods to display blood flow, it is angle-independent and does not interfere with the frame rate. This is potentially advantageous over color or power Doppler imaging when used in conjunction with

STIC for the evaluation of the fetal vasculature. In B-flow imaging the echoes from the tissue and that of the blood flow can be displayed with high resolution and without the overlay that characterizes color Doppler imaging. Moreover, B-flow may have less signal drop out when the ultrasound beam is perpendicular to the vessel. The use of B-flow in the case presented herein demonstrates that this imaging modality provides important insight into the location and nature of arch abnormalities in fetuses with coarctation of aorta. Indeed, B-flow allowed for a clear visualization of a thin and tortuous aortic arch as well as its spatial relationships with the fetal heart and other vascular structures (Fig **15**).

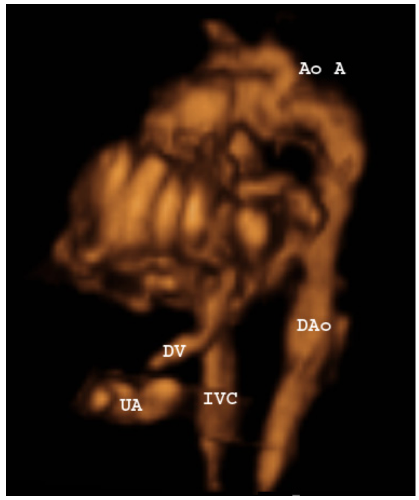

Figure 15: B-flow imaging of a narrow and tortuous aortic arch aortic arch and its relationship with the heart and other vascular structures: aortic arch (Ao A), descending aorta (Dao), ductus venosus (DV), inferior vena cava (IVC), umbilical artery (UA)

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