

Four D and 2D Echocardiographic Evaluation of Anomalies of the Venous Connections

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Abstract: Abnormalities of systemic and pulmonary venous connections are among the most frequently missed congenital heart disease (CHD) in prenatal ultrasound studies. In fact their prenatal US detection is difficult and requires adequate image resolution and attention to detail.

Recently, three-four D US has been suggested to provide a significant contribution to our understanding of the developing heart in both normal and anomalous cases. In particular “B-flow-STIC imaging” and “inversion mode” have been demonstrated to supply additional information over that provided by 2D US in the prenatal diagnosis of some congenital heart defects, including abnormalities of the venous connections.

In this chapter we report the 2D prenatal characterization of the most common anomalies of the venous connections, and describe the application and added value of 4D echocardiography with B-flow-STIC imaging or with inversion mode in the prenatal diagnosis of total anomalous pulmonary venous connections and abnormal systemic venous connections respectively

Key Words: 4D Sonography, Fetal Echocardiography, Venous Connection.

INTRODUCTION

Abnormalities of systemic and pulmonary venous connections are often associated with additional heart defects which may be simple or complex, such as those associated with a heterotaxy syndrome [1]. Their prenatal detection is difficult and requires adequate image resolution and attention to detail.

Abnormal systemic venous connections (ASVC) include anomalies of the left and right superior vena cava and coronary sinus, and anomalies of the inferior vena cava.

Anomalous pulmonary venous connections can be partial (PAPVC) or total (TAPVC). TAPVC is characterized by the anomalous drainage of all the pulmonary veins, whereas PAPVC is characterized by the anomalous drainage of one, two, or three of the four pulmonary veins.

Three-four D US has been suggested to provide a significant contribution to our understanding of the developing heart in both normal and anomalous cases [2-8]. In particular “B-flow-STIC imaging” and “inversion mode” have been demonstrated to supply additional information over that provided by 2D US in the prenatal diagnosis of some congenital heart defects (CHD) due to the ability to trace the spatial course of the vessels involved in the anomaly [3, 5, 8,-10], and to facilitate the identification of small vessels [8-10]. In-fact B-flow – STIC imaging seems to improve the accuracy of prenatal diagnosis either of TAPVC [8-10] and of ASVC whereas inversion mode has been used only in the cases of ASVC [5]. In this chapter we report the 2D prenatal characterization of the most common anomalies of the venous connections, namely total anomalous pulmonary veins connection, persistent left superior vena cava (LSVC) with dilation of the coronary sinus (CS), interrupted inferior vena cava (IVC) with azygos continuation and describe the application and added value of 4D echocardiography with B-flow-STIC imaging or with inversion mode in the prenatal diagnosis of TAPVC and ASVC respectively.

B-FLOW TECHNOLOGY

B-flow is a technique that uses digitally encoded sonographic technology to provide direct visualization of blood echoes in gray-scale [11]. It simultaneously displays both tissue morphology and blood flow using the same gray-scale schemes (unlike color Doppler flow, in which the color signals are superimposed onto structural gray-scale images). The B-flow image does not interfere with the information produced by B-mode because both utilize the same spatial resolution and frame rate.

When compared with color and power Doppler US, B-flow sonography has a higher frame rate and better spatial

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resolution. It allows angle independent detection of weak blood reflectors from vessels. In fact, the peripheral small blood vessels with low flow velocity can be demonstrated, because of direct visualization of blood reflectors.

The resulting image is a live gray-scale depiction of blood flow and part of the surrounding lumen. Since B-flow is one of the options of gray-scale mode a swift-switching between conventional 2D imaging and B-flow imaging can be easily obtained.

B-flow technology can be also combined with STIC (spatio temporal image correlation) (General Electrics, Kretztechnik, Zipf, Austria). STIC is an acquisition modality of fetal heart volume allowing the visualization of cardiac structures as a 4Dcine sequence, that can be combined with other applications by selecting the appropriate setting before acquisition (B-flow, color and power Doppler, ecc) or with post-processing visualization modalities (inversion mode, tomographic ultrasound imaging etc) [6].

As detailed above, B-flow with STIC allows to make precise evaluations of spatially complex vascular anomalies and to improve the visualization of very low flow and tiny vessels, which is of major interest in the definition of complex CHD including TAPVC.

The following descriptions and procedures are referred to B-flow combined with STIC.

Volume Acquisition

Before acquiring heart volume, B-flow sensitivity and persistence need to be set accordingly: the evaluation of arterial flow requires high sensitivity and low persistence, whereas the examination of venous flow with low velocity is achieved with a higher persistence and lower sensitivity.

The acquisition technique has been described elsewhere [6]. Briefly, once the sagittal and transverse view of the fetal heart is visualized, heart volume datasets are acquired with B-flow imaging and STIC using automatic sweeps through the fetal thorax. If the operator is interested in the evaluation of the 4D reconstruction of the heart or the outflow tracts, optimal volume datasets of the 4-chamber view using transverse sweeps through the fetal thorax need to be acquired. If the operator wants to review the aortic and ductal arches, high-quality volume datasets are best acquired using sagittal sweeps through the fetal thorax. A detailed study of pulmonary venous connections requires the use of either transverse and sagittal sweeps through the fetal thorax whereas only sagittal sweeps through the fetal thorax are required for the study of systemic venous connections. The volume of interest is acquired with a sweep angle of approximately 20–40° (depending on the size of the fetus) that is usually sufficient to include the stomach, the heart, its vascular connections, including the venous ones, and the neck vessels. The size of the acquisition box is adjusted by placing its borders just outside the skin of the fetal chest. The acquisition time can be selected between 7.5 and 15 seconds.

Multiplanar Display

Once a volume is successfully obtained, it is displayed on the screen in a multiplanar image format, demonstrating one cardiac cycle beating in the three orthogonal planes (Fig. 1).

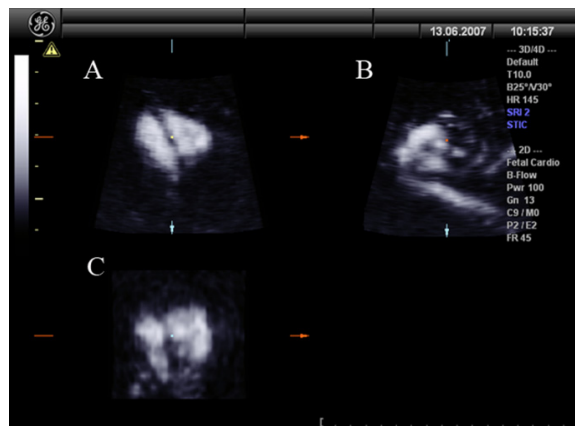


Figure 1: Multiplanar display of a volume dataset acquired using transverse sweep through the fetal thorax with B-flow and STIC. The A-plane is the acquisition plane and has the best image quality (upper left). The plane perpendicular to A but parallel to the ultrasound beam is identified with the letter B (upper right). The plane that is both perpendicular to A and to the ultrasound beam is defined as C (lower left) and is commonly referred to as the coronal plane. The B and C planes are the orthogonal planes

which have been reconstructed by the system. Therefore, the quality of the acquired volume can be estimated online by directly analyzing the B-plane.

The display and manipulation of volumes acquired by STIC and B-flow require a substantial learning curve. Spatial orientation may be difficult to determine and, in particular, the accurate anatomical identification of left/right and dorsal/ventral sides may be confusing after several rotations and changes of plane. These difficulties hold true for 3D volumes involving anatomically complex organs such as the fetal heart, but they are most true for a new technique of flow display such as B-flow technology. For these reasons, a standardization of the orientation of the fetal heart on-screen prior to the storage of dynamic volume datasets is a required initial step. A standardization of the modalities of display of heart volumes needs to be applied in the A, B, and C planes to ensure uniformity of orientation in the 3 dimensions. Each volume should be initially standardized in plane A (reference plane, 4-chamber view); the volume should be rotated so that the heart can be visualized at all times in a known anatomical position as if the fetus is always in vertex presentation with the apex of the heart on the left part of the panel A and the spine positioned at 6-o'clock.

In this position, on the panel B, a sagittal view of the fetal thorax is displayed with the fetal head on the left side, the fetal breech on the right side of the screen and the dorsal portion of the fetus at the bottom of the image. In this case, on the panel C, a coronal view of the fetal thorax is obtained (Fig. 2).

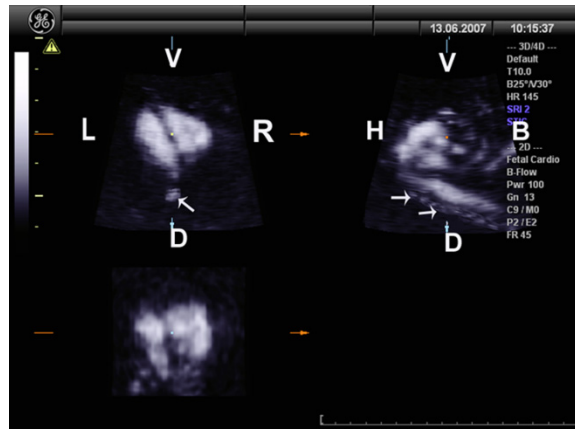


Figure 2: Multiplanar display of the B-flow-STIC volume in a fetus in a cephalic presentation. On panel A, the apex of the heart is positioned on the left part of the image (L); the spine (arrows) is at 6 o'clock position. On panel B, a longitudinal view of the fetal thorax is displayed with fetal head (H) on the left side of the image and fetal breech on the right side (B). R, right; V, ventral; D, dorsal.

If the fetus is lying in breech presentation with the heart apex on the right side of the panel A and with the fetal head on the right of the panel B (Fig. 3), an image rotation by 180° on the y-axis is required. In this way, the final appearance will be that shown in Fig. 2.

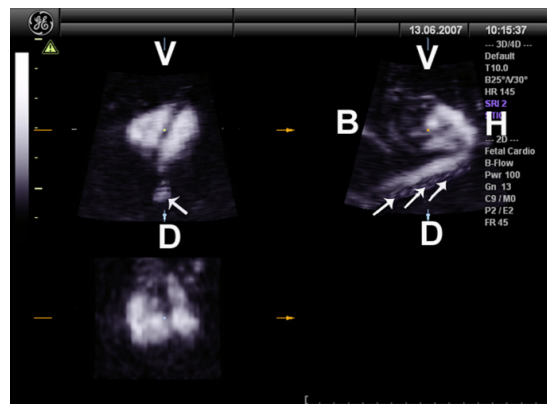


Figure 3: Multiplanar display of the B-flow-STIC volume in a fetus in a breech presentation. On panel A, the apex of the heart is positioned on the right side of the image; the spine (arrows) is at 6 o'clock position. On panel B, a longitudinal view of the fetal thorax is displayed with fetal head (H) on the right side of the image and fetal breech (B) on the left side. V, ventral; D, dorsal.

The use of this view will ensure that the spatial orientation of the fetus will always be the same, by simple manipulations of the volumes.

Rendering Mode

Rendering mode allows to obtain realistic images of structures of interest that may be difficult to obtain by B-flow alone. Once the volume rendering is applied to the dataset, 3D image is displayed in the right lower panel of the screen (panel D). When the render option is activated on the 4D-viewer software, the operator should change the direction of the region of interest (ROI) and he should select one among 6 options. A craniocaudal direction of the ROI (green line on the left side of the panel B) must be selected to obtain a 3D image with the same orientation as in panel A (Fig. 4).

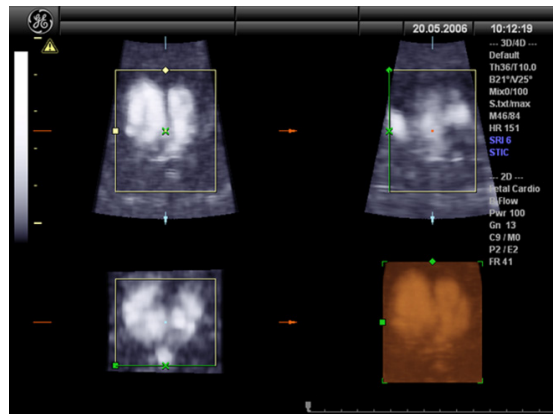


Figure 4: B-flow-STIC volume. When the render option is activated, a 3D rendered image is shown on panel D (lower right). Note that green line is on the left side of panel B to obtain a 3D rendered image with the same orientation as in panel A.

The thickness of the ROI may be adjusted in an attempt to display a thick-slice rendering comprising the fetal heart and its vascular connections, according to the endpoint of the rendering. Surface rendering mode may also be modified and a mixture of gradient light plus surface algorithms is selected ([Video 1](#)).

Post processing adjustments in image quality must be also performed as necessary and include: (1) gamma curve correction to optimize tissue contrast resolution, and (2) gray scale threshold and transparency to improve border recognition of surface-rendered volumes. Generally, the transparency level must be set to 20, and the threshold level between 70 and 80 (both scales range from 0 to 250). Finally, a rotation of the 3D image along the x- z- and y-axis may be needed to improve the visualization of the structures of interest.

INVERSION MODE

The “inversion mode” is a rendering algorithm that transforms echolucent structures into echogenic voxels. 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.

Since this technique, such as B-flow, does not use color or power Doppler sonography, it does not interfere with the frame rate and it does not have the inherent limitations to image reconstruction related to the angle of insonation, temporal resolution, or intensity of the Doppler signal.

The inversion mode has been proposed as a technique capable of producing digital casts of the aortic and ductal arches and as a useful method to improve prenatal diagnosis of abnormal systemic venous connections. Therefore, the relationships between the fetal heart and great vessels and other fluid-filled non-vascular structures such as the esophagus and stomach can be visualized in a single volume dataset. Limitations of inversion mode are the absence of information regarding the velocity or direction of blood flow and it does not differentiate blood vessels from other hollow structures.

Volume Acquisition

The inversion mode is applied to the volume data sets acquired with B-mode imaging. To obtain a high-quality volume dataset of the systemic venous connections, once the sagittal view of the heart is observed, the acquisition

should be performed with sagittal sweeps through the fetal chest and abdomen using the spatio-temporal image correlation (STIC) technique. The time of acquisition should be lasted between 7.5 and 12.5 s, and the acquisition angles should be varied from 15° to 35°.

Volume Rendering

Volume dataset is initially displayed using multiplanar slicing. Once the volume rendering is applied to the dataset and a 3D image with the same orientation as in Panel A is displayed in the right lower panel of the screen, the inversion mode should be then applied to the volume dataset.

A thick-slice rendered image of the volume dataset should be done showing the fetal heart and its connections. Surface rendering mode can be improved if a mixture of ‘gradient light’ and ‘surface’ algorithms is selected. Post processing adjustments should be performed as necessary, including gamma curve correction to optimize tissue contrast resolution and gray scale threshold, and transparency to improve image quality. Usually low threshold and transparency levels should be adjusted until the structures of interest are visualized.

Total Anomalous Pulmonary Venous Connection

TAPVC is a multifaceted group of malformations affecting the pulmonary veins (PVs). The essential feature of these anomalies is that all the PVs drain into a site other than the morphological left atrium [10], ([Video 2](#); Fig. 5A, B).

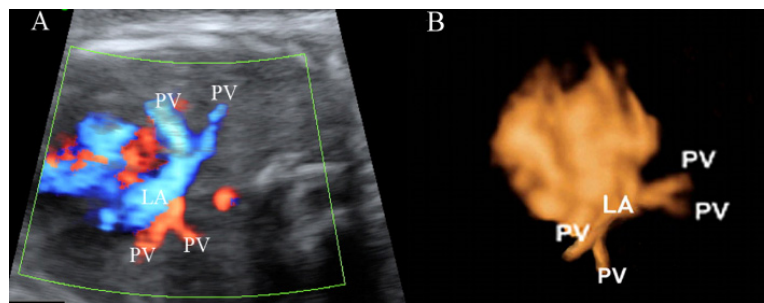


Figure 5: A. Two-dimensional ultrasound image. Color Doppler allows to visualize the four pulmonary veins entering the left atrium (LA). B. B-flow-STIC imaging. Normal connection of all four pulmonary veins (PV) to the left atrium (LA).

Usually, all PVs drain to the same site; however, in a few patients, different PVs are connected to separate anomalous sites. It can be categorized by the site of drainage in supracardiac, cardiac, infracardiac and mixed.

Supracardiac connection can be to the innominate vein, or directly to the right superior caval vein, to the azygos system of veins or to the left caval vein. In the most common pattern, all the 4 PVs join into a venous channel, traditionally termed the confluence, located behind the left atrium (Fig. 6A, B).

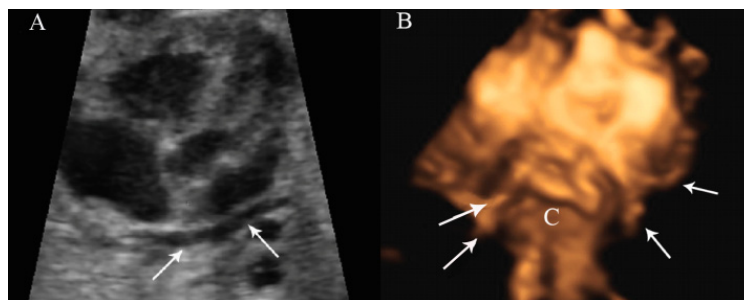


Figure 6: A. Two-dimensional ultrasound image showing the confluence (arrows) of pulmonary veins, posterior to the left atrium. B. B-flow-STIC imaging showing the drainage of each PV (arrow) into the confluence (C), which appears large and tortuous

From this horizontal channel, an ascending vertical vein (Fig. 7) runs up to join with the innominate vein, which then terminates in the right superior caval vein.

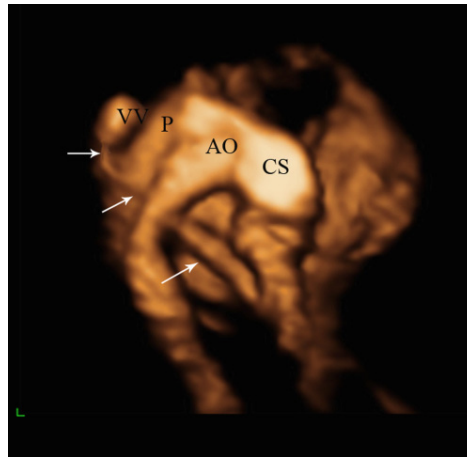


Figure 7: Supracardiac total anomalous pulmonary venous connection. B-flow-STIC imaging showing the ascending vertical vein (VV) and the spatial relationship between the confluence and the great vessels. The arrows indicate the entire course of the confluence. It is anterior to the thoracic aorta and drains into the ascending vertical vein. AO, thoracic aorta; C, superior vena cava; P, pulmonary artery.

The chance of obstruction of the vertical vein is crucially related to its course and is highest when the vein passes between the left pulmonary artery and the left bronchus, which thereby forms a vice constricting the anomalous vessel. Albeit less frequently, an obstruction can also occur at the opening of the innominate vein into the superior vena cava.

When TAPVC occurs through the coronary sinus (CS) it is defined as cardiac connection ([Video 3](#)). The enlarged CS could then function as an horizontal collecting venous channel. In this pattern of TAPVC, an obstruction to the venous return is rare. A direct connection of the PVs to the morphologically right atrium is seen most frequently in the setting of right isomerism. In this case both atria are of right morphology and the CS is absent. In the infracardiac pattern, PVs join together and enter a descending vertical vein that passes into the abdomen through the oesophageal orifice of the diaphragm ([Fig. 8A, B](#)).

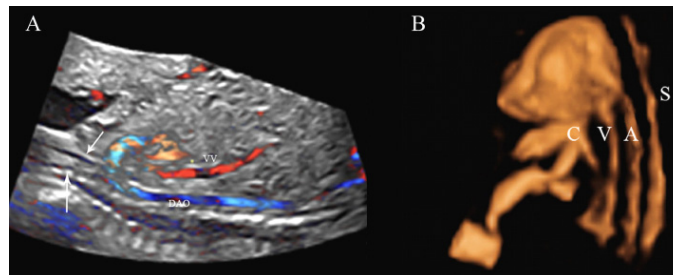


Figure 8: Infracardiac total anomalous pulmonary venous connection. **A.** Two-dimensional ultrasound image showing the descending vertical vein (VV) anterior to the descending aorta (DAO). The arrows indicate 2 neck vessels. **B.** B-flow- STIC imaging showing the descending vertical vein (V) which courses between the inferior vena cava (C) and the descending aorta (A); S, spine.

It then usually drains to the portal vein or to one of its tributaries and rarely to the inferior caval vein. In the former event, an obstruction is almost always present following the closure of the venous duct, because the blood must pass through the hepatic tissue to reach the systemic veins. Additionally, discrete stenoses can be found as the vertical vein passes through the diaphragm. The PVs confluence often tends to have a vertical course. Of note, it usually appears as a discrete chamber, but at times it is rather small behind the left atrium in its sopradiaphragmatic portion, and can be hardly appreciated by conventional 2D US. In the mixed pattern, the PVs drain separately to different anomalous sites.

Sonographic Findings

2D Echocardiography

Anomalous connection of the pulmonary veins is notoriously misdiagnosed prenatally, especially when isolated. In the few cases described prenatally, TAPVC is often associated with other cardiac anomalies in the context of heterotaxy syndromes. The diagnosis can be suspected on the 4-chamber view. Indirect signs of TAPVC are:

- 1) moderate atrioventricular disproportion, with the right sections larger than the left ones (in supradiaphragmatic forms).
- 2) a pulmonary artery significantly larger than the ascending aorta.

The fetal echocardiographic clues to the diagnosis of TAPVC include failure to demonstrate a direct pulmonary venous connection to the left atrium, the detection of a venous confluence behind the left atrium (Fig. 6A), and the visualization of an ascending or descending vertical vein (Fig. 8A). Color Doppler (with low PRF to detect the extremely low-velocity pulmonary venous flow) may be used to confirm the vascular nature of the sonolucent area behind the left atrium (differentiating it from the esophagus). Spectral Doppler assessment can then be used to detect the typical pulmonary velocity waveform.

4D Echocardiography

B-flow imaging and STIC can be advantageously used to locate normal (Fig. 5B) and abnormal pulmonary venous returns. It enables to clearly visualize the confluence of PVs (Fig. 6B), and the vertical vein departing from it (Fig. 7, 8 B). In addition, B-flow STIC imaging supplies a detailed view of the course and size of each PV, thereby allowing to reliably rule out the existence of single PV hypoplasia or atresia

Abnormalities of the Systemic Venous Connections

Interrupted Inferior Vena Cava with Azygos Continuation

The prevalence of abnormal systemic venous return to the heart in children with congenital heart disease is 6.6%, and can reach as much as 70% in complex heart defects such as heterotaxic syndromes[5]. A frequent venous anomaly associated with these syndromes is the absence of the IVC between the renal veins and the hepatic veins. The right supracardinal vein persists to connect the caudal IVC to the azygos vein. This form of abnormal venous return is the result of connection failure between the right subcardinal vein and hepatic veins, and is present in most of cases with left isomerism (80-90% of cases); however its association with right isomerism (2,5% of cases) or with usual atrial arrangements has been reported. When there is interruption of the inferior vena cava with azygos continuation, the venous blood from the lower part of the body is usually drained into a dilated azygos or hemiazygos vein and reaches the right atrium through a superior vena cava. Usually, with azygos continuation, this is the right superior vena cava, whereas with hemiazygos continuation, the blood often reaches the right atrium through a persistent left superior vena cava and dilated CS. The azygos or hemiazygos veins ascend in parallel to the right or the left of the descending aorta respectively, before joining their corresponding superior vena cava.

Persistent Left Superior Vena Cava with Dilation of the Coronary Sinus

A persistent left superior vena cava (PLSVC) is due to the persistence of a vessel that commonly obliterates in the first trimester of gestation. There are two types of PLSVC. PLSVC connecting to the right atrium via a dilated coronary sinus forms 90% of the anomalies of the superior vena cava. In the remaining 10%, PLSVC connects to the left atrium. It is estimated that PLSVC occurs in 0.3–0.5% of the general population and up to 10% of cases in patients with CHD [12-13]. Commonly, a normal right superior vena cava (RSVC) is associated. Less frequently, however, the RSVC is absent and the PLSVC represents the only systemic vein draining blood from the upper part of the body back to the heart [13].

During the sixth week of development the cardinal veins constitute the main systemic venous drainage of the embryo [12- 14]. In fact the primary atrium receives venous tributaries from both sides of the embryo through the common cardinal (caval) vein, which connects the paired superior (which drain the cranial parts) and inferior caval veins (which drain the caudal parts). At 8 weeks, the innominate vein forms between the 2 SVCs. At 9 weeks, the left SVC is normally obliterated and only the right SVC remains [12]. The presence of a persistent LSVC can be attributed to the persistence of the proximal part of the left anterior cardinal vein [13,14]. The coronary sinus, which collects myocardial venous blood, develops from the left common caval vein, initially connected to the left superior and inferior vena cava. This explains why the vein is connected to the coronary sinus in most cases of persistent left SVC [12].

A persistent LSVC, if isolated, usually is an asymptomatic condition of no haemodynamic significance [13,14]. However, due to its significant association with other heart defects and extra cardiac anomalies, the recognition of a PLSVC should prompt a detailed cardiac and extra cardiac examination [13,14].

Sonographic Findings

2D Echocardiography

When **interruption of the inferior vena cava with azygos continuation** is present, on the axial view of the abdomen, the azygos is close and lateral to the abdominal aorta ([Video 4](#)) and not anterior as with the inferior vena cava ([Video 5](#)). In addition on the four chamber view behind the left atrium 2 vessels rather than one of similar size but different pulsatility are identified ([Video 6](#), [Video 7](#)). The presence of two vessels behind the fetal heart has been described as the “two vessels sign”. This sonographic sign represents the descending aorta and a dilated azygos/hemiazygos vein. The connection of the azygos to the superior vena cava can be demonstrated in longitudinal view of thorax.

The echocardiographic feature of a dilated coronary sinus is easily recognized in cases of **left superior vena cava with connection to a coronary sinus**. In fact it appears prominent in a basal four-chamber view of the heart ([Fig. 9](#), [Video 8](#)).

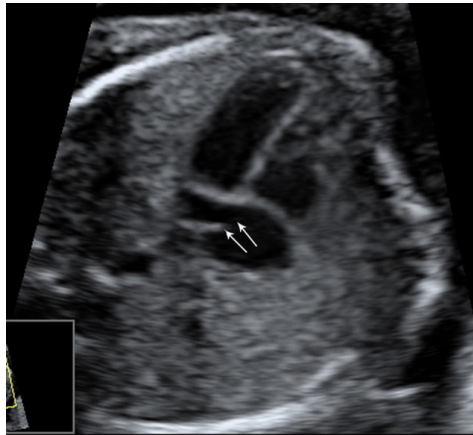


Figure 9: Persistent left superior vena cava. Two-dimensional ultrasound image. Axial view through the lower part of the 4-chamber view showing the dilated coronary sinus (arrows) posterior to the mitral valve.

The increased caliber of the CS is an important indirect marker of central venous drainage abnormalities [10]: in most cases it is associated with persistence of left SVC drainage into the CS, but, less frequently, it may be associated with the presence of cardiac TAPVC. The diagnosis of left superior vena cava is confirmed on the “three vessel view” ([Fig. 10](#)) where PLSVC can be identified to the left of the pulmonary trunk. If RSVC is also present, four instead of three vessels are seen ([Video 9](#)).

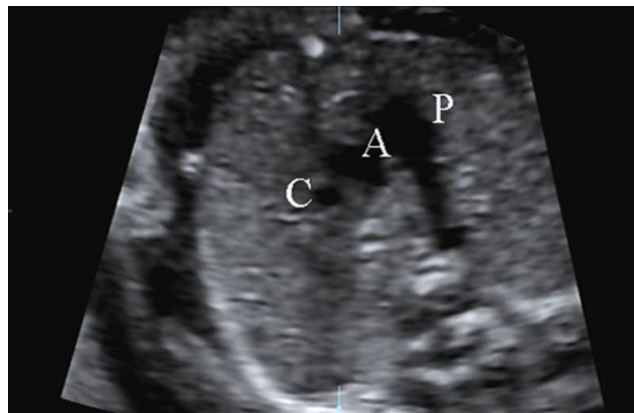


Figure 10: Three-vessel view of a normal fetus. The three vessels are (from right to left) the superior vena cava (C), the ascending aorta (A), and the pulmonary trunk (P). The pulmonary trunk is the largest vessel and most anterior; the superior vena cava is the smallest vessel and most posterior; the ascending aorta is in between.

When the RSVC is absent there are only three vessels: LSVC, pulmonary trunk and ascending aorta ([video 10](#)). Sagittal view of the heart, demonstrates indirect drainage of PLSVC via the coronary sinus into the right atrium ([Fig. 11](#)).

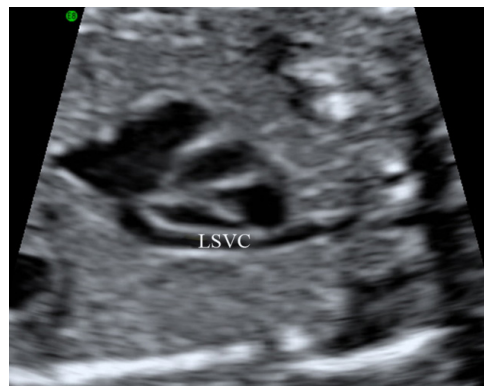


Figure 11: Persistent left superior vena cava. Two-dimensional ultrasound image. Sagittal view of the fetal thorax showing the persistent left superior vena cava (LSVC) and coronary sinus forming a J-shaped channel.

4D Echocardiography

4D with inversion mode clearly shows the dilated azygos vein which ascends parallel, and to the right of the descending aorta before joining the SVC (Fig. 12).

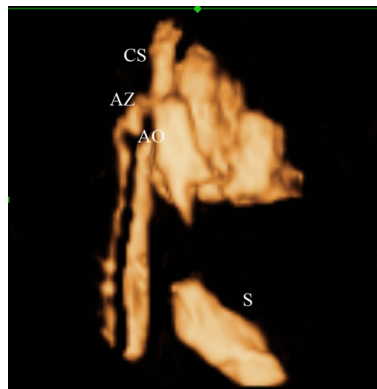


Figure 12: Interrupted inferior vena cava with azygos vein continuation. Three-dimensional image of a fetal heart rendered with inversion mode showing the arch of the azygos vein (AZ) joining the superior vena cava (SVC) before entering the right atrium. The parallel course of the dilated azygos vein and aorta (AO) can be seen.

In addition inversion mode improves prenatal visualization of spatial relationship of the azygos vein with the surrounding cardiovascular structures including the descending aorta.

A persistent left SVC and its spatial relationship with the surrounding cardiac structures is clearly visualized with 4D with inversion mode (Fig. 13).

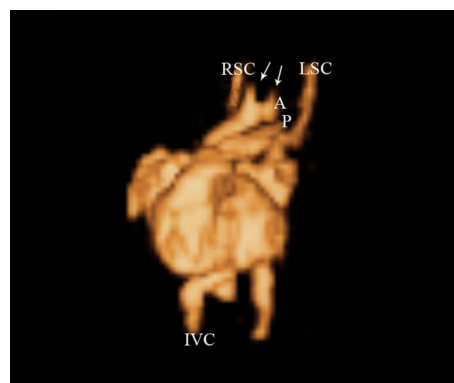


Figure 13: Persistent left superior vena cava. Three-dimensional image of a fetal heart rendered with inversion mode showing a persistent left SVC and its spatial relationship with the surrounding great vessels. The arrows indicate 2 neck vessels. RSC, right superior vena cava; P, pulmonary artery; A, aortic arch; IVC, inferior vena cava.

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