Chapter 22

Spatial and Temporal Image Correlation and Other Volume Ultrasound Techniques in the Fetal Heart Evaluation After 10 Years of Practice

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INTRODUCTION

It has been over 10 years since the first attempts of using three-dimensional (3D) ultrasound in fetal echocardiography were made.[1-5] At first, there were hopes that with the use of this method, we would be able to obtain more accurate images and would have access to cardiac views impossible to visualize with the use of two-dimensional (2D) ultrasound.[2] From the very beginning of applying 3D methods, new teleconsulting opportunities have been created in this field.[6,7] In the recent years, there was a progress in shortening of the acquisition time of 3D volume data with the use of matrix transducers.[8,9] From the time perspective, the authors of this chapter, being modern imaging techniques practitioners, reached the conclusion that the greatest achievement of utilizing those methods is the possibility of understanding of complex anatomy of a normal fetal heart and a heart with congenital defects by a noncardiologist. Because of this fact, fetal heart examination is easier to systematize and standardize. Taking the above into consideration, 3D techniques are of a priceless didactic value. Owing to them, it is possible to simulate the evaluation of congenital heart disease and compare this situation with the 3D datasets during the training sessions and workshops. On the basis of 3D fetal echocardiography, three-dimensional printouts used for learning to diagnose fetal heart diseases have been worked out.[10] However, a wider application of these methods in screening is more difficult because of obvious limitations of volume ultrasound like motion artifacts, shadowing behind fetal skeletal structures and changing scanning conditions even in the same patient.[11,12] All these elements, which are essential factors of ultrasound examination, limit reproducibility of volume ultrasound in fetal heart evaluation. A number of methods based on automated mapping of fetal heart views from 3D volume datasets have been developed.[13-15] Nevertheless, all these methods are based on the analysis of normal heart geometry and their diagnostic application, according to the authors, is very limited. In terms of scan duration these techniques are most of the time inferior to simple 2D sweeps in grey scale and color mapping. However, the producers of ultrasound equipment are still developing automated methods and taking into account the progress in the aspect of shortening the acquisition duration, under the condition of considering differences among geometric hearts with congenital diseases, those methods may bring the expected diagnostic results in the future.

TECHNICAL ASPECTS

At this point in time, among 3D techniques used for assessment of fetal heart, it is possible to distinguish the following acquisition techniques:

- Static 3D
- Spatial and temporal image correlation (STIC)
- 4D real time/3D live in multiplanar view and biplanar view.

Static 3D

Due to the dynamic character of examined organ, which contracts with a great frequency, 3D static acquisition is done in exceptional cases. It is usually used for acquisition of the whole fetal trunk in order to obtain information about the visceral situs and both thoracic and abdominal organs considering their structure **(Figs 22.1 and 22.2)**.

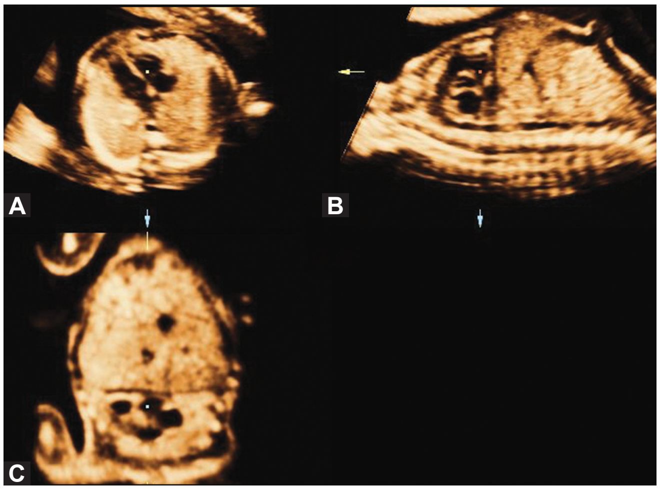


Figure 22.1 A 3D static dataset presenting the multiplanar view of the fetal heart with the correct arrangement of viscera (situs solitus). This is a properly oriented volume dataset. In the A plane (upper left image) the axis of the heart is directed to the left. In the B plane the section is through the ductal arch (the heart seen on the left). In the C plane the coronal section through the fetal chest in shown

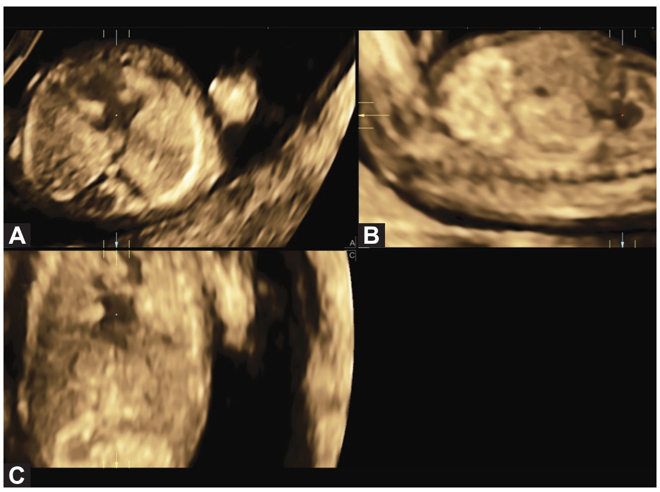


Figure 22.2 A 3D static dataset presenting the multiplanar view of the fetal heart with the abnormal arrangement of viscera (situs inversus). This is a properly oriented volume dataset. In the A plane (upper left image) the axis of the heart is directed to the left. In the B plane the heart is seen on the right. In the C plane the coronal section through the fetal chest in shown

With this method, it is possible to detect situs abnormalities and severe abnormalities in the cardiac structure.

The main cause of its limited use is the fact that static examination does not include the functional aspect. Therefore, the most often-used volume technique to examine a fetal heart is STIC because of fast fetal heart rate, which is about 150 BPM.

Spatial and Temporal Image Correlation

The concept of spatial and temporal image correlation (STIC) consists of a slower static 3D acquisition of the fetal heart, encompassing approximately 25 cycles. During the process of acquisition, the beam is swept through the heart capturing diastole and systole in tiny subphases. (**Fig. 22.3**).[2,16] For example, as the beam sweeps into the four chamber view it is recorded in the phase of early then mid and late diastole, then early mid and late systole. As the sweep continues into

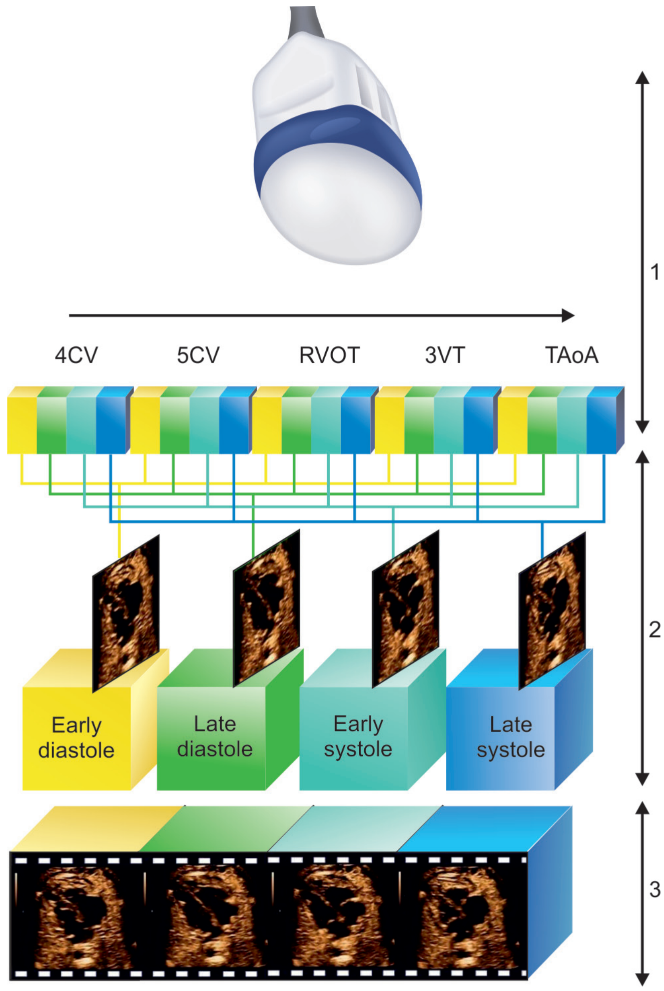
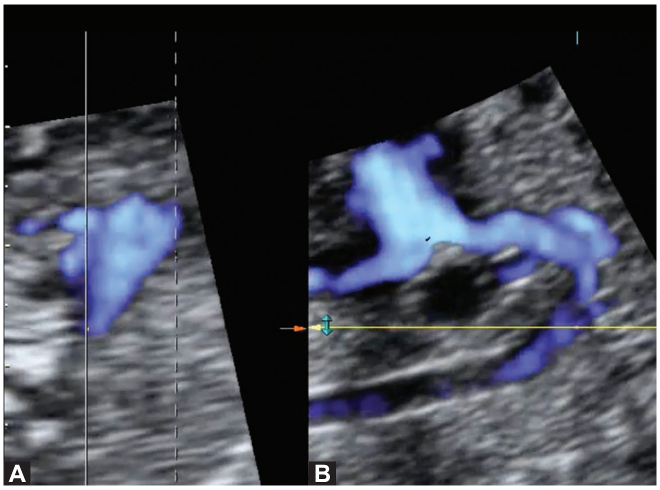


Figure 22.3 STIC acquisition and processing is presented: One slow 3D sweep. The machine detects the location and timing of each systolic beat and calculates the heart rate. Then the system determines the time frame between each beat which allows for rearranging of the B-mode frames into a new order depending on their temporal event within the heart cycle. Since, the machine knows the length of the sweep and the heart rate it can calculate the location of each peak systolic frame and other points in the cardiac cycle and combine the information in it with all the other frames of the corresponding times. Because many frames at the exact time reference are averaged together the temporal resolution compares to a high frame rate B-mode image. The rearranging results in a final product of one heart cycle replayed in a continuous cine loop

the five chamber view it is also captured in the phase of early mid and late diastole, then early mid and late systole, and so on, until the sweep reaches the most superior part of the heart, the transverse section of the aortic arch. The result is one large static volume block. Each individual subphase of the cardiac cycle is then rearranged temporally and grouped into new separate volume blocks. Eventually, approximately 20 to 40 blocks come into being.[2] The quality of the final product depends on the speed of the acquisition sweep. A slower sweep allows for more subphases of the cardiac cycle to be obtained, grouped together and rearranged, which adds spatial information to the final product. The final product is presented in the form of an orderly dynamic sequence, a clip, which is arranged into 1 full cardiac cycle, from the early phase of diastole to the late phase of systole in all planes, from the four-chamber view to the transverse section of the aortic arch.



Figures 22.4A and B Biplanar view. (A) Three-vessel and trachea view presenting a tiny aortic arch; (B) Sagittal view of the hypoplastic aortic arch

4D Real Time

Despite technological progress, 4D technique is still of worse quality than the STIC and even with the use of the most modern matrix transducers the STIC acquisition is preferred because of higher frequency of recorded volume datasets. Because of that more subphases of the cardiac cycle can be displayed, what provides the examiner with more comprehensive functional information. Classic hybrid volume transducers allow capturing the fetal heart in 4D mode on the level of a few volumes per second on average, which is not to be accepted in fetal heart examination. Matrix transducers allow recording with the frequency of 15 volumes on average. However, an average of STIC acquisition in B-mode has better results with the frequency of approximately 40 volumes per second. However, if the examiner considers an analysis of a particular part of the heart, like e.g. the aortic arch or systemic veins, 4D offers a unique method of biplanar view in real time.[9] With the use of this technique, the examiner is able to follow aortic arch in axial and sagittal views at the same time. Such imaging may be of a great importance in the assessment of aortic coarctation, aortic arch hypoplasia, or aortic arch interruption **(Figs 22.4A and B)**.

Because of above-mentioned facts, the authors will focus on STIC mode in the further part of the chapter.

THE PROCESS OF STIC ACQUISITION

It is to be divided into two fundamental stages:

- The first one is connected to the preparation to the acquisition and the acquisition itself
- The second one consists of the verification of conducted acquisition, saving volume dataset in the scanner memory and volume dataset review by the use of wide spectrum of visualization modes.

Preacquisition and Acquisition Stages of Fetal Heart Assessment in STIC mode

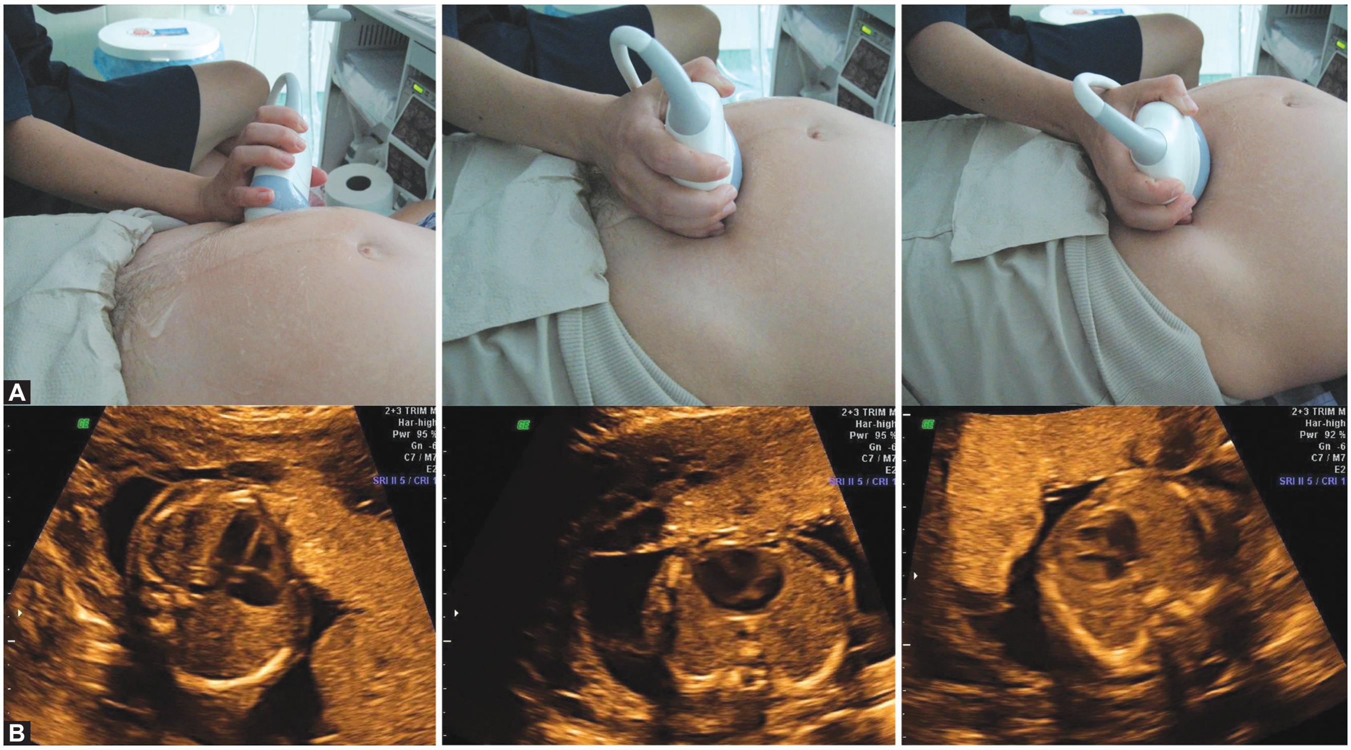
Before Acquisition

Every volume dataset irrespective of applied method should be preceded by a series of preparatory proceedings. The first and the most important is the choice of acoustic window, which is the shortest way to the examined organ, which reduces the number of artifacts.

There are two most often used techniques of acquisition: axial and sagittal one. This is the reason why the preparatory proceedings should be explained for each of these techniques separately.

Axial Acquisition

At this stage, the examiner is forced to find the most optimal place to apply the transducer, which allows for the sweep of cardiac views presenting lack or minimal shadowing resulting from fetal skeletal structures. "Escaping" from acoustic shadows is of utmost importance and every sonologist and sonographer must assure that shadows are not encountered in any section of the heart. So before the STIC acquisition is initiated, it is prudent to make a 2D sweep through the heart imitating the STIC acquisition. If on some sections shadows are visible, one should seek a better acoustic window. It must be remembered that shadows from 2D images will always be rewritten on the three-dimensional dataset.



Figures 22.5A and B Translation technique is shown, which is actually nothing more than changing the application point of the transducer. At the time of translation the same section through the fetal chest is displayed on the monitor, but the relationship between the transducer and the target changes. Translation is used for identifying the most suitable insonation angle. (A) Movements with the probe on the patient's abdomen; (B) Effect of translation on the image

On account of that, on the basis of the authors' experience, the preferred insonation angle to interventricular septum (IVS) should reach about 45 degrees. Apical view with the apex at the 12 o'clock position is better to be avoided due to the suboptimal insonation to the IVS. The same situation concerns basal view, which is always connected with moderate shadowing from fetal ribs. The correction of the insonation angle may be conducted with the use of the transducer—by translation maneuver **(Figs 22.5A and B)**.

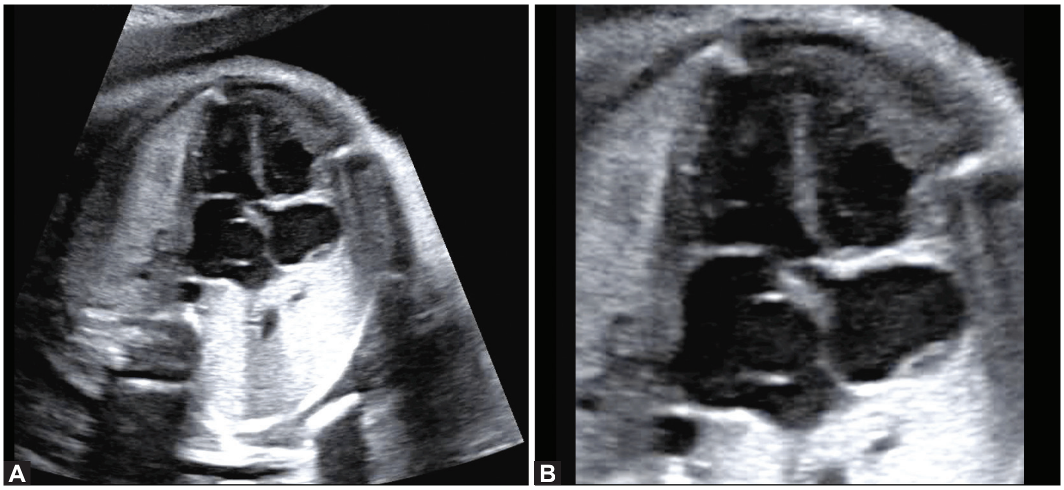
It should be also emphasized, especially for beginners, that the examiner should avoid oblique views during the acquisition. The acquisition should be conducted in possibly most accurate axial views. To maintain "clear" axial view it is helpful to make fetal ribs, which are a perfect landmark of symmetric cross-section through the fetal thorax. If on the screen there are a few ribs visible on one side, it means that the view should be corrected before the acquisition. Watch carefully for the ribs in the fetal chest to appear similar on both the right and left sides, and that the fetal abdomen and chest are round and not elongated. Keep your image angle wide enough to view the entire width of the fetus so you can easily identify structures that will help you recognize that you are in a true transverse section of the fetus.

Sagittal Acquisition

It is best if acoustic window allows clear visualization of sagittal views, without shadowing. Perpendicular insonation to the anterior thoracic wall is preferable, what minimizes shadowing artifacts.

B-mode Settings, Zooming and Framing

The next stage in the preparation for acquisition is a correct setting of the scanner, which equals to applying the highest transducer frequency, which does not enhance shadowing artifacts. Furthermore, in order to prepare for the STIC acquisition, the authors successfully apply presets based on the combination of harmonic imaging, compounding and speckle reduction. In addition, it reduces artifacts resulting from excessive ultrasound dispersion in fetal tissues. Together with the presented basic rules of setting the scanner in B-mode, paying special attention to saving volume datasets of fetal heart, HD zooming and framing is of a great importance. At the beginning, it is advised to set zooming and framing which cover the whole fetal chest. After going through basic learning process, which includes about 200 acquisitions, when the examiner is able to maintain the symmetry of axial and sagittal sections



Figures 22.6A and B 2D image preparation for STIC acquisition—framing and zooming. (A) A frame covers the whole chest with small magnification; (B) A frame covers only the heart and includes the descending aorta, high magnification

correctly, it is possible to apply HD zooming and set framing in such a way to show only the heart and descending aorta **(Figs 22.6A and B)**.

Such a manipulation increases the frame rate in 2D-mode, which in turn, leads to higher frequency of captured volumes in STIC mode. As a result, it gives a greater number of saved subphases of the heart cycle in the analyzed sequence of volumes. At this point, it should be emphasized that it is very useful in acquisition including information with color Doppler mapping, Power Doppler and bidirectional power Doppler. The minimum frame rate before volume acquisition in 2D when vascular mapping is on is 20 Hz. If it is lower, then the acquired color information is strongly disturbed.

Acquisition Settings

Now after a proper acoustic window has been selected it is time to make decisions regarding 2 important STIC parameters, the STIC volume angle and the STIC acquisition time.

The STIC volume angle refers to the length of the sweep. One should determine how large of an area that you want to acquire information within. The decision to set the volume angle is dependent on the size of the heart. The greater the size of the heart (gestational age of the fetus) the greater volume angle you will need. A rule of thumb for setting the degree of the angle coincidently coincides with the gestational age in weeks of the fetus.

When acquiring your volume from a transverse plane pick a volume angle that is bigger of 5 to 10 degrees than the gestational age in weeks. Example: an angle of 25 degrees is a good choice for a 20 week fetus. Use a 35 to 40 degree angle for a 30 week fetus.

When acquiring your volume from a sagital plane pick a volume angle that is the same as the gestational age in weeks plus 10 degrees. Example: an angle of 30 degrees is a good choice for a 20 week fetus. Use a 40 degree angle for a 30 week fetus.

Of course these numbers need to be adjusted larger in cases of cardiomegaly. A minimum angle size, which is acceptable for STIC use is 15 degrees.

The STIC acquisition time determines the length of the duration of the acquisition. Your choice in setting the acquisition time should depend on how active the fetus is at the time that you are trying to do your STIC acquisition. A longer time will create a sweep, which has more time to obtain information thus adding to the quality of the volume dataset. However, with a longer time also comes more opportunity for the fetus to move creating motion artifacts. You of course will have the opportunity to delete the volume and try again if the fetus moves during the acquisition. A minimum time for a STIC acquisition is 2 seconds and a maximum time is 15 seconds depending on the applied probe.

STIC Acquisition

After setting the equipment, the examiner should possibly quickly find the starting view (SV), which refers to the center point of the volume of information, which you are trying to create. It is the midpoint of the volume angle. The SV is the place on the image that you locate from which the sweep will back up ½ the distance of the angle that you have decided on and begin the sweep. The sweep will begin, come to the midpoint (the SV) and continue past the SV for another ½ of the sweep angle. This is the same way in which classic three-dimensional volume acquisition is performed. See the diagram below **(Fig. 22.7)**.

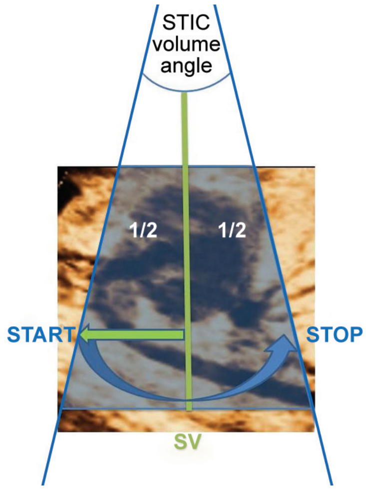


Figure 22.7 Volume acquisition. The starting view (SV) is the mid point of the selected volume angle and thus the central section of the volume dataset. The SV is chosen and the transducer automatically sweeps 50% of the chosen volume angle away from the SV. The sweep then begins acquiring information towards the OPA, the sweep continues past the OPA and ends at the equidistance away from the SV at which it began

The recommended SV for acquisitions done in the axial view is five-chamber view and in the sagittal plane is the ventricular short axis view just below the level of the atrio-ventricular valves **(Figs 22.8 and 22.9)**.

In case of acquisition conducted with the use of matrix transducers, the acquisition preview shown on the screen is unimportant because of its short duration of about 2-4 seconds.

However, in case of classic volume transducers during about 10-second acquisition, the acquisition you can watch as the sweep moves through the different levels of the heart. The acquisition is conveniently played at a slow speed so you can watch to make sure the sweep encompassed the stomach on one end and the transverse section of the aortic arch on the other end. You can also watch to see that the fetus did not move and that the proper positioning was maintained to visualize the common views. The experienced eye can detect even the smallest movements of the fetus such as hiccups or respiratory movements, which can cause artifacts **(Figs 22.10 and 22.11)**.

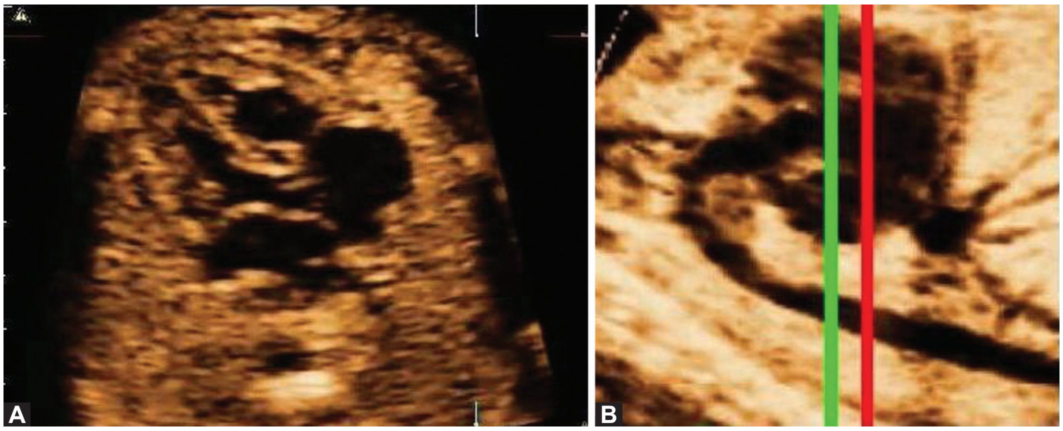
Postacquisition Stages of Fetal Heart Assessment in STIC Mode

Verifying the Machines Calculation of the Heart Rate

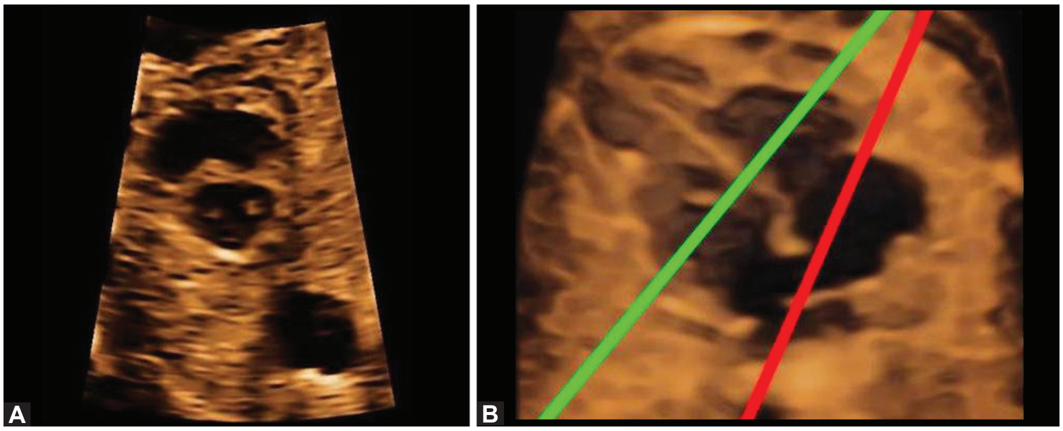
The machine detects the location and timing of each systolic beat and calculates the heart rate. After the acquisition of the volume, a box will appear telling you the machines calculation of the estimated fetal heart rate. If the machines estimated heart rate is not consistent with what you observed while imaging the heart you must cancel the acquisition and try again.

Initial Review of the Volume Dataset

A following element of the estimation of the quality of a newly acquired volume sequence of datasets is the quick review. You will be looking for any reason to reject this particular dataset sequence or to decide whether or not you will save it to the machine hard drive for later review and manipulation. The most obvious reasons for rejection of the STIC dataset are motion and/or shadowing artifacts.



Figures 22.8A and B The starting view (SV) in transverse STIC technique; (A) The five chamber view; (B) A reconstructed image of the heart in the sagittal plane. The green line demonstrates the level of the SV for the transverse STIC acquisition, which is the level of the five chamber view. The red line demonstrates the level of the 4-chamber view. As you can see, the green line (the 5-chamber view) depicts the midpoint of the information which we would like to include in the sweep. The red line (the 4-chamber view) is located too inferior



Figures 22.9A and B The starting view (SV) in sagittal STIC technique: (A) Ventricular short axis view just below the atrio-ventricular valves; (B) A reconstructed image of the heart in the transverse plane. The green line demonstrates the level of the SV for the sagittal STIC acquisition, which is at the level of the ventricular short axis view. The red line demonstrates the level of the aortic arch which would be too far to the right for an optimal STIC acquisition

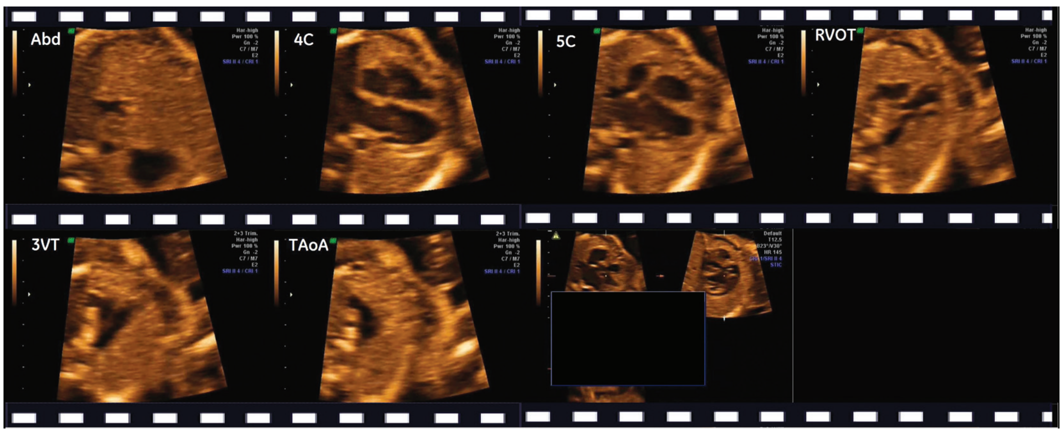


Figure 22.10 The static illustration of the preview in progress of the transverse, transabdominal STIC acquisition. The viewing permits the examiner to watch each transverse section of the fetal heart during the acquisition and to check whether or not artifacts occurred

Abbreviations: Abd, upper abdominal view; 4C, four-chamber view; 5C, five-chamber view; RVOT, right outflow tract; 3VT, three vessels and trachea view; TAoA, the transverse section through the aortic arch

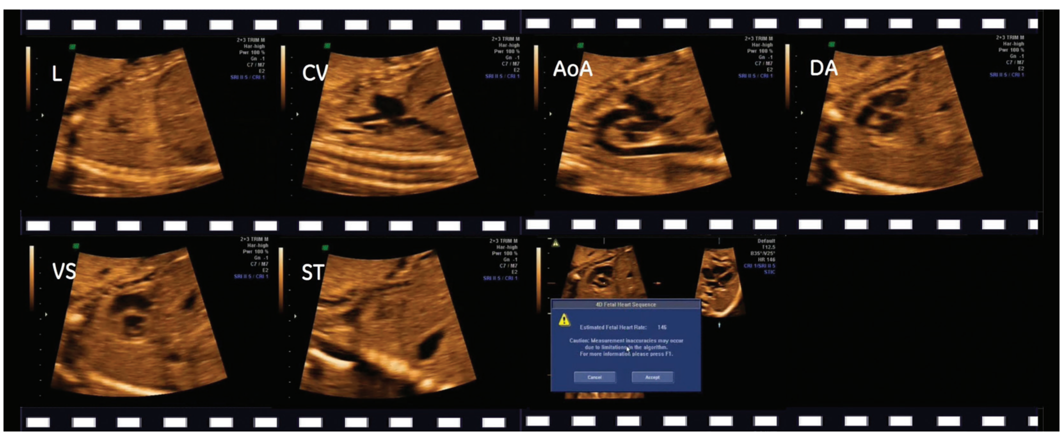


Figure 22.11 The static illustration of the preview in progress of the sagittal, transabdominal STIC acquisition. The viewing permits the examiner to watch each sagittal section of the fetal heart during the acquisition and to check whether or not artifacts occurred.

Abbreviations: L, section through right lung; CV, long axis caval view; AoA, aortic arch; DA, ductal arch; VS, ventricular short axis view; ST, sagittal section through the fetal trunk at the level of the stomach

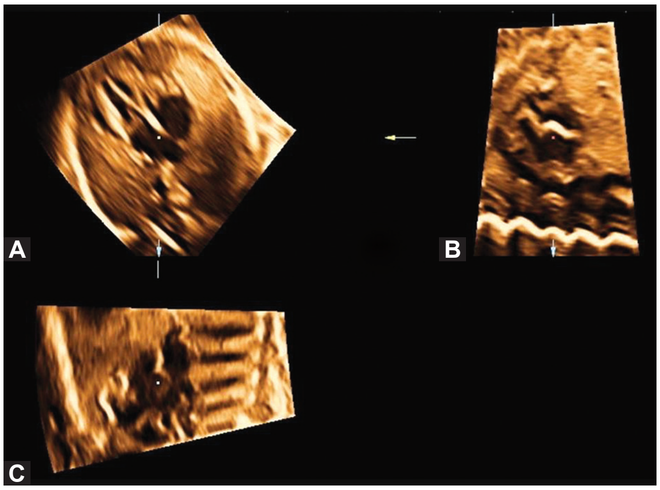


Figure 22.12 Quality rating of a new STIC dataset-motion artifacts. The multiplanar view of the fetal heart. Reference images B and C demonstrate numerous breaks in the reconstruction signifying motion of the fetus during the progress of acquisition

Using the multiplanar imaging option easily does this quick review. Here you will want to activate the reference image B and look for breaks in the reconstruction, which signify motion by the fetus during the acquisition **(Fig. 22.12)**.

Then, within the same reference image B, which is the sagittal plane, one can move the pivot point horizontally, to the right and left, while watching the A plane. Each of the recommended views from the transverse aortic arch view to the level of the stomach in the abdomen will come into view and can be evaluated for motion or shadowing artifacts, or any other undesirable quality.

If after previewing the quality of the volume dataset and verifying that the fetal heart rate is correct then the STIC volume dataset should be stored to the hard drive of the ultrasound machine. If you forget to store the volume this information will be unavailable later for review and manipulation.

STIC Dataset Anatomic Orientation

Similarly as in 2D, 3D fetal echocardiography is based on standardized cardiac sections.[17-20] An innovation and advantage in STIC is the ability to always review the STIC images in the identical orientation from one exam to the next, one institution to the next, and even one country to the next. This is possible due to the ability to manipulate the images by means of rotational knobs, which are standardized among equipment manufactures. This takes away the variability of fetal lie and promotes a continuity and unification of the prenatal diagnoses of congenital heart disease by the use of STIC.

The orientation of STIC volumes is a completely new sonographic skill.[21] It exists in the consistent anatomical arrangement of every heart, stored in STIC mode, according to the same repeatable rules, so as to prepare the volume block for review in a well-organized and reproducible manner.

Foundations of the three-dimensional orientation of the fetal heart were laid in 2001 by Bega and co-authors on static 3D volumes.[17] In the following years it was refined by other authors.[18,20,22-24]

For correct orientation of STIC volumes, knobs are available which rotate images on the x, y and z axis. Coupled with the parallel shift control knob virtually any acquired position of the fetal heart can be manipulated into standard orientations. The image below represents a correctly oriented volume data block of the heart, ready for review and interpretation.

Above is a multiplanar view of a STIC volume dataset. The examiner has arranged the anatomy in the standard viewing planes first described by Bega and coworkers which is, in the A plane, with the apex of the heart to the left of the screen.[17] If the heart is normal the B plane will show the aortic or ductal arch to the left of the image also. Some others have proposed orientating STIC images with the apex of the heart to the right rather than the left. We believe that orientation with the apex to the left of the image is a good standard and will use this orientation throughout the remainder of this chapter.

Orientating a STIC volume is the process of image orientation in which the operator utilizes the x, y and z knobs and the parallel shift knob on the machine to twist, rotate or flip the images until they end up in a standardized viewing layout whereas the A plane is a transverse 4-chamber image of the heart with the apex to the left of the image. The B plane is a reconstructed sagittal image showing superior to the left and inferior to the right, and the C place is a reconstructed coronal image. This will place the images in planes, which will make review and manipulation easy and predictable.

There are several ways to arrive at this standard orientation of the apex to the left in the A plane. These methods all are based on the utilization of linear structures, situated in the anatomical neighborhood of the heart. These structures include: the spine, the descending aorta, the interventricular septum and the ductal arch. The orientation should be always performed in the multiplanar view. In multiplanar mode each image has a small dot, which is called the pivot point. By utilizing the x, y and z knobs the image will rotate on this pivot point allowing you to align structures within the image to a standardized orientation.

In **Figures 22.13 to 22.17** manipulation of the images into a standard viewing orientation is shown.

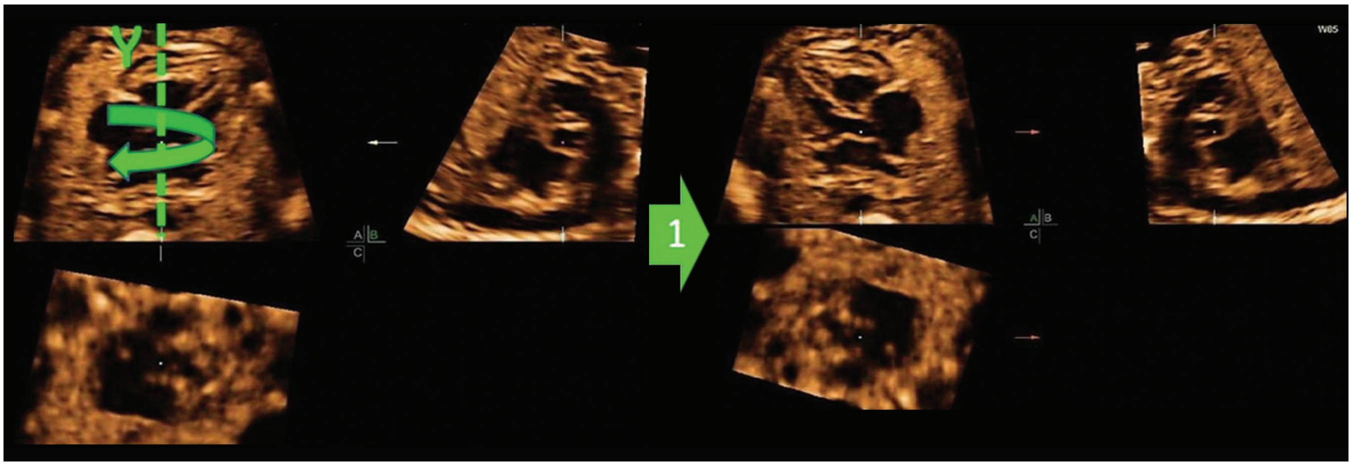


Figure 22.13 The dataset in the top picture was acquired with the apex of the heart to the right of the image. Since we always want to view our volumes with the apex to the left one must turn the image of 4CV in the reference plane A by 180 degrees using the Y-axis rotation knob. The result is the bottom picture

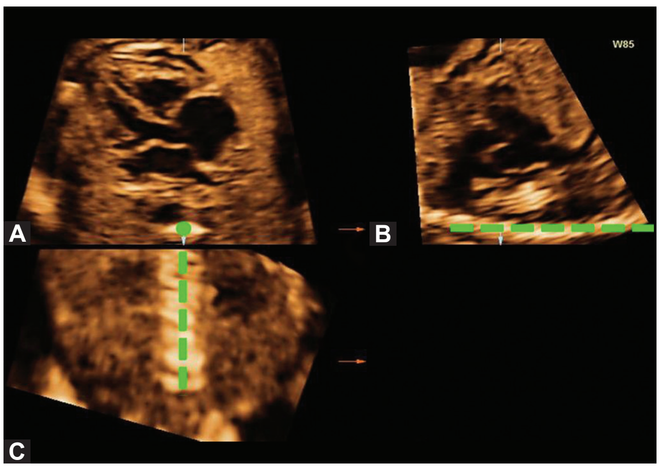


Figure 22.14 The pivot point in the A plane on the spine. The spine was used in the B and C planes to line up the images horizontally in B, and vertically in C. This resulted in an optimal orientation of the volume which can now be reviewed

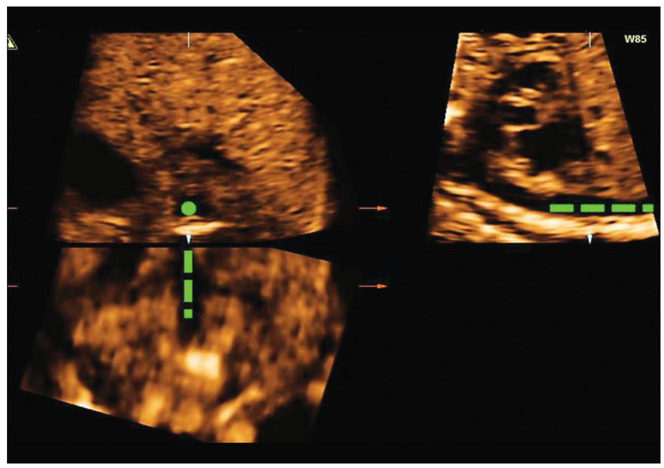
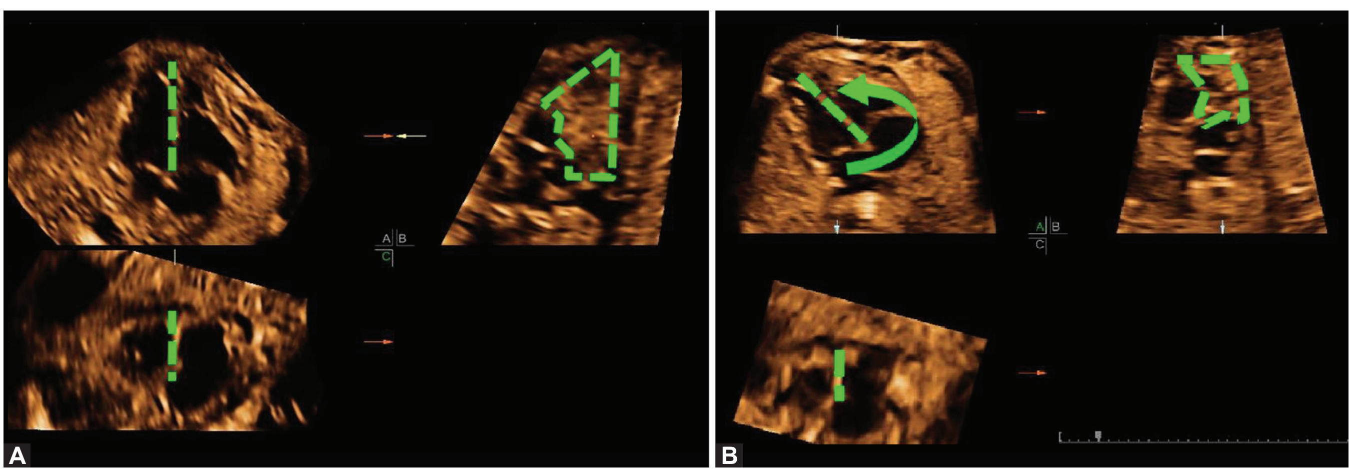


Figure 22.15 In this picture the descending aorta was used in like manner as the spine



Figures 22.16A and B (A) This picture shows orientation of the volume by using the interventricular septum placed along Y-axis in the A plane, the B plane shows the 'IVS in-plane view' and in the C plane the 'ventricular short axis view' comes into plane; (B) A z-axis rotation is the used to again turn the axis of the heart to the left in the A plane

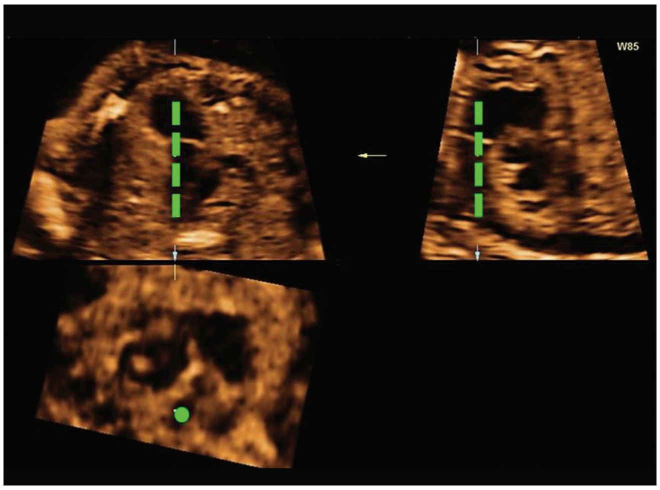
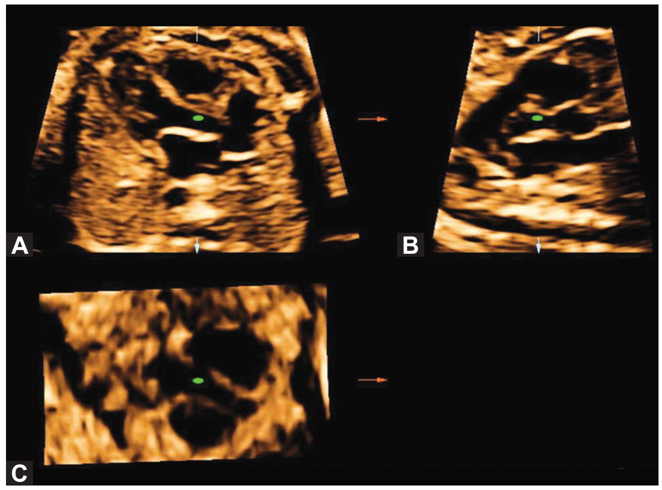


Figure 22.17 The ductal arch was aligned vertically along the Y axis in the A plane



Figures 22.18A to C (A) Multiplanar view showing the pivot point in the aortic root; (B) This same geographic location is represented again by the pivot point in the aortic root, now in a sagittal view; (C) The coronal view of the aortic root is represented again

Any of the above methods will work to manipulate the volume into the standard viewing orientation in which the apex of the heart is on the left in the A plane.

STIC Volume Review and the Spectrum of Viewing Options

Once proper orientation of the volume is obtained it is ready for review and interpretation. When the volume is put into motion in the format of a clip, it represents one full heart cycle played over and over again. It is possible to slow down the speed of the clip to about 50%, which creates superb spatial orientation for review. It is also possible to utilize the frame after frame review option. There are many STIC volume three-dimensional viewing options availalbe. These will be discussed below.

Multiplanar View/STIC 2D

Perhaps the most important and most basic of all viewing options is the multiplanar view.[17,18,24-26] In this view 3 planes are shown which are perpendicular to each other **(Figs 22.18A to C)**. They have in common one point, the pivot point, which is represented on the screen by a dot. The location of this point in the reference image of plane A, e.g. the root of the aorta, identifies the same structure in the B and C planes. Important tools in the multiplanar view are a parallel shift control, which allows for navigating through the image in a layer after layer manner in any of the 3 planes. Other tools are the x, y and z-axis rotational knobs used for volume manipulation.

In **Figure 22.19** a clinical example of the use of the multiplanar imaging is shown. The anomaly in this case is a ventricular septal defect. The detailed multiplanar evaluation gave the clear picture of this abnormality.

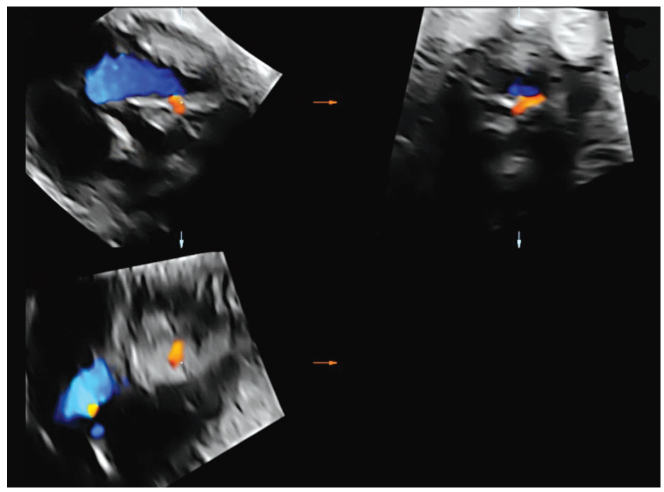


Figure 22.19 A muscular ventricular septal defect is show in multiplanar view in all reference images

Ultrasound Tomography

Another viewing option for a STIC volume is ultrasound tomography (commercial names: Multislice View/ Tomographic Ultrasound Imaging/iSlice). It has many advantages and is utilized often by many examiners.[19,27-29] Tomography allows for the viewing of multiple slices of the same image, by means of **1**, **3, 5, 8, 11, or 15** sections on one screen along with a reference image which is perpendicular to the tomographic sections with an overlay of the tomographic lines of slices. The distance between the

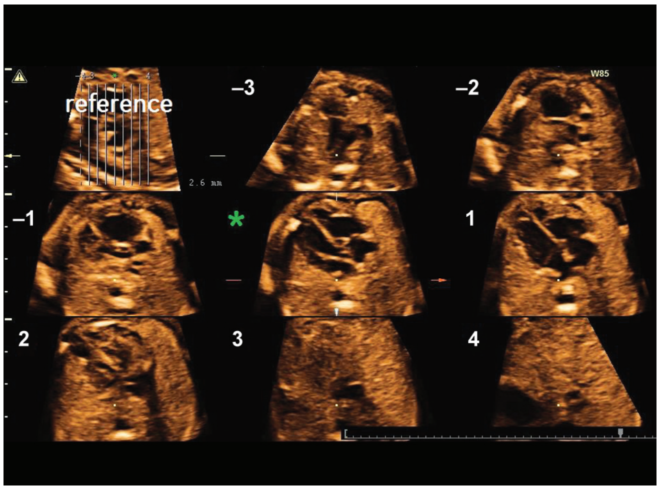


Figure 22.20 Tomographic ultrasound imaging in a STIC volume in diastole in a normal heart. In the top left section the overlay image is presented, which is perpendicular to the tomographic layers, demonstrating section levels

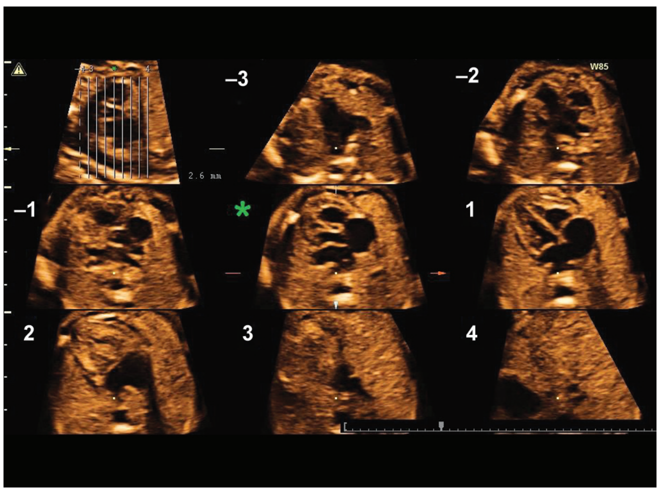


Figure 22.21 Ultrasound tomography in systole in a normal heart

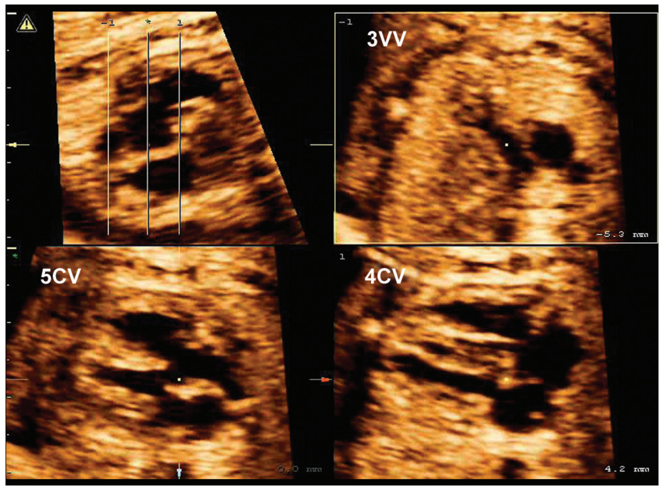


Figure 22.22 Tetralogy of Fallot in tomographic ultrasound imaging. Levels of four-chamber view (4CV); five-chamber view (5CV) and three vessel view (3VV) are presented

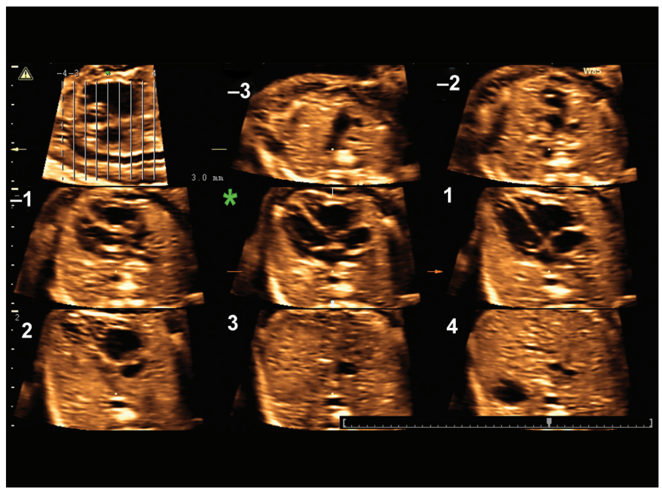
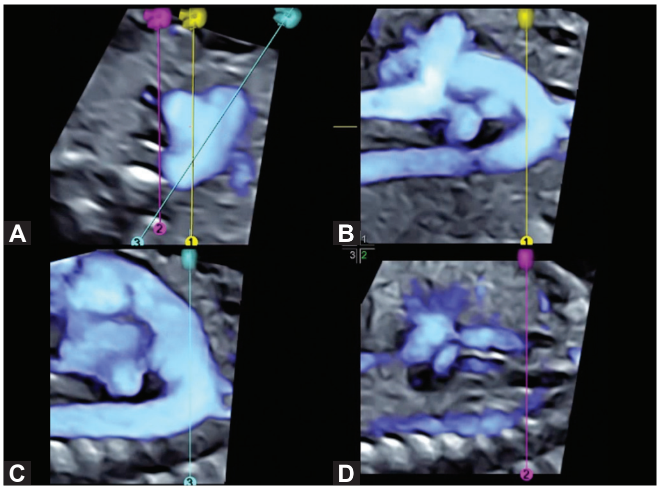


Figure 22.23 Presentation of d-transposition of great arteries: level * shows normal four-chamber view; level 1—two semilunar valves at the same time (five-chamber view); level 2—abnormal arrangement of great arteries (three-vessel view)—aorta pushed anteriorly; and level 3—singular arterial vessel= aortic arch (three-vessel and trachea view)

slices can be set with equal or any distances **(Figs 22.20 to 22.23)**. The mid slice is represented on the overlay by an asterisk. Slices to the left of the center line are described by negatives slice numbers and slices to the right of the center line are represented by positive slice numbers. This makes identification of the slices in comparison to the reference image easy. It was proposed the use of 3 standardized tomographic distances, which demonstrate the three cardiac planes in which most of the abnormalities of the heart can be recognized. These 3 planes are the 4-chamber view, the 5-chamber view and the right outflow tract view. In cases of complex defects of the heart ultrasound tomography is an excellent way to illustrate the margins of the defect on one screen. In the pictures below both a normal heart, a heart with tetralogy of Fallot and with d-transposition of great arteries is illustrated with the use of tomographic imaging.

Any Plane Techniques

Commercially named functionalities Omni View or Oblique View techniques allow for drawing arbitrary straight or curved sections from the reference image and displaying those sections next to the reference image.[30,31] These techniques may simplify fetal heart evaluation in a volume dataset **(Figs 22.24A to D)**.



Figures 22.24A to D Omni view imaging in a normal fetal heart: colored lines are arbitrarily placed on the reference image (A); (B) Represents a perpendicular plane to the yellow line on the reference image (aortic arch view); (C) Represents a perpendicular plane to the blue line on the reference image (the ductal arch view); (D) Represents a perpendicular plane to the purple line on the reference image (the long axis caval view)

Rendering

A completely different kind of volume viewing option, which can be utilized in STIC is rendering. This is a technique of three-dimensional reconstruction from flat multiplanar images.[18,32-34] Surface rendering gives the impression of depth, causing the final images to resemble autopsy sections. The surface which one wishes to examine can be chosen and applied by the use of a rendering box. Because we are using volumes of information a direction that one wishes to look from can be chosen from any plane. The thickness of the box determines the "depth" of tissue that one wants to see in the rendered image **(Fig. 22.25)**.

Surface rendering takes place on comparatively narrow thicknesses of the region of interest **(Fig. 22.26)**.

Most of the rendering directions can be applied in the STIC mode from the volumes obtained by a transverse acquisition technique **(Figs 22.27A to D)**.

In surface rendering of the fetal heart the options available for optimization are very important. We have found excellent results with the use of HDlive/Realistic view or *gradient light mode* mixed with *surface* with very low levels of *threshold low* and transparency **(Figs 22.28A to D)**.

For the evaluation of the relationships of the great arteries, arches and evaluation of cardiac chambers *minimum transparent mode* or *inversion mode* rendering can be utilized.[35,36] Below is an example of these modes in a case of transposed great arteries. Here the region of interest box has been enlarged so that all of the essential anatomical elements can be seen. The inversion rendering seen on the right image below uses the HDlive/Realistic view mode and an increase of lower threshold and transparency **(Fig. 22.29)**. This is a particularly good combination utilized with a sagittal acquisition. The visualization rates of inversion mode ranged from 55 to 100%. This method allows better visualization of complex congenital heart disease and may be considered an addition to 2D fetal echocardiography.[37,38]

In the inversion mode, it is also possible to use a narrow region of interest box, encompassing only the cardiac chambers. This focuses on the relation of the size of ventricles, their contractility, the cross of the heart, the interventricular septum, the composition of the atrio-ventricular valves, atrial appendages, or the relationship of the outflow tracts **(Figs 22.30A and B)**.

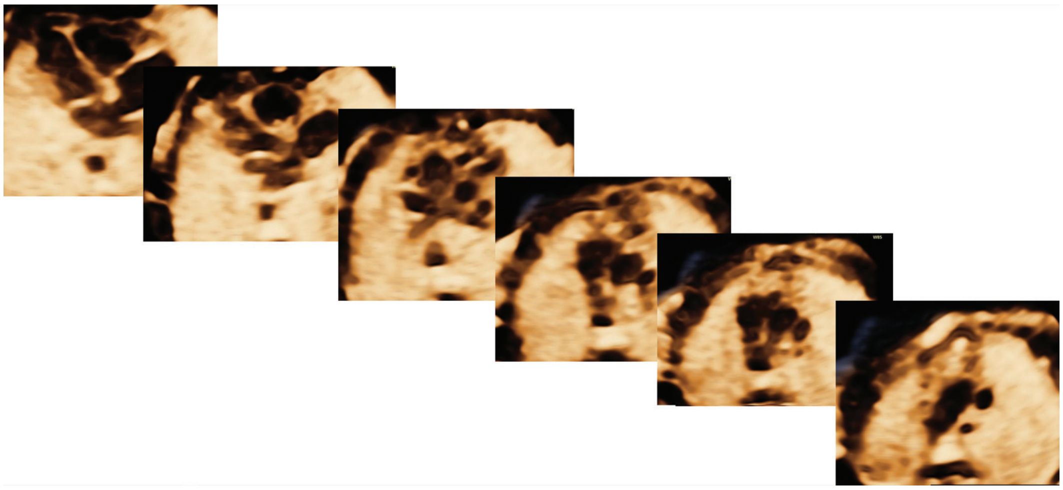


Figure 22.25 Surface rendering of the fetal heart from a STIC volume obtained at 21 weeks of gestation. Rendering direction which was applied is front to back. Subsequent cardiac views are represented starting from the four-chamber view through the five-chamber view, the three vessel view, the transverse section through ductal arch, the three vessel and trachea view and the transverse section through aortic arch. In all the presented images the effect of depth is clearly seen

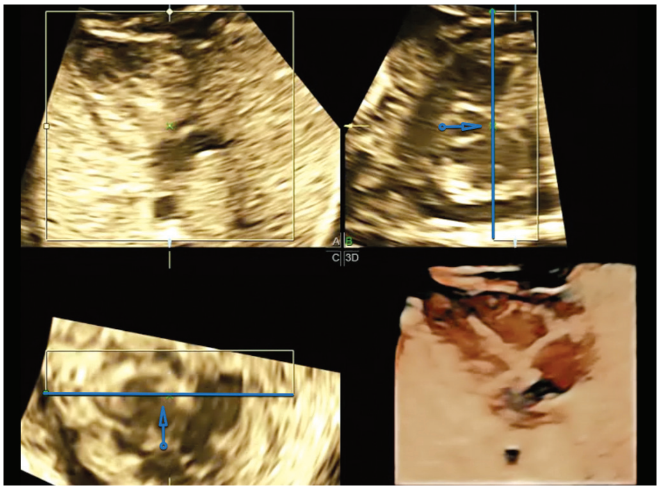
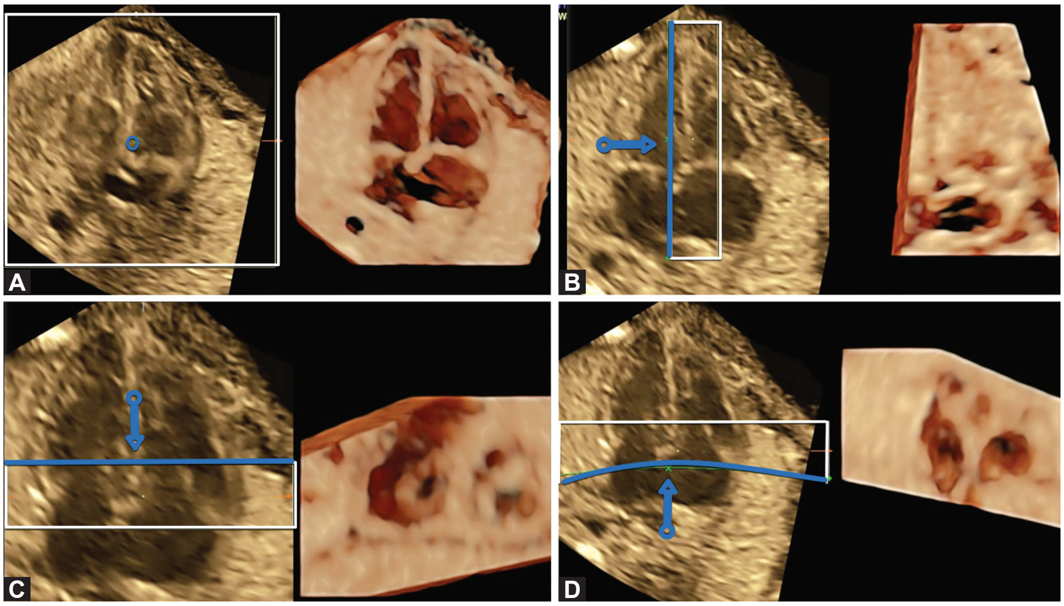


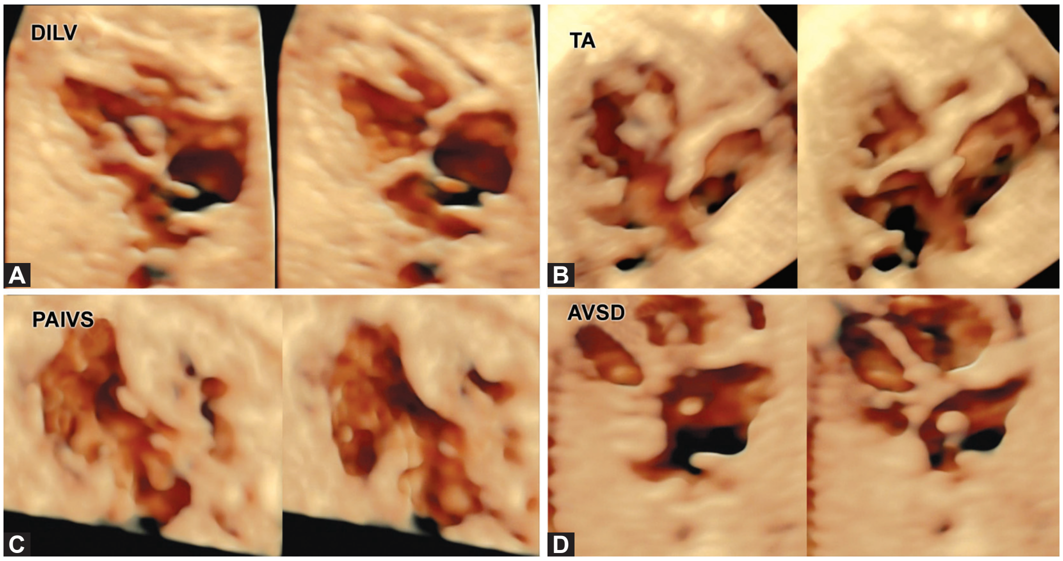
Figure 22.26 Multiplanar view of the fetal heart along with 3D rendering. In the B and C reference images a narrow region of interest is chosen which is essential for surface rendering of the heart. Note the blue line representing the direction of rendering



Figures 22.27A to D Rendering directions in surface rendering of the fetal heart shown in the plane A: a 4-chamber rendered view using a front to back render direction (A); in plane view of the interventricular septum (B) left to right direction; atrioventricular valves (C) up to down direction; the base of the heart presenting the relation between the four valves (D) down to up direction

For STIC volumes utilizing B-mode information accompanied by color mapping, the same viewing options are accessible as for STIC gray scale datasets.[39,40] A STIC acquisition can be done in gray scale with B-mode alone, or with the addition of color, power, or bidirectional power Doppler mapping (HD flow) **(Figs 22.31 and 22.32)**. These techniques allow for demonstration functional aspects of the fetal heart as well as geometric relation between the ventricles, great arteries and arches.[39] A rendering modality called "glass body" imaging writes the color information on the background of the grayscale information. Below are examples of vascular mapping with STIC.

An option available with STIC imaging is the use of B-flow imaging. B-flow imaging is an exceptionally sensitive form of coding of the blood flow, allowing visualization of extremely small vessels.[41] It is a Doppler independent B-mode option based on the use of the highest frequencies transmitted by the probe allowing for the enhancement of signals representing blood flow while simultaneously ignoring signals from stationary tissue. This allows for the



Figures 22.28A to D Surface rendering of four anomalies in diastole and systole at the level of four-chamber view: (A) Double inlet left ventricle (DILV); (B) Tricuspid atresia (TA); (C) Pulmonary atresia with intact interventricilar septum (PAIVS); (D) Atrioventricular spetal defect (AVSD)

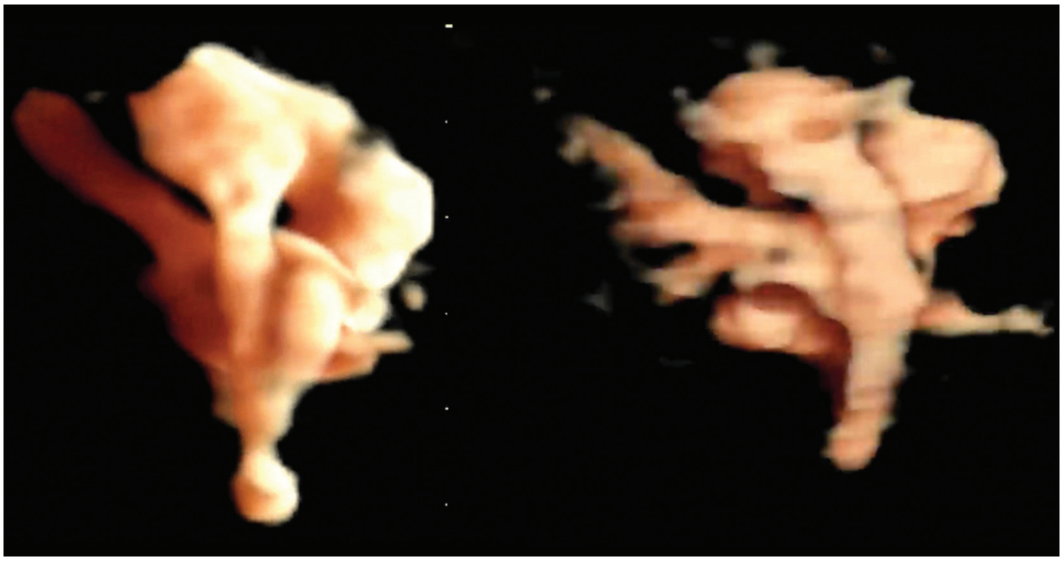
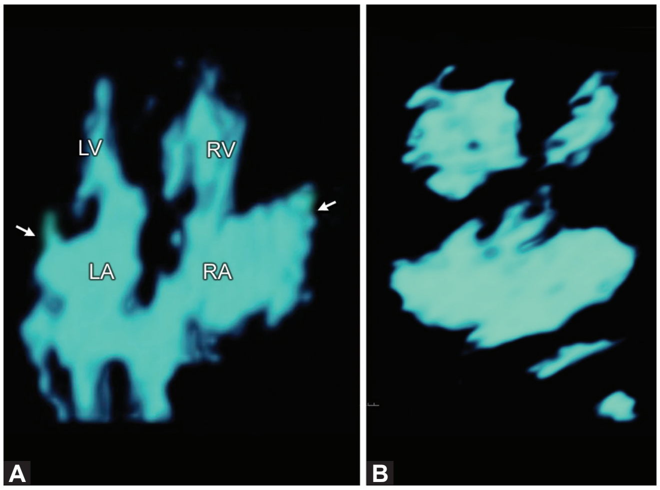


Figure 22.29 Normal heart (left) and d-transposition of great arteries in inversion mode rendering. Notice the very different geometry of outflow tracts between these two examples.

visualization of vascular information independent of tissue information **(Fig. 22.33)**.

2D and Volume Measurements in STIC Datasets

Measurements can be made from STIC volumes in the same manner as classic two-dimensional measurements. Since 2006 Z-score measurements have been available for use in relating cardiac measurements to gestational age. This method simplifies the expression of measurements providing the examiner with calculations in standard deviations rather than in millimeters in relation to any given gestational age and measured BPD and FL.[42] It simplifies the precise quantification of the size of fetal cardiac structures. This method of calculation has become a standard in the majority of reference centers nowadays. However, it should be emphasized that there is a risk that in volume datasets of



Figures 22.30A and B Inversion mode rendering with the application of a narrow region of interest box focused on the four-chamber view: (A) Shows a normal case; (B) Shows right atral isomerism with atrioventricular septal defect

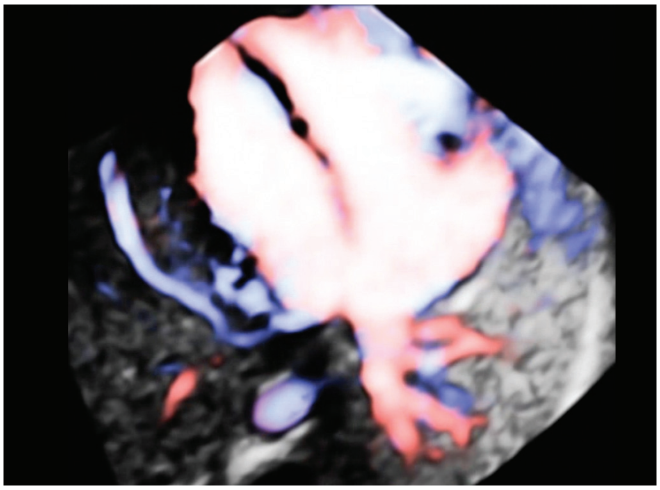
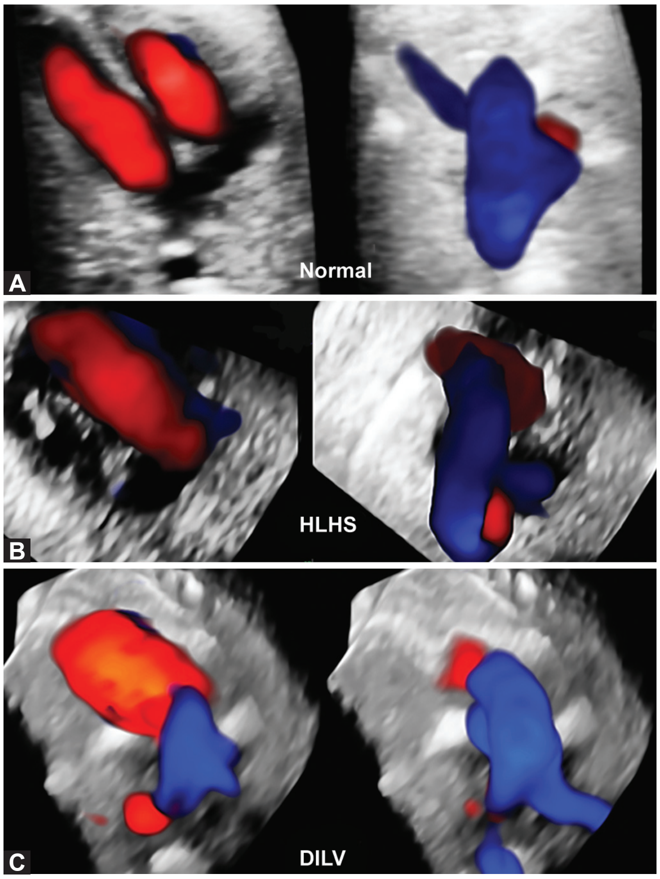


Figure 22.32 Glass body rendering in bidirectional Doppler mapping using a shallow region of interest box in diastole in a case of partial anomalous pulmonary venous return (PAPVR). Note the abnormal drainage of pulmonary veins and the small size of the left atrium



Figures 22.31A to C Glass body rendering in color Doppler mapping using a deep region of interest box in diastole and systole. (A) Normal heart; (B) Hypoplastic left heart (HLHS); (C) Double inlet left ventricle (DILV) with transposed great arteries

Figure 22.33 Surface rendering on the basis of b-flow imaging presenting the aortic arch and brachiocephalic vessels

a lower quality, performed measurements would not be in accordance with measurements carried out in 2D.

Because of the capacity of three-dimensional acquisition, STIC datasets allow to calculate typical volume measurements. VOCAL and SonoAVC techniques could be an example.[43,44] The use of the VOCAL method requires mechanical or automated tracing by the examiner of whatever structure one wishes to perform a volumetric measurement of. SonoAVC is also utilized for volume calculation however it is a machine derived volume, which can only be used for volume measurements of fluid structures. When volumetric measurements are performed in both systole and diastole calculations of cardiac stroke volume can be easily derived. The calculations of these algorithms have been validated on artificial models.[45] An application of this is to assess cardiac chamber volumes in various phases of the cardiac cycle. Due to the contrast between the ventricular walls and cardiac chamber 3D measurements allow for reproducible calculations of ventricular volumes even by the use of automatic contour finder.[46] A good agreement was shown between these two methods for estimating fetal stroke volume and they were even suggested as methods of choice in this area.[47] Basing on 3D measurements normograms for left and right ventricular stroke volumes, ventricular cardiac outputs, and ejection fraction were elaborated with appropriate reproducibility.[48-50] 3D stroke volume readings were compared with 2D Doppler techniques and presented high level of agreement.[51] Thanks to 3D calculations fetal physiology explained similar left and right ventricular stroke volumes and cardiac outputs as a result of larger volume of the fetal right ventricle and a greater ejection fraction of the left ventricle.[52] From diagnostic point of view SonoAVC was also applied for the assessment of atrial appendages in cases of heterotaxy **(Figs 22.34 and 22.35)**.[53]

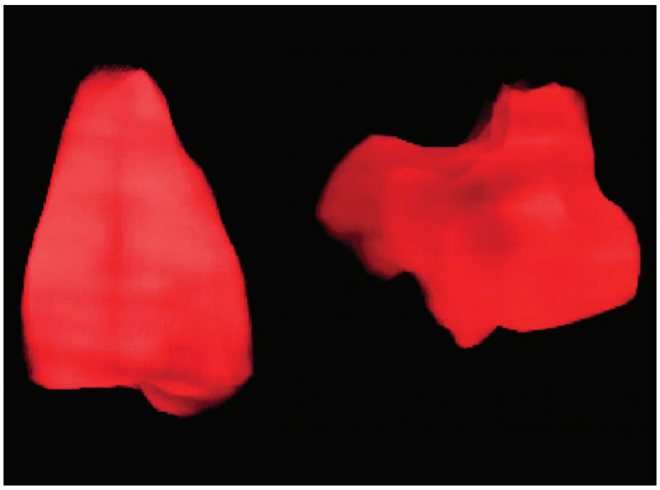


Figure 22.34 Volume calculations of cardiac ventricles by the use of vocal technique

STIC M-mode

In 2009 STIC M-mode was introduced into clinical practice allowing for the capability of placing arbitrary M-mode lines into the volume dataset allowing for M-mode measurements to be taken from positions that are not available by two dimensional imaging. As an example in 2013 tricuspid annular plane systolic excursion (TAPSE) measurements were described in STIC M-mode.[54] This is an old method of ventricular function assessment that is used in echocardiography of adults in coronary disease. In the fetus it is of importance in the right ventricular function evaluation. For the left ventricle function mitral annular plane systolic excursion (MAPSE) can be applied **(Figs 22.36 and 22.37)**.

Volume Automation Methods in Fetal Heart Evaluation

A few years after introducing three-dimensional techniques of fetal heart evaluation, examiners began to look for algorithms, which would allow mapping the views of the fetal heart in STIC volume datasets automatically.[13-15] The very first method was volume computer-aided diagnosis

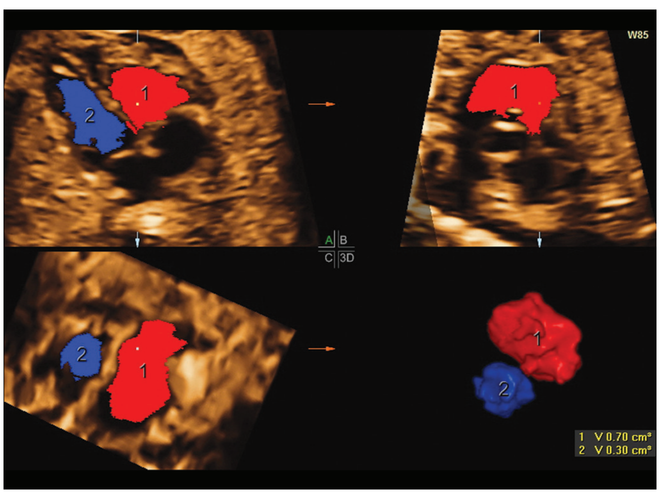


Figure 22.35 Volume calculations of cardiac ventricles by the use of SonoAVC

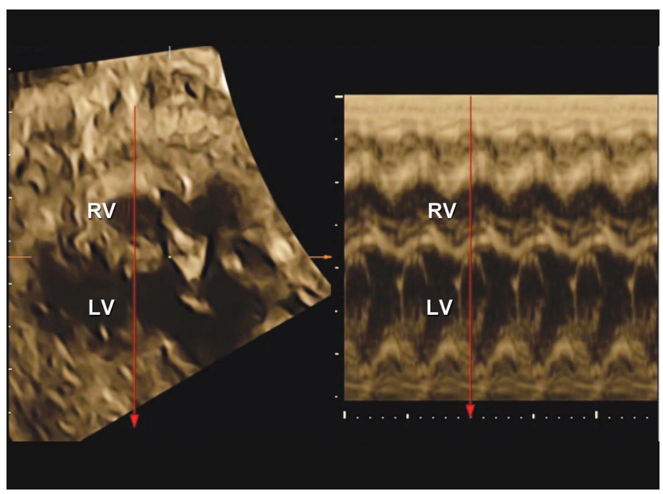
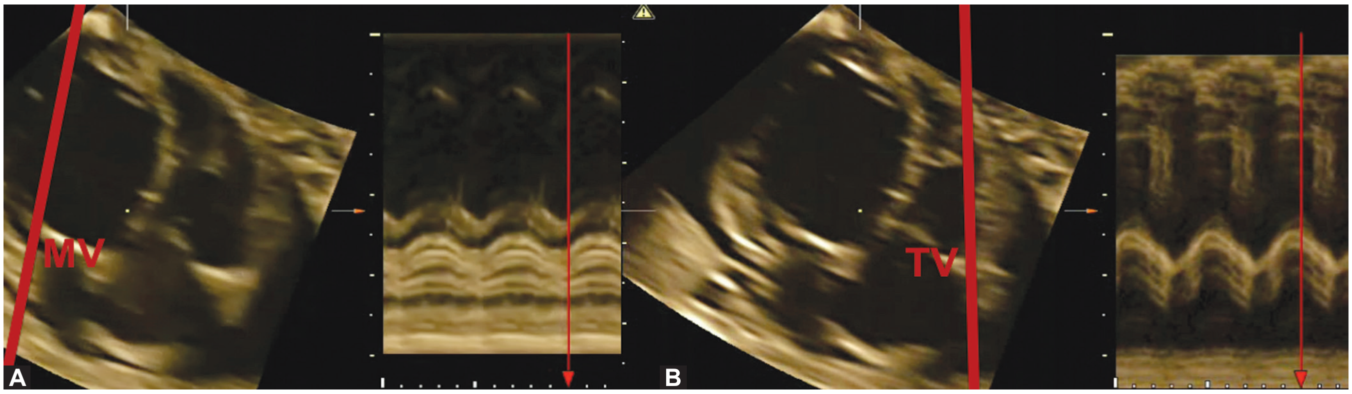


Figure 22.36 STIC M-mode technique has the capability of placing arbitrary anatomic lines allowing for M-mode measurements to be taken from positions that are hardly available by two-dimensional imaging. A case of pulmonary atresia with intact interventricular septum (PAIVS)—note the thickening of the right ventricular wall and its small lumen



Figures 22.37A and B STIC M-mode technique in a case of critical aortic stenosis. (A) MAPSE; (B) TAPSE

(VCAD). This technique was brought into use with fetal heart imaging between 18 and 23 weeks of gestation. In this time period the heart increases in size as the whole but relationships of the sizes of the main cardiac structures remain similar. Because of this fact an automated system can be used during this time to aid in the identification of basic cardiac views.[55] After a volume is achieved the examiner must orient the A plane so that the 4-chamber view is showing and the apex of the heart is to the left. When VCAD is enabled a green template of a heart, ribs and spine appears overlying the A plane image and a green dotted line appears on the B plane representing the sagittal spine. The examiner lines up the volume in the A and B planes with the green templates, which essentially orientates the volume into an optimum position **(Fig. 22.38)**.

Because the volume is now in a standardized position the VCAD algorithm can automatically identify the following cardiac views: left outflow tract (Cardiac 1); right outflow tract (Cardiac 2); upper abdominal (Cardiac 3); long-axis caval (Cardiac 4); ductal arch (Cardiac 5); and aortic arch (Cardiac 6) **(Fig. 22.39)**.

In case when the algorithm makes a mistake, assuming, that the examined subject is a normal heart, the examiner can correct the image of particular views owing to the fact that VCAD is based on tomographic ultrasound imaging. It is possible even in case of oblique views, which require partial automated volume rotation such as Cardiac 1 and Cardiac 6. However, in datasets affected by motion artifacts, all sagittal views (Cardiac 4, 5 and 6) will not be shown correctly. The next method, called Fetal Heart Navigation (FHN), was based on automated volume orientation, according to the course of descending aorta and ductal arch. This algorithm does not have limitations resulting from gestational age because after automated orientation is carried out, the examiner himself assigns the levels of representative cardiac views by comparing observed layers with the schematic images presenting expected views

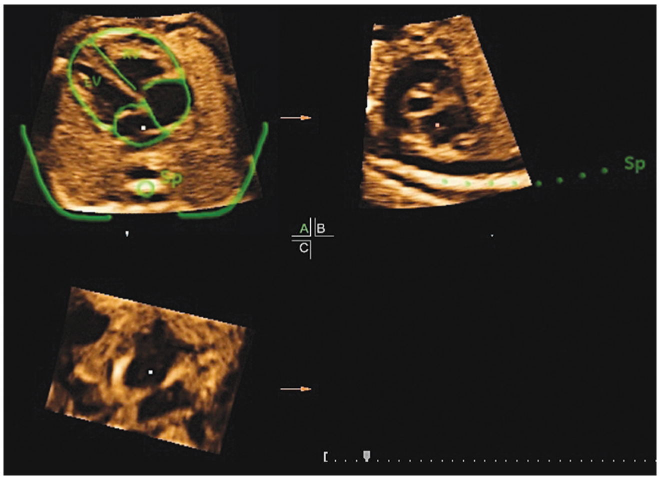


Figure 22.38 VCAD modality. Initial stage after simplified orientation according to templates marked with green line (in reference images A and B)

including four-chamber view, left outflow tract, and three-vessel view **(Figs 22.40A to D)**.

The newest algorithm is called Fetal Intelligent Navigation Echocardiography (FINE), and is also recognized the under trade name 5D HEART.[13] It is based on geometric landmarks necessary to guide the ultrasound system in identification of 9 cardiac views. After the acquisition, the examiner has to highlight those anatomical points on the screen at particular levels, moving the layers of axial sections through the fetal chest. Those points include: at the level of upper abdominal view: descending aorta, at the level of four chamber view: descending aorta, cardiac crux, interventricular septum and the wall of the right atrium, at the level of three-vessel view: pulmonary valve and superior caval vein, and finally, at the level of transverse aortic arch view: mid-point of the transverse aortic arch **(Fig. 22.41)**.

After the correct selection, upper abdominal view, four-chamber view, five-chamber view, left outflow tract view,

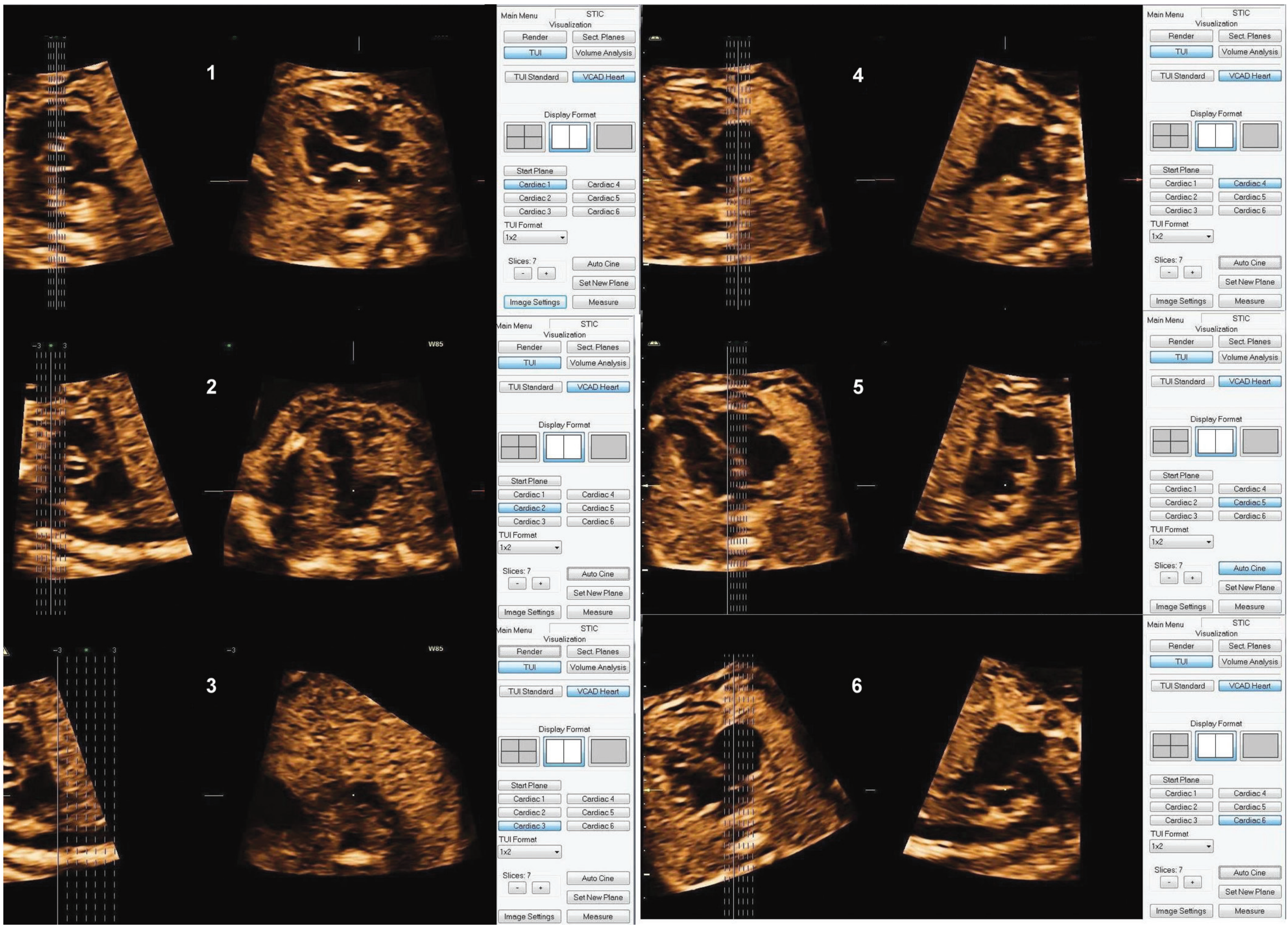


Figure 22.39 VCAD modality in the final stage. Automated identification of cardiac views: 1-left outflow tract; 2-right outflow tract; 3-upper abdominal view; 4-long axis caval view; 5-ductal arch; 6-aortic arch

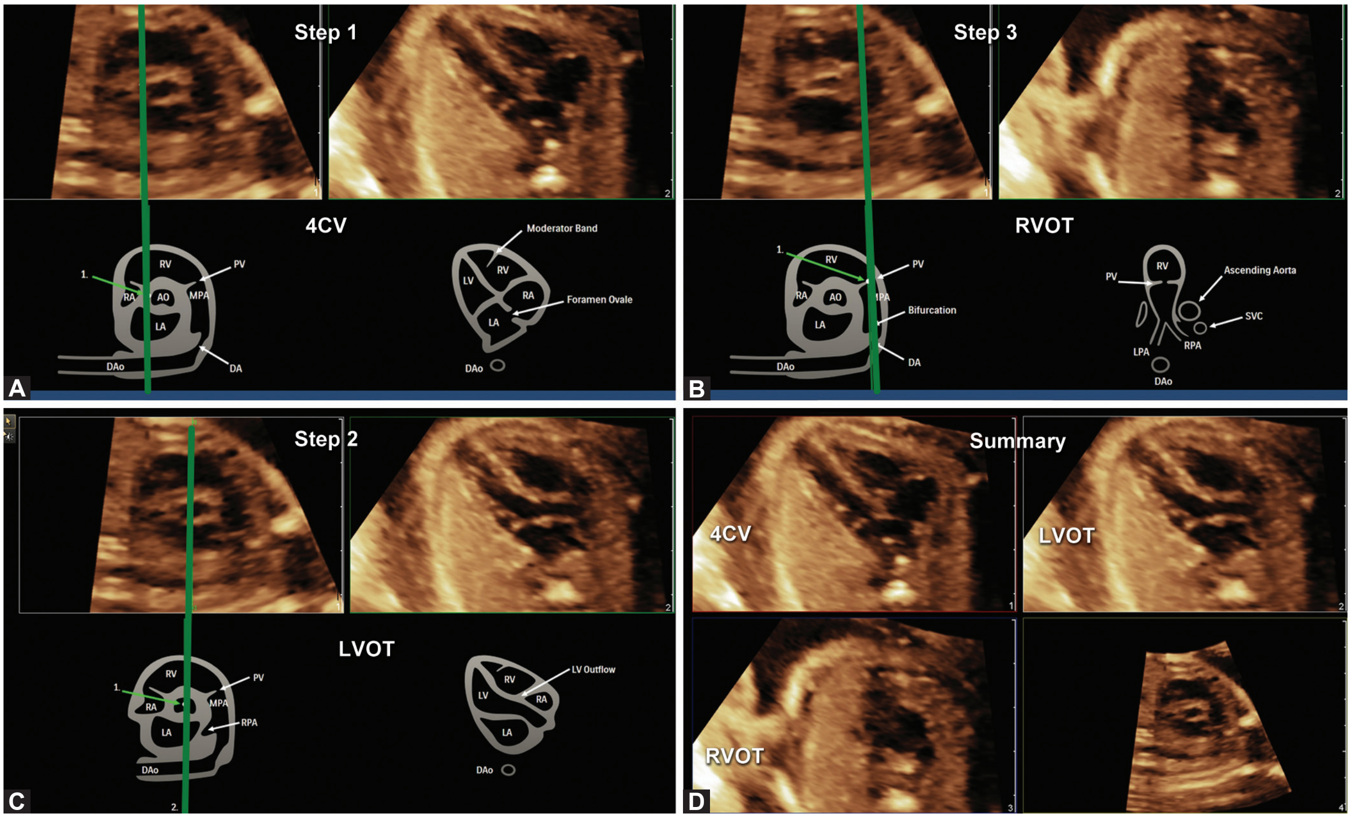
short axis view, three-vessel and trachea view, aortic arch view, ductal arch view and long axis caval view are produced on the screen **(Fig. 22.42)**.

This method, like the remaining ones, allows analyzing volume datasets, which include information obtained with the use of color mapping.

None of recently introduced methods can identify and align cardiac views correctly in cases of cardiac malformations or mediastinal shift. These algorithms can only provide suspicion of anomaly taking into account that expected cardiac views could not be presented as in a normal fetal heart. In case of congenital heart diseases, the examiner can make a correction manually and assign particular layers of cross-sections to recommended views, e.g. in 5D technique. Nevertheless, it is more difficult and time consuming than a routine 2D sweep, like, for instance, in cases of conotruncal anomalies. It is caused by technical imperfection, which results from basing described algorithms only on the geometry of a normal heart. The geometry of anomalies is unique for most of them, which, in turn, causes technical difficulties in present automated three-dimensional techniques. Therefore, in case of anomalies, 2D evaluation still allows to obtain diagnostic views faster and more efficiently, and as a result, quickly interpret the image.

STIC IN THE FIRST TRIMESTER

The biggest potential obstacle of this method is the first trimester fetal activity that may increase the chance of motion artifacts. Second obstacle is rather suboptimal 2D image resolution for the fetal heart at this stage of gestation. However, first descriptions of the STIC application in the first trimester showed promising results of 71% of success rate in volume acquisitions.[56] It was also presented that first trimester STIC volumes can be applied in tele-consultations.[56] The preferable first trimester STIC viewing technique that was raised in literature is ultrasound tomography in color mode **(Fig. 22.43)**.[57]



Figures 22.40A to D Fetal heart navigation modality after the arrangement. Identification of cardiac views: Four-chamber view (step 1); left outflow tract (step 2); and right oulflow tract view (step 3). After the process is finished all selected cardiac views are summarized (summary)

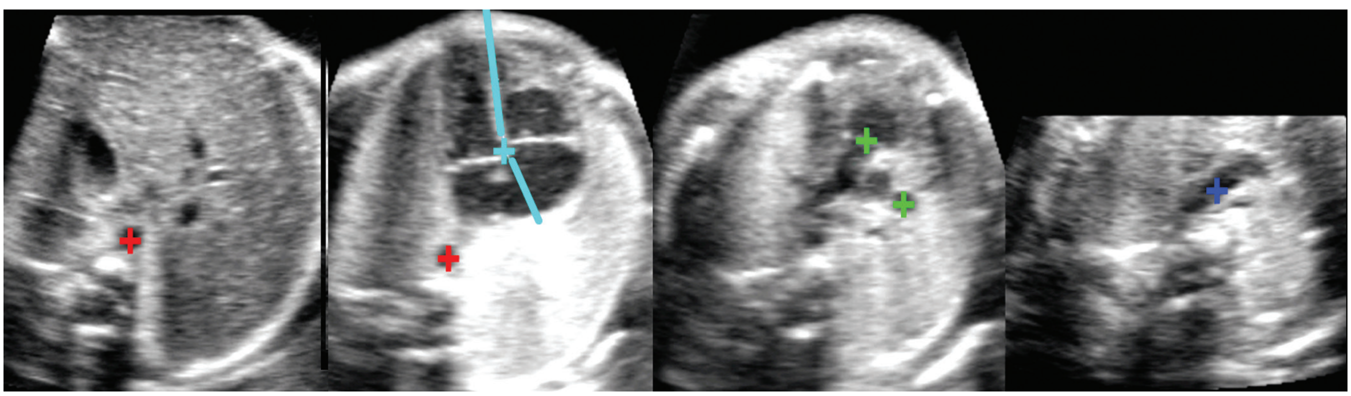


Figure 22.41 Fetal intelligent navigation echocardiography (FINE=5D heart) modality in the early stage. Required anatomical landmarks, which need to be highlighted by the examiner

But in fact this method shows no more details, which can be presented, in a 2D transversal sweep. This is why 2D remains superior to STIC at 11–14 weeks scan.[58] Optimal imaging of first trimester four-chamber view in STIC 2D pre-acquisition remains crucial for successful volume capture.[59] Other visualization modes are also feasible in the first trimester STIC, but they require ideal scanning conditions **(Figs 22.44 and 22.45)**.

In a small-population study the total accuracy of first trimester STIC was 95.3%, with sensitivity, specificity, and positive and negative predictive values of 90.9%, 96.2%, 83.3% and 98.1%. On contrary in this study 2D early fetal echocardiography showed the accuracy of 98.4%, which was better than that of STIC, and presented no false-positive results.[58] In another study also based on a small population accuracy of STIC was 88.7% and of conventional early fetal echocardiography 94.2%.[60]

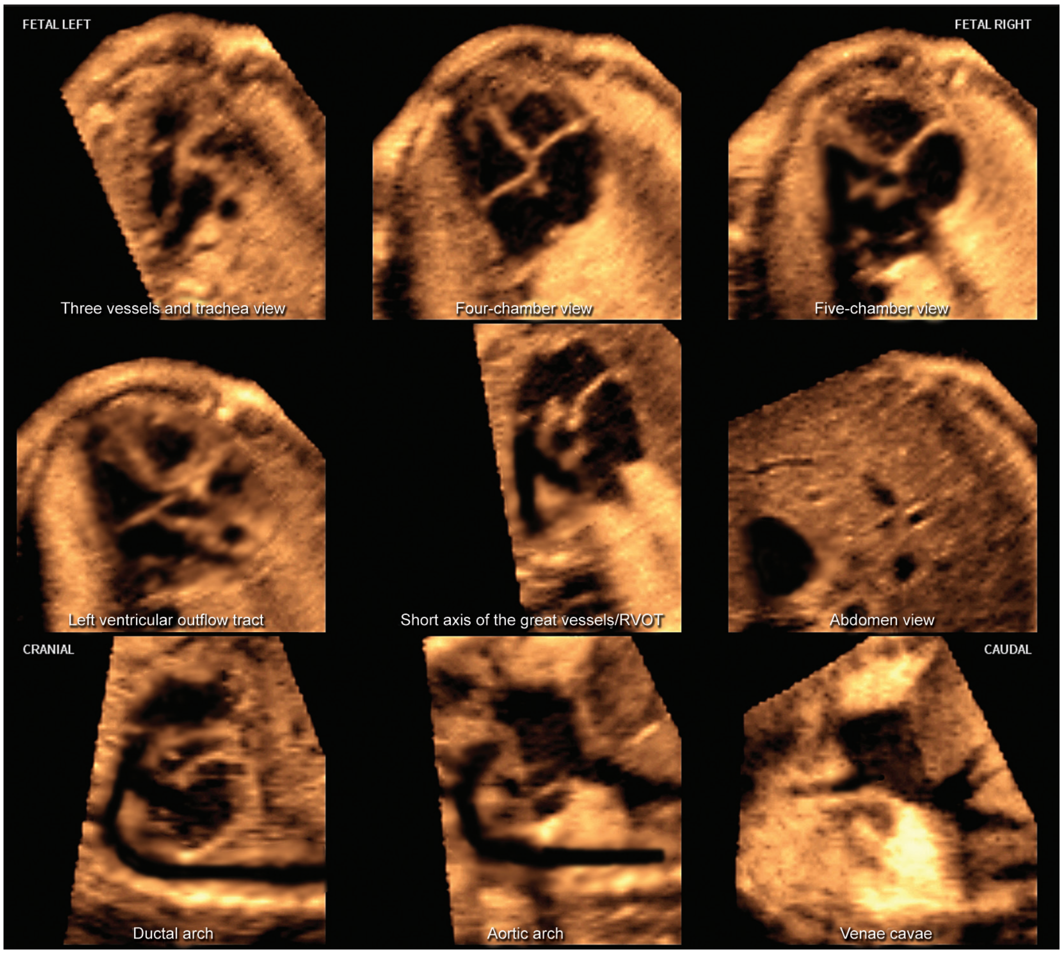


Figure 22.42 FINE modality in the final stage. Automated identification of cardiac views

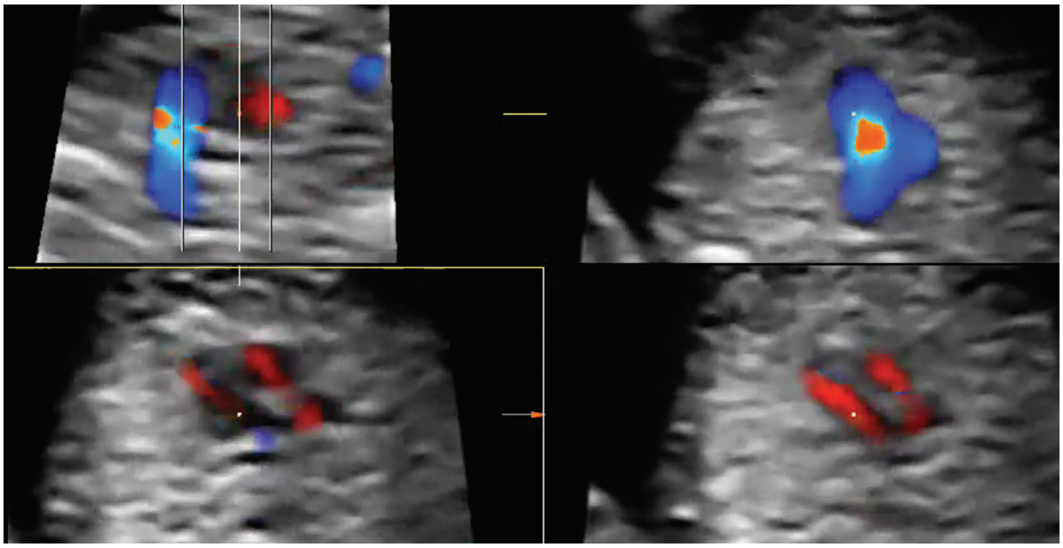


Figure 22.43 First trimester STIC ultrasound tomography of a normal heart

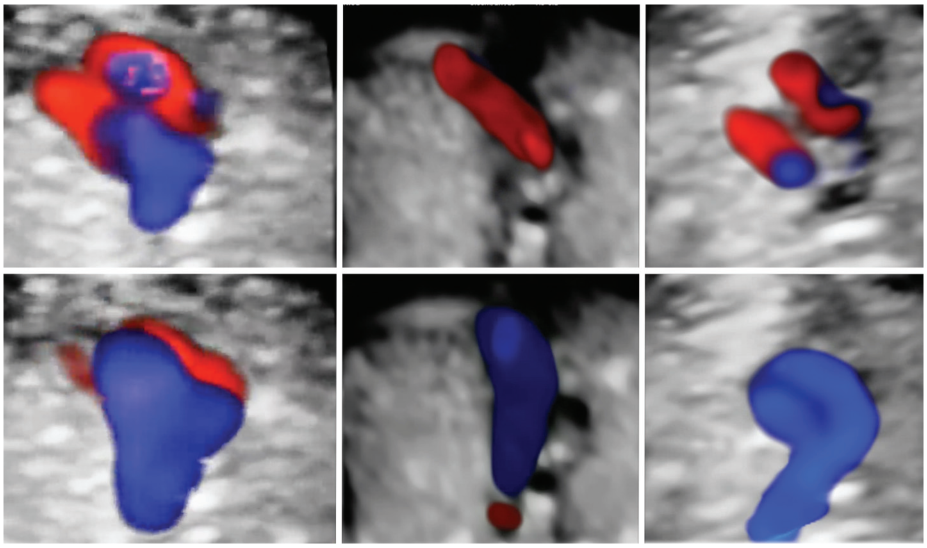
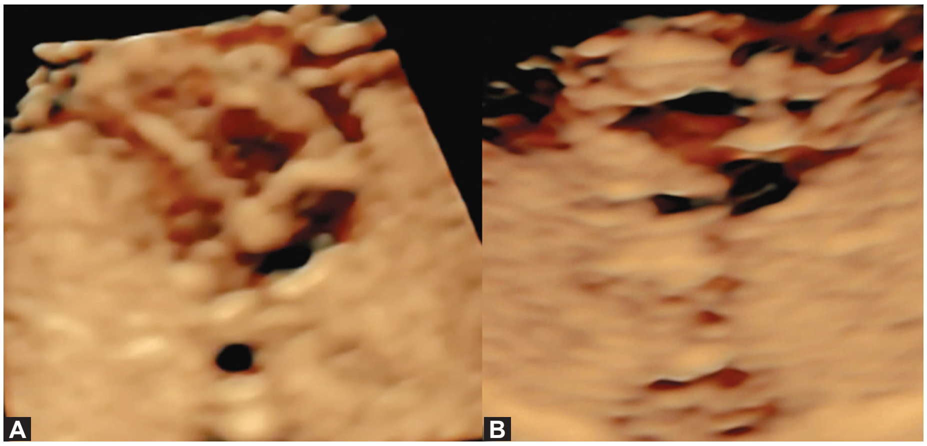


Figure 22.44 First trimester STIC color Doppler glass body rendering (four-chamber view-top and three-vessel and trachea view-bottom). Left-normal heart, middle-hypoplastic left heart (HLHS), right- d-transposition of the great arteries (d-TGA)



Figures 22.45A and B First trimester STIC surface rendering of the four-chamber view. (A) Normal heart; (B) Hypoplastic left heart

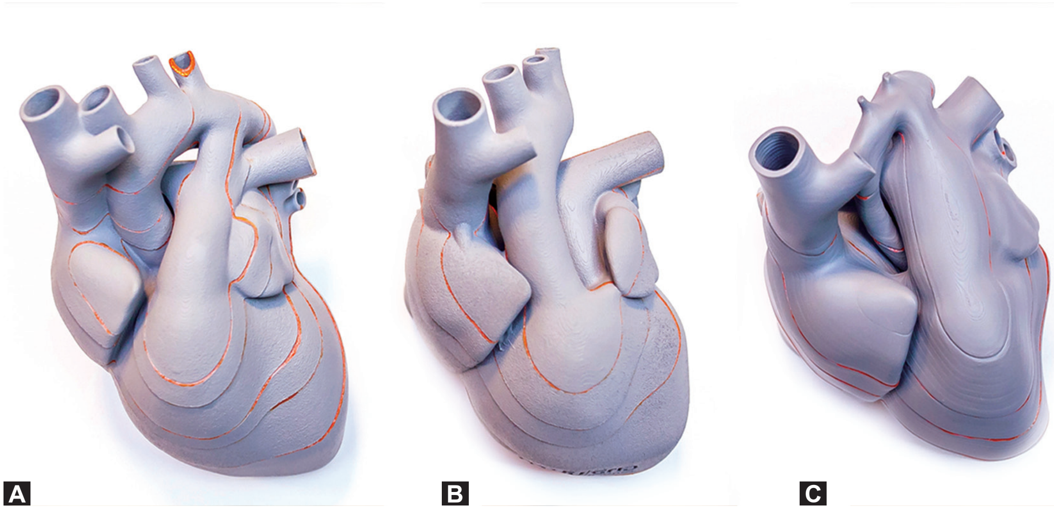
THREE-DIMENSIONAL PRINTING

The first 3D printouts concerned rare congenital anomalies and were based on views obtained with the use of computed tomography technique.[61] Cardiac surgeons used these printouts in planning of surgery in specific cases. When it comes to the fetal heart, in 2015 the authors of this chapter worked out the first 3D printouts in the world on the basis of STIC volumes **(Figs 22.46A to C)**.

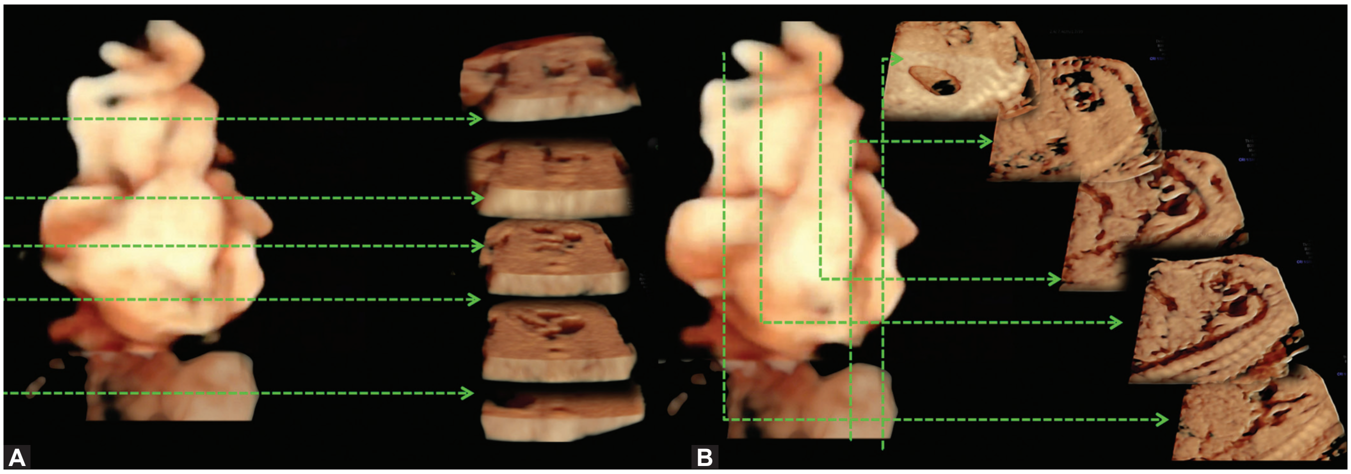
According to the authors, they could be significant in education of obstetric and gynecological physicians and sonographers learning fetal heart screening and fetal echocardiography. Additionally, 3D printouts of a fetal heart will be used while consulting parents, whose child was prenatally diagnosed with a heart disease.

CONCLUSION

Three-dimensional techniques have had a considerable significance in the development of fetal echocardiography in the recent years.[20,32] One of the main reasons of this situation was the fact that owing to those methods, advanced fetal heart examination is now open for non-cardiologists. Until the era of 3D ultrasound, only pediatric cardiologists were familiar with geometry of particular congenital heart diseases and their typical patterns, mainly on the basis of cardiac catherization imaging. This method is not available for the sake of obstetric and gynecological physicians and sonographers' education. However, introducing three-dimensional ultrasound allowed them to understand anatomical differences between a normal fetal heart and particular congenital heart diseases **(Figs 22.47A and B)**.



Figures 22.46A to C Fetal heart 3D models as a result of 3D-printing. Left-normal heart, middle- d-transposition of the great arteries (d-TGA), right- hypoplastic left heart (HLHS). Note the very different geometry between cardiac structures in the normal heart and in anomalies



Figures 22.47A and B Better understanding through 3D ultrasound of fetal heart anatomy. From one dataset numerous cross-sections are available [in transversal plane (A) and in sagittal plane (B)]

According to the authors, it is the greatest benefit of applying advanced ultrasound imaging techniques in fetal evaluation. However, the routine application of volume fetal echocardiography remains challenging due to the character of fetal ultrasound, which is strongly dependent on the scanning conditions. As an example successful STIC acquisition can be obtained in approximately 75% of cases.[62] Total time duration dedicated to volume acquisitions of the fetal heart vary between 0.9 to 6 minutes and the interpretation time is significantly longer than the time required for 2D fetal echocardiography.[63] It is also important that the clinical effectiveness of 2D measurements performed in volume datasets showed marginal clinical effectiveness mainly as a result of unsatisfactory STIC acquisitions.[63] On the other hand sonologists with low-to-intermediate expertise in fetal anomaly ultrasound demonstrated reasonably high sensitivity, specificity, positive and negative predictive values at the level of 83%, 87%, 80% and 89%, respectively for outflow tract anomalies in STIC fetal echocardiography.[64] Overall added value of 3D/4D fetal echocardiography was estimated for 6%.[65] As an example it refers to the anomalies of aortic arch and pulmonary veins. In these areas an accurate prenatal 3D imaging shows details to a degree that is conventionally obtainable only by postpartum imaging.[66-68] Also in major anomalies like in atrioventricular septal defect, 3D techniques thanks to the better perception of depth contribute in detailed evaluation of the valvular apparatus.[69] Better spatial understanding translates into the improvement of 2D fetal heart scanning technique in

Figure 22.48 Teaching session with the use of laptop stations with installed STIC volume dataset review software. A case of d-transposition is discussed—MWU postgraduate School of Ultrasound in Poland

the aspect of obtaining correct symmetric views and the knowledge of layered heart anatomy in every plane. Another example could be the improvement of scanning technique in order to visualize left ventricular outflow tract view, aortic arch view and ductal arch view noted in examiners after training in three-dimensional techniques. Comprehension of the geometry of a heart with a congenital disease gives a chance to make a correct diagnosis on the basis of pattern recognition, what shortens the diagnostic time **(Fig. 22.48)**.

Some authors believed that 3D ultrasound may reduce operator's dependency in fetal echocardiography.[70] But in fact its application reduced this factor more in 2D than in 3D evaluation by better understanding of fetal heart anatomy. Three-dimensional ultrasound techniques also allow fetal heart models 3D printing, which make the comprehension of the geometry of heart with particular anomalies even easier. Not without significance is also a greater care for image optimization, which examiners gain during three-dimensional ultrasound training. They start realizing the stronger influence of artifacts and shadowing on the quality of 3D and 2D ultrasound images. In order to avoid artifacts, the examiners more carefully utilize larger spectrum of filters correcting the image quality, such as, e.g. compounding, while using 3D as well as 2D. Three-dimensional techniques created new opportunities, not only in tele consulting but also in self-education. They enable the examiner to browse spatial views of fetal heart without the patient's presence with the use of computer 3D volume review software.[70] Owing to this method, tele-consultants or physicians taking part in training are able to analyze saved images without additional stress resulting from the patient's presence. The consultation may take place on the following day after the scan and thorough off-line examination of the volume datasets.

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