How to Acquire Cardiac Volumes for Sonographic Examination of the Fetal Heart

Part 2

Lami Yeo, MD, Roberto Romero, MD, DMedSci

The effective performance of fetal cardiac examination using spatiotemporal image correlation (STIC) technology requires 2 essential steps: volume acquisition and postprocessing. An important prerequisite is training sonologists to acquire high-quality volume data sets so that when analyzed, such volumes are informative. This article is part 2 of a series on 4-dimensional sonography with STIC. Part 1 focused on STIC technology and its features, the importance of operator training/experience and acquisition of high-quality STIC volumes, factors that affect STIC volume acquisition rates, and general recommendations on performing 4D sonography with STIC. In part 2, we discuss a detailed and practical stepwise approach for STIC volume acquisition, along with methods to determine whether such volumes are appropriate for analysis.

Key Words—fetal echocardiography; fetus; 4-dimensional; spatiotemporal image correlation; STICLoop; ultrasound

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Address correspondence to Lami Yeo, MD, Perinatology Research Branch, Eunice Kennedy Shriver *National Institute of Child Health and Human Development, National Institutes of Health, Department of Health and Human Services, Hutzel Women's Hospital, 3990 John R, 4 Brush, Detroit, MI 48201 USA.*

E-mail: lyeo@med.wayne.edu

Abbreviations
CHD, congenital heart disease; 4D, 4-dimensional; ROI, region of interest; STIC, spatiotemporal image correlation; 2D, 2-dimensional

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The effective performance of fetal cardiac examination using spatiotemporal image correlation (STIC) technology requires 2 essential steps: volume acquisition and postprocessing. An important prerequisite is training sonologists to acquire high-quality volume data sets so that when analyzed, such volumes are informative (eg, allow the successful display of cardiac views and anatomic structures). This article is part 2 of a 2-part series on 4-dimensional (4D) sonography with STIC. Part 1 focused on STIC technology and its features, the importance of operator training/experience and acquisition of high-quality STIC volumes, factors that affect STIC volume acquisition rates, and general recommendations on performing 4D sonography with STIC.[1] In part 2, we discuss a detailed and practical stepwise approach for STIC volume acquisition, along with methods to determine whether such volumes are appropriate for analysis.

How to Perform 4D Sonography With STIC

Four-dimensional sonography with STIC technology allows the acquisition of a fetal cardiac volume data set and visualization of cardiac structures as a cine loop of a complete single cardiac cycle in motion.[2–5] Such technology is readily available across many ultrasound platforms and is integrated into the system's basic software option. Once STIC has been activated, the array within the transducer housing begins an automatic single sweep over the region of interest (ROI).[3,6] The STIC volume display is thus composed of thousands of 2-dimensional (2D) images acquired through this area of interest during the sweep. Once the image data have been analyzed according to their spatial and temporal domain (hence, the term *spatiotemporal image correlation*), the dynamic image sequence can be displayed as a multiplanar view, single plane, and/or rendered image.[3] The end result is that STIC volume data sets contain all the necessary information for an adequate examination of the fetal heart, having an unlimited number of cardiac images available for review in any plane and orientation. This fact is relevant, since the standard fetal cardiac views recommended by professional organizations[7–10] for prenatal diagnosis can be generated.

A solid body of evidence suggests that 4D sonography with STIC facilitates examination of the fetal heart[3,4,5,11–37] and may also be used to evaluate fetal cardiac function.[18,22,27,30,31,33,38–46] This modality has also been used in the prenatal evaluation and diagnosis of congenital heart disease (CHD)[2,20,47–71] because it improves the ability to identify complex intracardiac relationships and can shorten the examination time.[3,17,72] These facts are important, since evaluation of the normal and abnormal fetal heart[73–75] using 2D sonography is one of the most challenging tasks in prenatal diagnosis. Indeed, structural cardiac abnormalities are among the major malformations that are most frequently missed on prenatal sonographic examinations.[76–78] STIC technology also has the potential to reduce the operator dependency associated with 2D sonography. This aspect is relevant, since the most important factor affecting the prenatal detection of CHD is operator skill and expertise,[79–85] in which mental reconstruction of a sequence of individual cross-sectional images is required.[86]

Three main time points deserve focus when acquiring STIC volume data sets and determining their appropriateness for analysis[1]: (1) before acquisition of STIC volumes; (2) acquisition of STIC volumes; and (3) immediately after acquisition of STIC volumes (ie, multiplanar display and/or STICLoop[87]).

Before obtaining STIC volume data sets, it is essential to enhance the overall sonographic image. This can be accomplished through the following steps.

Before the Acquisition of STIC Volumes

1. *Optimize the Quality of the 2D Image*—An important concept is that the image quality of STIC volume data sets depends primarily on the original quality of the 2D image, along with prior adjustments in grayscale (and color Doppler, if used) parameters.[88] Thus, if the 2D image quality is suboptimal (eg, poor resolution due to maternal habitus or acoustic shadowing), it will also generally be the case for the STIC volume data set.[89] The goal is to enhance the temporal and spatial resolution of the volume by highly optimizing 2D images before the acquisition. Settings should be adjusted to obtain clear visualization of the fetal heart, an image that is neither too bright nor dark, and one that is characterized by increased contrast and high resolution.[9] Ultrasound platforms frequently have settings specifically designed for fetal cardiac examination. Thus, the operator can choose this setting initially and then make adjustments based on preference. Some have reported that highly optimized 2D image resolution (required to obtain proper STIC volume reconstruction) improves with sonographer experience.[90]

2. *Maximize the Frame Rate*—A high frame rate leads to a STIC volume data set with improved quality, since there will be more frames within such volume. This goal can be accomplished by decreasing 3 parameters: (1) depth, so that there is less depth below the fetal heart in the imaging window; (2) sector width (or viewing angle) around the heart, so that other irrelevant structures are not in the field of view; and (3) number of focal zones, so that there is a single zone. How does imaging depth affect temporal resolution? Shallow imaging increases the frame rate and improves temporal resolution, whereas deeper imaging decreases the frame rate and degrades temporal resolution.[91] Thus, an inverse relationship exists between imaging depth and frame rate. When the sector width is narrowed, the number of pulses required to make an image decreases, and there is increased temporal resolution along with a higher frame rate.[91] The number of focal zones also influences the frame rate. The focal zone is a region around the focus where the beam is relatively narrow and where image detail is superior.[91] With single-focus imaging, only one sound pulse is transmitted down each scan line, which results in superior temporal resolution and a higher frame rate.

3. *Adjust the Focal Zone Location*—Besides the number of focal zones, the location of the focal zone also influences the sonographic image. Reflections that arise from the focal zone create images that are more accurate than those from other depths.[91] Thus, the single focal zone should be placed at, or below, the level of the fetal heart in the imaging window.

4. *Magnify the Image*—Magnification of the fetal heart should be performed before STIC volume acquisition to improve visualization of cardiac anatomy. However, it is noteworthy that the image should not be magnified so much, that the entire 4-chamber view and fetal chest are not visualized fully on the monitor screen.

Acquisition of STIC Volumes

When obtaining STIC volume data sets, it is important to: (1) prepare the acquisition settings (eg, acquisition angle); (2) follow preset criteria; (3) obtain an appropriate apical 4-chamber view; and (4) recognize when to discard volumes and when volumes should not be obtained. We will now review each of these steps in detail.

1. *Prepare the Acquisition Settings (ie, ROI, Acquisition Angle, and Acquisition Time)*—Besides the frame rate, the quality of a STIC volume data set also depends on the acquisition angle and acquisition time.[5] The more images that are stored per acquisition period, the greater the number available for volume reconstruction, and the better the image resolution. In other words, the longer the sweep or acquisition time, the greater the number of frames collected for the STIC volume data set, and the better the spatial resolution. Acquisition settings that should be adjusted include the ROI, acquisition angle, and acquisition time.

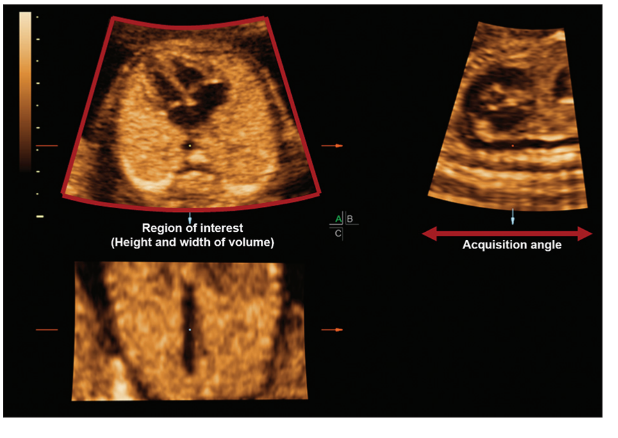
a. *Region of interest*: The ROI box determines the height (y-plane) and width (x-plane) of the STIC volume data set (Figure 1 and Video 1). Contrary to what one may think, a large and/or wide ROI is associated with lower frame rates that may negatively impact the temporal resolution and quality of the volume. Thus, adjusting the ROI box size to be as small as possible will maximize the frame rate during acquisition and also improve the temporal resolution of the volume data set.[88] The box should be adjusted to encompass the entire fetal chest circumference, so that it contains all the anatomic information of the fetal heart (Figure 1 and Video 1). Moreover, the heart should occupy the maximum proportion of the image to be acquired. It is important during the actual sweep by the transducer array to observe on the monitor screen the sequential images within the ROI box. By doing so, it will be apparent whether either the size or location of the ROI box is inappropriate.

b. *Acquisition angle*: The acquisition angle (eg, 15°–60°) determines the acquisition depth (ie, amount of information acquired in the z-plane; Figure 1 and Video 1). Thus, a smaller acquisition angle is equivalent to a shorter distance covered during the sweep. The angle should be selected by the sonologist before STIC volume acquisition, and the goal is to encompass all the anatomic structures of interest. For example, when volume acquisitions are performed in the transverse plane of the fetal heart, the upper mediastinum through the upper abdomen/stomach of the fetus should ideally be included in the volume data set.[2] This process ensures that all standard transverse planes (eg, 3-vessel view) are available for assessment.

The acquisition plane is defined as the starting 2D plane for a volume acquisition (Figure 1 and Video 1). Once the acquisition plane (eg, apical 4-chamber view) has been obtained and the acquisition angle is selected by the sonologist (eg, 15°), the STIC volume data set is initially created by a mechanical sweeping of the beam 7.5° from such acquisition plane. The acquisition process then begins, coming back toward the acquisition plane and then continuing for another 7.5° to create a total volume of information of 15°. Therefore, a total sweep of 15° cranial and caudal to the apical 4-chamber view is obtained, in which the acquisition plane is located in the middle of the sweep box.

How does one determine the appropriate acquisition angle for the STIC volume data set? The angle should always be adjusted, depending on whether there is a smaller or larger fetal size. A useful rule of thumb is to set the acquisition angle at least 5° more than the gestational age (eg, at 30 weeks' gestation, the angle could be set at 35°). An earlier gestational age will therefore require a narrower angle.

Figure 1. Multiplanar display of a STIC volume (normal fetal heart). The ROI box around the acquisition plane (apical 4-chamber view) determines the height (y-plane) and width (x-plane) of the volume. Note that the box encompasses the entire fetal chest circumference. The B plane (sagittal image; upper right corner) demonstrates the acquisition angle of the volume, which determines the acquisition depth. Since the reference dot has been placed in the cross section of the descending aorta in the A plane, the longitudinal descending aorta is visible in both the B and C planes.



It is also essential that one not obtain too wide of an acquisition angle, believing that "more is better," because for a selected acquisition time, the image resolution of the B and C planes in the multiplanar display (see description of these planes later) will actually be lower when the angle is 40° (versus 15°).[92] Moreover, when the volume sweep angle is larger than the structure(s) being examined, this leads to: (1) redundant information being included within the volume; (2) decreased volume resolution; and (3) an increased chance of artifacts being introduced (eg, fetal movements). Therefore, it is desirable to set the minimum acquisition angle that will include only the area(s) of interest. Doing so will reduce artifacts and optimize volume quality.[26] On the other hand, if an acquisition angle is too narrow, anatomic structures(s) may not be included within the volume data set at all, and it becomes uninformative. Viñals et al[2] obtained standard fetal cardiac planes by scrolling through STIC volume data sets from the upper abdomen to the mediastinum. However, low visualization rates were observed for structures located in the mediastinal or abdominal areas. These results were attributed to a lack of operator experience, in which the acquisition angle was not set wide enough to include such structures.[2]

How can one determine whether the appropriate acquisition angle for the STIC volume has been set? During the actual volume sweep, it is necessary to observe the images on the monitor screen to determine whether the structure(s) of interest have been included. For a 4-chamber view acquisition plane, the sonologist should evaluate whether the fetal upper mediastinum (start of the sweep) and the stomach (end of the sweep) are visible on the screen (Video 2). If neither of the views have been included (ie, angle of acquisition too narrow), the STIC volume can be immediately discarded, and for subsequent acquisitions, the acquisition angle should be increased. On the other hand, if one observes planes that are inferior to the stomach during the acquisition sweep, the acquisition angle is probably too wide, and it should be decreased for future acquisitions. Once the STIC volume has been obtained, one can also evaluate the multiplanar display to determine whether the acquisition angle was appropriate (also see "Acquisition Angle in B plane" later; Figure 1 and Video 1).

c. *Acquisition time*: The acquisition time (or duration of acquisition) determines the speed at which the transducer sweeps the ROI. An inverse relationship exists between the acquisition time and sweep speed. Therefore, the shorter the acquisition time (eg, 7.5 seconds), the faster the sweep speed of the transducer. All ultrasound platforms allow the operator to select the volume acquisition speed, and the acquisition times generally range from 5 to 15 seconds in duration.

For a fixed acquisition angle (eg, 30°), the number of acquired frames will increase as the duration of the acquisition time goes up.[92] Thus, the quality of a STIC volume acquisition is essentially reflected by the acquisition time.[26] It is desirable to obtain volumes containing the greatest possible number of 2D images from which the data set will be constructed. With increasing STIC acquisition times (eg, 15 seconds) or a slower sweep speed, the image resolution of the B and C planes in the multiplanar display will be higher. Conversely, with decreasing acquisition times (eg, 7 seconds) or a faster sweep speed, the image resolution in the B and C planes will be lower.

Therefore, STIC volumes should be obtained by using the longest possible acquisition time. Some women, however, may have difficulty holding their breath for 15 seconds. Moreover, there is a higher likelihood that artifacts related to fetal motion or breathing may be introduced into the volume data set, thus compromising quality.[40] In our experience, since most women can hold their breath without difficulty for 10 to 12.5 seconds during the STIC acquisition, we recommend setting the acquisition time for at least 10 seconds. However, when fetuses are very active (eg, movements), there may be no choice but to set the shortest possible acquisition time to minimize motion artifacts, recognizing that this set time will be at the expense of optimal spatial resolution.

Taken together, the goal is to identify an acquisition time (or sweep speed) that will optimize image resolution but not allow the introduction of artifacts (eg, fetal breathing or movements) into the B and C planes, which can occur if the sweep speed is too slow. Typically, we preset the time for 10 to 12.5 seconds and then adjust it according to the presence/absence of fetal breathing or movements.

A recent development is the introduction of an electronic matrix 4D probe that allows up to a 75% reduction in the STIC acquisition time, along with improved resolution in the B and C planes.[93] High-resolution subvolumes are acquired, in which each subvolume contains a portion of the fetal heart. The system analyzes each subvolume and combines them to display the entire fetal heart for a full cardiac cycle. With subvolume acquisitions, the A and B plane line densities are tuned pair-wise to have similar image quality.[93] Therefore, due to the marked reduction in the acquisition time and improved image resolution in the B and C planes, the electronic matrix probe may prove to be useful when performing 4D sonography with STIC.

2. *Spine Position Between 5 and 7 o'clock*—To assess cardiac views from a STIC volume data set, the fetal spine ideally should be positioned between 5 and 7 o'clock (ie, an apical 4-chamber view; Figure 2) because this position reduces the possibility of acoustic shadowing from the ribs or spine. Such shadowing can obscure visualization of cardiac structures (Video 3) and is more likely to occur if the fetal spine is located at other clock "times" (eg, between 11 and 1 o'clock). Indeed, a fetus with the spine located in an anterior position (ie, "back-up") has been associated with a significantly lower probability (by 72%) that cardiac views (4 chamber and left and right ventricular outflow tracts) would be regarded as satisfactory for screening.[25] It should be noted, however, that high-quality STIC volumes can still be obtained when the fetal spine position is outside the recommended 5- to 7-o'clock times (eg, 4 o'clock).

An interesting concept is whether it is possible to "change" the fetal spine position so that the location appears more optimal on the monitor screen. Effective methods that can actually alter the true fetal spine position include asking the supine mother to turn (or roll) laterally onto her side (eg, "clockwise roll") in the same direction that you desire the fetal cardiac apex to turn (see part 1 of this series for further explanation[1]). Other options include gently "moving" the fetus into the desired position by placing one's hands on the maternal abdomen or having the patient sit up/ambulate for a brief period. Extra time can also be allowed during the sonographic examination so that the fetus changes to a more optimal position.

a. *Driving the transducer*: A technique that we have found to be effective in "converting" the fetal spine to a posterior position on the monitor screen is what we term "driving the transducer" (Figures 3 and 4 and Videos 4 and 5). The fetus itself does not change position but, rather, the transducer (and, thus, its beam) is "driven" on the maternal abdomen so that it comes to lie above the anterior (versus lateral) fetal chest.

To accomplish this technique, one should take advantage of the entire maternal abdominal field by moving the transducer in different locations on the abdomen, even near the flanks. Such a technique is based on the following principle. When steering a car with one hand, the driver fixes his or her hand on the steering wheel and can only rotate the wheel to the right or left direction in a fixed arc. Even if one twists the hand while on the steering wheel, this action cannot change the fixed arc, since steering wheels are rigid and stationary in place. Similarly, one can "drive" or steer the transducer in a fixed arc around the transverse fetal chest (from one side to the other) by moving the transducer across the maternal abdomen (typically from one flank to the other). In this technique, the 4-chamber view can be thought of as the center of a steering wheel. Essentially, the objective is to always move the probe on the maternal abdomen so that it comes to lie above the anterior fetal chest, leading the spine to be more posteriorly located on the screen, and the cardiac apex to be "up" (Figures 3 and 4).

Figure 2. Apical 4-chamber view with the fetal spine positioned at different locations: **A**, 7 o'clock; **B**, 6 o'clock; **C**, 5 o'clock. Such positions reduce the possibility of acoustic shadowing from the fetal ribs or spine.

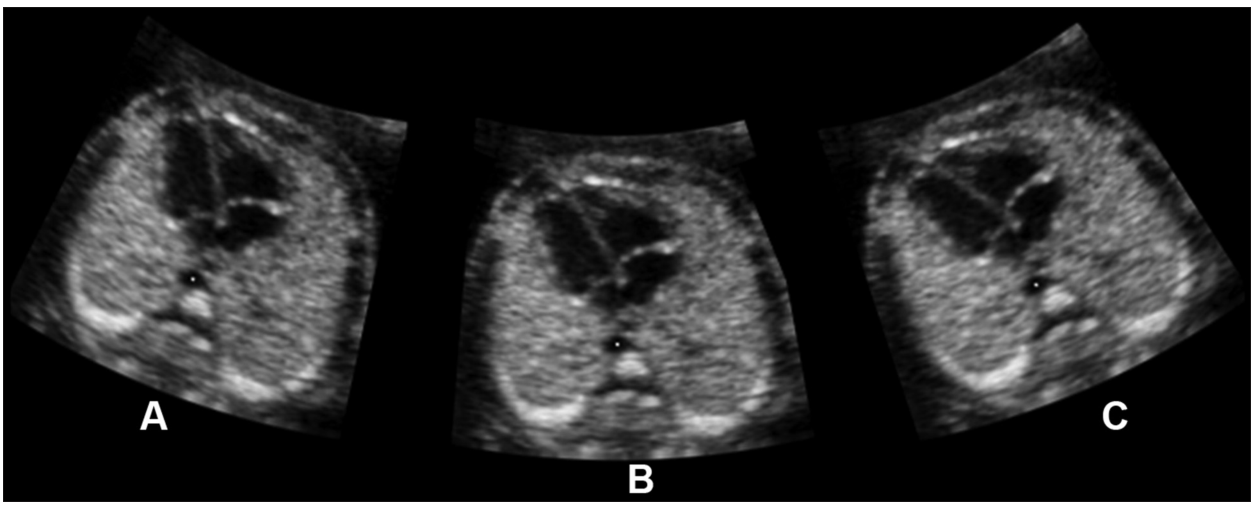


Figure 3. Driving the transducer technique in a vertex fetus. **A**, Spine originally located at 8 o'clock in the apical 4-chamber view. **B**, The transducer is driven on the maternal abdomen (toward the fetal right side) in a fixed arc until it lies above the cardiac apex. **C**, On the monitor screen, the fetal spine has converted to a more posterior position (6 o'clock), and the cardiac apex is now up. **D**, Spine located at 5 o'clock in the apical 4-chamber view. **E**, The transducer is driven leftward on the maternal abdomen (toward the fetal left side) in a fixed arc until it lies above the cardiac apex. **F**, On the monitor screen, the fetal spine has converted to a more posterior position (6 o'clock), and the cardiac apex is now up. L indicates fetal left; and R, fetal right.

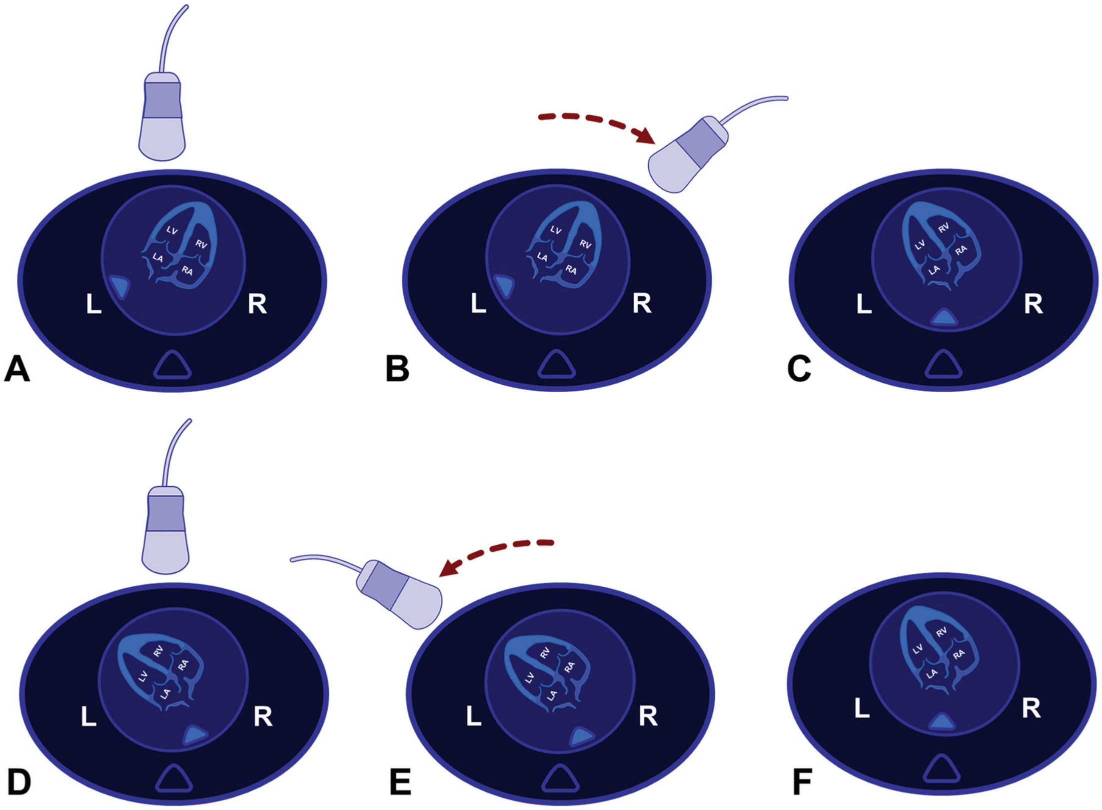
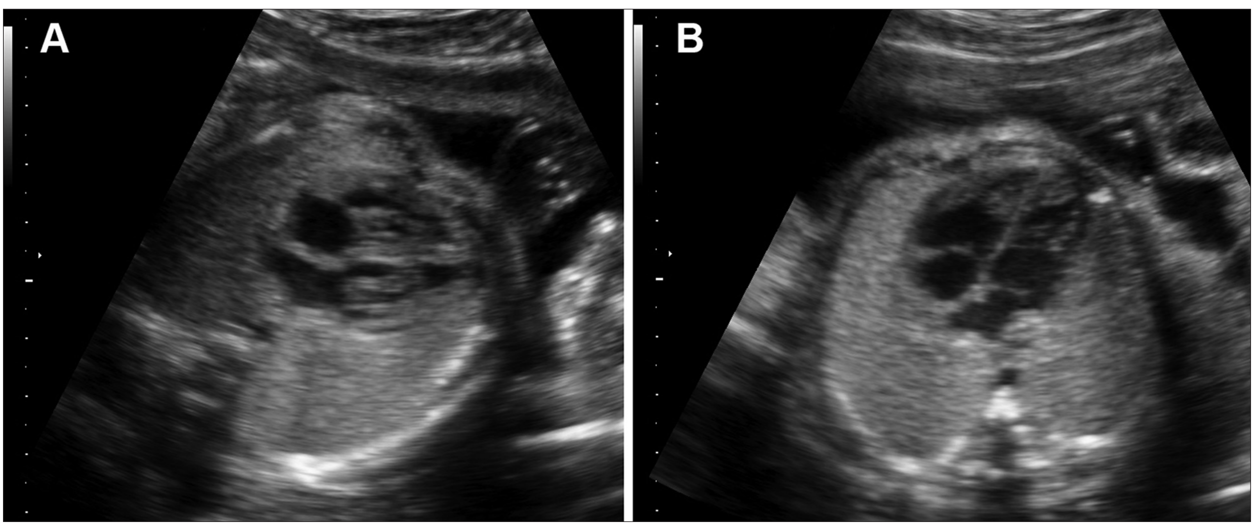


Figure 4. Driving the transducer technique in a breech fetus. **A**, Spine originally located at 8 o'clock in the subcostal 4-chamber view. The transducer is driven on the maternal abdomen (to the operator's right, toward the fetal left side) in a fixed arc until it lies above the cardiac apex. **B**, On the monitor screen, the fetal spine has converted to a 6 o'clock position, and the apical 4-chamber view is visible.



The steps to be performed are the following. Once the 4-chamber view has been identified on the monitor screen, the sonologist should hold the transducer (ie, steering wheel) in a fixed manner without twisting the hand. Next, one should drive the probe in a fixed arc either to the operator's right or left (maternal left or right, respectively, if the patient faces the operator) until it lies above the anterior fetal chest, always keeping the 4-chamber view on the screen. If one drives with the probe but twists the hand at the same time, the 4-chamber view will no longer be visualized on the screen but, rather, a different cardiac plane (eg, left ventricular outflow tract). Therefore, it is essential that the driving movements of the transducer should simulate that of rotating a steering wheel in a fixed arc to the operator's right or left side. If such a technique is done correctly, often the fetal spine in the 4-chamber view will convert to a more posterior position on the monitor screen, and the cardiac apex will be up (Figures 3 and 4 and Videos 4 and 5).

Although the method is not complicated, we have found that it may be difficult for beginners to learn how to drive with the transducer because: (1) random (versus targeted) scanning movements are made with the probe; (2) the entire maternal abdominal field is not scanned; and (3) twisting of the hand occurs during the sonographic examination. Therefore, driving the transducer initially requires some practice.

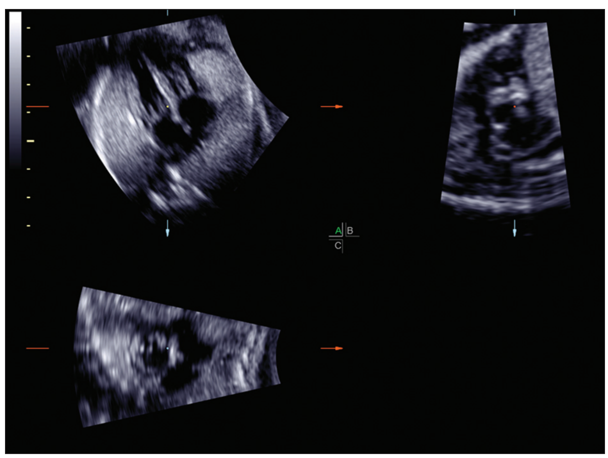
Since complete rotation of a STIC volume data set around a 360° axis is manually possible using software,[1] a question often asked is why a given STIC volume cannot just be rotated so that the fetal spine location is between 5 and 7 o'clock. There are 2 issues that arise from this action. First, simply rotating a STIC volume on the z-axis (ie, rotating clockwise or counterclockwise) can never "erase" acoustic shadowing, dropout, or artifacts already contained within the data set. It is not possible to do this once a STIC volume has been acquired. The second issue is that when the acquisition plane is rotated on the z-axis (eg, 4-chamber view with the spine located at 4 o'clock now rotated to 6 o'clock), it alters the normal aspect of the image in terms of ultrasound wave reflection and refraction.[94] As a result, the B-plane image in the multiplanar view becomes more blurred or "waxy," and the image clarity/quality diminishes (Figure 5 and Video 6). It is worth repeating that any movement or rotational changes to the acquisition plane image will also lead to respective changes in the images of the B and C planes.[1]

3. *Minimal or Absent Shadowing of the 4-Chamber View (Including the Upper Mediastinum)*—Acoustic shadowing is defined as signal loss in the sound path secondary to echogenic structures, whereas acoustic dropout is defined as signal loss in the sound path without intervening structures.[30] When acquiring STIC volume data sets, it is important that there is minimal or absent acoustic shadowing/dropout in the ROI. In addition to clear visualization of the 4-chamber view acquisition plane within the ROI, the same applies to the upper fetal mediastinum (Video 7). If acoustic shadowing or dropout is present, it may obscure visualization of the cardiac anatomy and structures in STIC reconstruction.

Even when the fetal spine is ideally positioned between 5 and 7 o'clock, acoustic shadowing or dropout may still occur secondary to the fetal extremities, fetal ribs or sternum, an anterior placenta, cotwin, maternal umbilicus, and maternal abdominal scarring. Therefore, to avoid these issues, it may be necessary to move the transducer to different locations on the maternal abdomen, adjust the rotational position or tilt of the transducer, or wait for fetal parts to move out of the field of view.

4. *Minimal or Absent Fetal Breathing and Gross Movements*—Ideally, there should be minimal to absent fetal breathing and gross movements during the STIC acquisition. All such conditions can lead to motion artifacts within the volume data set, with distortion of images and anatomic structures (Figure 6 and Video 8; also see "wavy lasagna

Figure 5. STIC volume acquired from the subcostal 4-chamber view, in which the spine was originally located at 4 o'clock. The acquisition plane (A plane) has been manually rotated on the z-axis so that the spine location is at 6 o'clock. As a result, the B-plane image (ductal arch) becomes more blurred or waxy in appearance, with diminished image clarity.



wall" later). Indeed, STIC motion artifacts have interfered with the evaluation of anatomic relationships between great vessels and cardiac chambers, leading to an incorrect diagnosis.[95] Therefore, it is prudent to acquire multiple STIC volumes when CHD is suspected, to avoid misdiagnosis.[89] The presence of fetal hiccups (regular or irregular) will also lead to motion artifacts within the STIC volume data set (see "piano keys" later).

Thus, one should attempt to obtain STIC volumes when fetal breathing and gross movements are absent or have subsided. In a few cases, it will be impossible, and the following points are noteworthy. When fetal breathing/movements occur during the acquisition, their degree (mild or intense), frequency (regular or irregular), and location (relative to fetal anatomy) will cause orthogonal planes to range from being minimally altered to completely uninterpretable. Specifically: (1) minimal and occasional fetal breathing/gross movements may not affect image resolution; (2) regular and intense fetal breathing/movements throughout the STIC volume acquisition will lead to an uninterpretable and distorted image (see "wavy lasagna wall" later); moreover, the fetal heart rate depicted on the monitor screen immediately after the acquisition is completed will usually be abnormal; and (3) if fetal breathing/movements occur in certain anatomic areas of interest (eg, upper mediastinum; Figure 6 and Video 8), the volume will be uninformative and, thus, unacceptable. However, if such movements occur only in the area of the fetal abdomen (Video 9), the cardiac planes may still be very informative.

Taken together, it seems that a major limitation of STIC technology is the requirement to obtain volumes in a quiescent fetus who is lying supine. However, multiple investigators have shown how this condition can easily be met during routine sonographic examinations.[5,17,19]

5. *Visualization of the Transverse Aortic Arch ("Dolphin")*—Just immediately before beginning a STIC acquisition of the 4-chamber view, the transducer should be tilted or rocked slightly to ensure that the transverse aortic arch (dolphin) is clearly visible in the upper fetal mediastinum (Figure 7 and Video 10). Confirming visibility of the transverse aortic arch maximizes the chances that it will also be discernible in later volume reconstruction. If the transverse aortic arch is not evident, the transducer should be repositioned and/or tilted on the maternal abdomen until the 4-chamber view and dolphin are clearly visualized. This process may require driving the transducer in a fixed arc around the transverse fetal chest (see above). The transverse aortic arch may not be clearly visible due to acoustic shadowing from the fetal sternum or extremities or because there is a cardiac abnormality (eg, coarctation of the aorta).

6. *Four-Chamber View as the Acquisition Plane*—In most cases, the starting 2D plane for the STIC volume acquisition (ie, acquisition plane) will be the 4-chamber view (versus 5-chamber view, for example) for several reasons.

Figure 6. During the STIC volume acquisition, fetal breathing occurred at the beginning, leading to a motion artifact in the area of the upper mediastinum. As a result, there is distortion of the 3-vessel and trachea view, as evidenced in the acquisition plane (upper left corner). Note that the pulmonary artery and ductus arteriosus (ductal arch view, B plane) appear distorted, and the anatomy cannot be assessed with confidence.

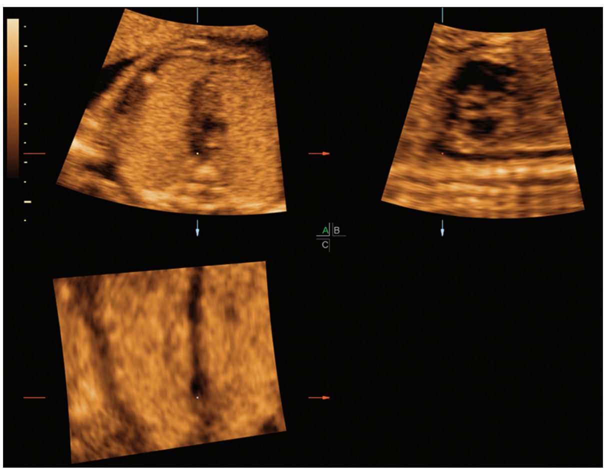
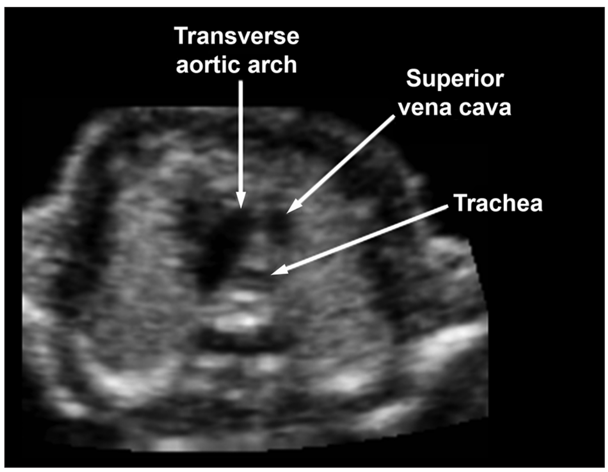


Figure 7. Transverse view of the fetal upper mediastinum, demonstrating the transverse aortic arch (dolphin), cross section of the superior vena cava, and cross section of the trachea. Just immediately before beginning a STIC volume acquisition of the 4-chamber view, one should tilt the transducer to ensure that the transverse aortic arch is also clearly visualized.



First, the 4-chamber view is best suited as the reference plane to evaluate transverse cardiac views, which include the cardiac chambers, origin of the great vessels, 3-vessel view, and 3-vessel and trachea view.[26] Although optimal evaluation of the aortic arch, ductal arch, and venous connections is best achieved through a sagittal STIC volume acquisition of the fetal chest,[4,35] such structures can also be successfully obtained from a transverse sweep through the fetal chest.[16,29,34,87,96–98] Second, the sonographic plane most easily obtained in the fetal heart is the 4-chamber view.[99] Indeed, such a view can be obtained in 95% to 98% of fetuses in a nonselected population during the second trimester.[100–102] Moreover, in a study of 3-dimensional sonographic evaluation of the fetal heart, the 4-chamber view acquisition plane was most often obtained (93%) and was also the most valuable, since it yielded the maximum number of cardiac views.[103] Finally, Turan et al[90] reported that optimal imaging of the 4-chamber view in the first trimester (eg, at STIC volume acquisition) was the cornerstone for identifying CHD.

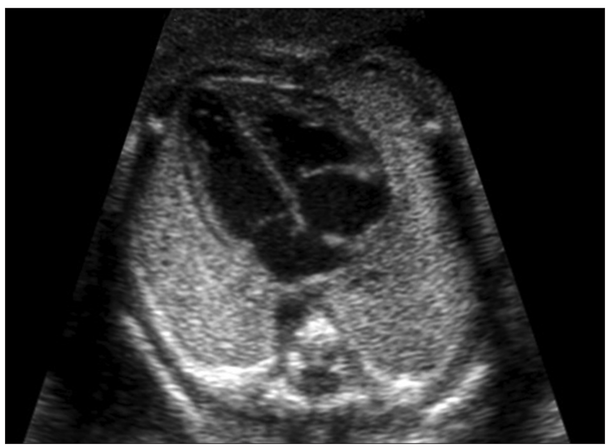
Through proper training, all sonologists should be able to obtain an appropriate STIC volume data set, which is acquired from the 4-chamber view. Yet, it is noteworthy that acquiring an apical 4-chamber view per se is not enough; it should also be the correct (or appropriate) 4-chamber view (ie, true cross section of the thorax with proper alignment in the axial plane).[29] We will now review how this view can be achieved.

7. *How to Acquire an Appropriate Apical 4-Chamber View*—The 4-chamber view is imaged through a transverse section of the fetal thorax. Once a true axial plane of the apical 4-chamber view is achieved (Figure 8 and Video 11), a STIC volume can be obtained. This process may seem fairly straightforward (ie, depicting 4 cardiac chambers is not difficult); however, the key is insonating the fetal heart so that the correct 4-chamber view appears. It is well known that the appearance of the 4 cardiac chambers can vary, depending on the orientation of the ultrasound beam to the heart.[104] Therefore, proper orientation of the transducer is essential. Indeed, investigators have noted that it is easy to obtain an improper plane of the 4-chamber view, since the ultrasound beam may be tilted, resulting in asymmetry of both sides of the fetal heart.[105] Thus, many sonologists technically obtain a "4-chamber view," but one that is characterized by improper alignment in the axial plane, as well as azimuth. In this situation, for example, the sizes of the fetal lungs will appear asymmetric on either side of the heart, or a portion of the liver may be visualized in the 4-chamber view plane. In our experience, sonologists tend to foreshorten the left (versus right) side of the fetal heart when imaging the apical 4-chamber view, and, as a result, the left atrium and ventricle will appear "cut off" compared to the right side (Video 12).

Why is obtaining the appropriate apical 4-chamber view important in STIC volume acquisition? There are several reasons. First, if there is improper alignment in the axial plane and the presence of azimuth, the operator will need to manually navigate and manipulate the STIC volume data set to "correct" the 4-chamber view. Manual navigation[106] is accomplished by using controls to interrogate the 3 orthogonal planes in the multiplanar display, which can be challenging, cumbersome, and time-consuming. An inexperienced sonologist may have difficulty manipulating the STIC volume data set to obtain the proper acquisition plane (in this case, the apical 4-chamber view). Therefore, it is likely to be easier obtaining the appropriate apical 4-chamber view at the time of STIC acquisition (ie, real-time sonography) than via manual navigation of the multiplanar display.

Second, failing to begin the STIC acquisition from the correct transverse plane of the 4-chamber view leads to incomplete acquisition of fetal cardiac structures and/or views toward the far ends of the automatic sweep.[55] This situation occurs because the acquisition axis does not coincide with the fetal body axis.[55] Others also recommend that sonologists identify a perfect 4-chamber view at the time of STIC volume acquisition.[107] The reason is that when the exact 4-chamber view is the initial plane before scrolling inside the STIC volume ("cardiac-based technique"),

Figure 8. Transverse section of the fetal thorax demonstrating a true axial plane of the apical 4-chamber view (vertex presentation). Note that the size of the fetal lungs is symmetric, and the left atrium and ventricle are not foreshortened in this insonation.



there are higher success rates of obtaining transverse cardiac views (ie, 4 chamber, 5 chamber, 3 vessel, 3-vessel and trachea, and transverse aortic arch views) than if one uses a "body-based technique" (ie, placing the fetus in an exact dorsal supine position as the initial plane before scrolling inside the STIC volume).[107]

Our recommendation is that once an apical 4-chamber view has been obtained on 2D sonography, transducer movements should be minimal and focused to fine tune the apical 4-chamber view plane to the correct one. Since the size of the fetal heart is small, anatomic structures are therefore close to each other within a small area. Thus, broad, random, and abrupt movements when using the transducer may change the cardiac plane completely (eg, from a 4-chamber view to an outflow tract). The following section describes guidelines for obtaining an appropriate apical 4-chamber view of the fetal heart when the fetus is in a vertex presentation, as well as frequent errors that are made.

a. *Obtain a 4-chamber view*: We have observed sonologists to be slightly "off" plane when capturing STIC volumes. Specifically, a 5-chamber view is obtained and on the monitor screen at the exact moment the sonologist presses the button to activate the STIC volume sweep. It is essential that the acquisition plane is not the 5-chamber view with the aortic root or the left ventricular outflow tract. If either view is being obtained, the transducer may have been rotated rightward on the y-axis. To correct this situation, the operator should rotate the transducer in the opposite manner (ie, leftwards on the y-axis) to obtain the actual 4-chamber view.

b. *Symmetry of the left and right sides of the heart*: There is often a tendency to foreshorten the left (versus right) side of the fetal heart when imaging the apical 4-chamber view (Video 12). If this situation occurs, the transducer should be tilted and readjusted, so that there is symmetry of both the left and right sides of the heart (the atria and ventricle constitute one side). Of course, asymmetry between the left and right sides of the fetal heart may represent CHD, and this possibility should be ruled out.

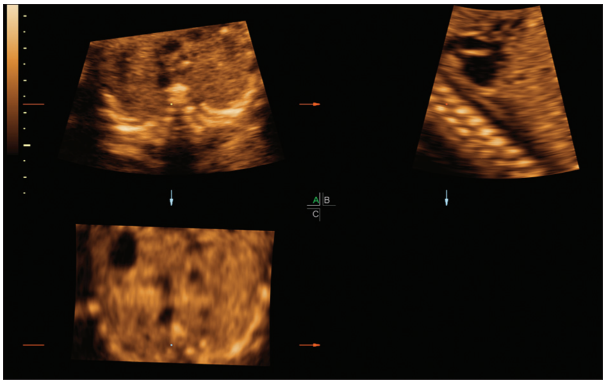
c. *Lungs symmetric on either side of the heart*: In the apical 4-chamber view, each fetal lung should be similar in size to each other. If one side is smaller (ie, foreshortened) or larger than the other, it could indicate an azimuthal issue in which the probe has been tilted. The sonologist should read just the probe so that both lungs appear symmetric in size.

d. *Fetal liver or stomach should not be visualized*: If any portion of the fetal liver or stomach is seen within the plane of the 4-chamber view of a normal fetus (Video 13), it means that the transverse plane of the fetal chest is actually oblique and should be corrected by tilting/readjusting the probe. On the other hand, congenital anomalies (eg, diaphragmatic hernia) may give this appearance. Thus, before acquiring a STIC volume, the fetal liver or stomach should never be visible in the same plane as the 4-chamber view.

e. *Absence of a staircase spine*: Visualizing a fetal staircase spine indicates that a true transverse plane of the fetal chest has not been obtained. Let us assume that a normal fetus is lying completely supine (ie, 0°) in a longitudinal lie and vertex presentation, similar to a loaf of bread. If the transducer is positioned horizontally on the maternal abdomen, and the beam is exactly perpendicular (versus oblique) to the fetus, a single plane will depict the fetal spine location at 6 o'clock, with its 3 ossification centers. An analogy would be visualizing a single "slice" from the loaf of bread. During a volume acquisition sweep of this fetus, the 3 spinal ossification centers will be visible in each serial transverse plane and located at the same area or point on the screen (ie, 6 o'clock; Video 14). However, if the same probe has now been tilted forward or backward on the maternal abdomen so that the insonation beam is oblique (versus perpendicular) to the fetus, a staircase spine will be visualized on the screen.

Therefore, we have coined the term "staircase spine" (or "caterpillar spine") to refer to a fetus in which the transverse view on sonography shows spinal ossification centers "stacked" on each other like a staircase or caterpillar (Figure 9 and Videos 15 and 16). In addition, a coronal view of the curved ribs may also be seen. Therefore, the fetal

Figure 9. Staircase spine (downstairs type). In the A plane (transverse view) of the STIC volume, note that the ossification centers of the spine appear stacked on each other like a staircase or caterpillar, and a coronal view of the curved ribs can be seen because the ossification centers are being imaged obliquely. The staircase spine is confirmed in the B plane, which shows the fetus inclined vertically downward. During a STIC volume acquisition, the ossification centers will appear to be moving in a vertical direction on the monitor screen.



spine appears to look like a staircase, in that the ossification centers are imaged obliquely and appear to be moving in a vertical direction on the monitor screen, as the STIC volume is being acquired. There are 2 situations that can lead to visualization of a staircase spine: (1) the fetus itself is inclined vertically at an angle to the floor (eg, like a seesaw) with the top of the fetus tilted either downward or upward, but with the transducer beam perpendicular to the floor; or (2) the fetus is lying completely flat (ie, 0°), but the transducer beam insonates the fetus in an oblique or tilted manner. When a staircase spine is apparent on the monitor screen, STIC volume acquisitions should be avoided, unless there is only a mild degree of incline.

The staircase spine can also be further subdivided into either an "upstairs spine" or a "downstairs spine." With an upstairs spine (Figure 10 and Video 16), the fetus is tilted upward (feet raised higher than the head), and an exaggerated view of the ventricles will be evident in the apical 4-chamber view. Specifically, the ventricles will appear more prominent in size than usual, and their trabeculations may be seen. Additionally, the pulmonary valve and a portion of the liver may be noticeable when moving through serial transverse planes. To correct this situation (ie, obtain an appropriate apical 4-chamber view), one should move the transducer inferiorly on the maternal abdomen (towards the bladder) and tilt the transducer backwards (operator's wrist bending backwards).

With a downstairs spine (Figure 9 and Video 15), the fetus is tilted downward (head raised higher than the feet), and the left atria may appear foreshortened in the apical 4-chamber view. The Eustachian valve (or valve of the inferior vena cava) may be visible as well. To correct this situation (ie, obtain an appropriate apical 4-chamber view), one should move the transducer superiorly on the maternal abdomen (toward her head) and tilt the transducer forward (operator's wrist bending forward). One of the possible issues with a downstairs spine is that the longitudinal pulmonary artery with its valve may not be visualized in its entirety when moving through serial transverse planes. In our experience, downstairs spines occur more frequently than upstairs spines.

It is noteworthy that the characteristics described above for a fetal staircase spine and how to correct it pertain to fetuses in a vertex presentation. When a fetus is in a breech presentation, the adjustment in transducer movements and tilting to obtain an appropriate apical 4-chamber view will be the opposite of that described above. We have also observed that, generally, sonologists have more difficulty in obtaining an appropriate apical 4-chamber view when the fetus is in a breech presentation (versus vertex).

After an appropriate apical 4-chamber view has been obtained, the sonologist should next quickly tilt or rock the probe slightly to ensure that the transverse aortic arch is clearly visible in the upper fetal mediastinum (Figure 7 and Video 10) and then return back to the 4-chamber view. While keeping this view on the monitor screen, the STIC volume acquisition is begun by pressing a button on the console. A key point is that when this action occurs, the fetal anatomic plane on the monitor screen will become the acquisition plane of the STIC volume. Therefore, it is crucial that the sonologist precisely coordinate pressing of the button to start the volume acquisition with attaining the correct apical 4-chamber view on the screen. For example, if the 5-chamber view instead is depicted on the screen, the transducer should be readjusted to obtain the 4-chamber view before pressing the button for STIC acquisition.

8. *Maternal Breath Holding and Movement*—Maternal breathing or movements during the STIC acquisition may also lead to motion artifacts within the volume. Therefore, women should be asked to take a deep breath and hold it for the entire duration of the STIC acquisition. We have found that it is very helpful to verbally support and encourage patients throughout the breath hold. Patients should be informed when the sweep has been completed, so that breathing can resume immediately. As a useful gauge, sonographic monitor screens usually have a small trapezoid-shaped icon that fills in with color as the STIC volume acquisition is occurring. Thus, the sonologist can determine what proportion of the acquisition has been completed and

Figure 10. Staircase spine (upstairs type). With the fetus tilted upward (feet raised higher than the head), this position leads to an upstairs spine. In this image, the fetal head is located on the right side (not in view). The fetal bladder is visualized on the left side.

how much remains. If a television monitor is available that simultaneously depicts the images on the sonographic monitor screen, it is useful for patients to also observe the STIC acquisition, since it focuses their attention. Since maternal movements may lead to motion artifacts in the volume, women should be asked to momentarily suspend any body movements in addition to breathing.

Occasionally, patients are unable to perform a breath hold. In this situation, they should then be asked to minimize the intensity and frequency of abdominal movements that occur during breathing as much as possible. On the flip side, some women are so eager to cooperate that they inspire deeply enough to actually shift the fetal heart location on the screen. Specifically, the 4-chamber view will either shift outside the ROI box or move inferiorly off the monitor screen. To address this situation, minor adjustments should be made with the transducer or to the image depth, ROI box, etc, so that the 4-chamber view is again visible on the screen, and the ROI box encompasses the entire fetal chest circumference. An alternative is to repeat another maternal breath hold but with more shallow breaths to diminish the maternal abdominal excursion.

9. *Operator movement*—During the STIC volume acquisition, it is also important for sonologists to remain motionless (not move their hand on the transducer) while maintaining the transducer fixed and in good contact with the maternal abdomen.

10. *When to Discard STIC Volumes and When Not to Obtain Them*—In general, it is important to practice efficiency[1] during the sonographic examination to be successful in STIC volume acquisition, especially because the sonologist may have only a single and limited window of opportunity to capture volumes. Efficiency, however, implies more than just procedurally performing the acquisition process. This concept also refers to an immediate awareness of when a volume will be uninformative and needs to be discarded. Such evaluation can occur: (1) after STIC volumes are displayed in the multiplanar view or through STICLoop (see later); or (2) during the actual acquisition process itself. For example, if there is obvious fetal movement and/or breathing during the acquisition, such a process can be terminated immediately (Video 17). If the fetus was initially motionless during the volume capture, but (1) suddenly changes position or moves; (2) the fetal heart shifts outside the ROI box; (3) an extremity moves into the field of view (leading to acoustic shadowing of the cardiac structures); or (4) the acquisition angle is insufficient, the STIC acquisition should be ended immediately or the volume discarded. Therefore, the goal is to capture and save as many volumes as possible in rapid succession when the environment is appropriate while discarding those that are obviously inappropriate. Even so, it may not always be clearly evident which STIC volume(s) will turn out later to be good. In such cases, it is prudent to be cautious by capturing and saving volumes anyway, since they can always be discarded later, if necessary. Moreover, protocols that include the acquisition of more than a single volume increase the chances that relevant information can be obtained.[108] If the initial STIC volumes are unsatisfactory or inappropriate, additional volumes should be obtained when possible.

If the sonologist has already captured appropriate and informative STIC volumes, this becomes advantageous when an optimal fetal position suddenly changes during the course of a sonographic examination. Thus, one clinical approach is to acquire several STIC volumes while the fetal position is optimal and then continue with 2D sonography. If the latter does not allow one to successfully obtain cardiac views, the STIC volume data sets are still available for analysis.[87]

Besides fetal motion or breathing leading to artifacts within the STIC volume, they can also occur with changes in the fetal heart rate.[109] Moreover, in the presence of an abnormal fetal heart rate (eg, tachycardia or bradycardia), sudden changes in the fetal heart rate, or cardiac rhythm disturbances/arrhythmias, a STIC volume acquisition may not be feasible. This is because when there are severe changes in the fetal heart rate during the STIC capture, the algorithm has difficulties in calculating the average heart rate correctly, which can lead to artifacts secondary to rearrangement of noncorresponding images.[3] In other words, there is significant misregistration of the information required for precise reconstruction of moving cardiac structures.[4]

Evaluation of STIC Volumes to Determine Their Appropriateness for Analysis

Immediately after a STIC volume acquisition, the volume may be displayed in the multiplanar view or automatically converted into a 2D cine loop (STICLoop).[87] These methods of STIC volume display are useful to promptly determine whether the volume is appropriate for further analysis (eg, to obtain fetal cardiac views). This process is an important and necessary next step because STIC volumes must also be informative.[98] In this article, we will not describe the initial adjustment of STIC volume data sets for standardization purposes, which is done before navigation is performed. Such adjustment has been suggested to simplify the STIC orientation and enable reproducible planes for analysis; the interested reader is referred elsewhere for this information.[94,110]

Various factors influence the success of a protocol for STIC volume acquisition, including whether there is a standardized acquisition technique along with feedback regarding technical errors.[108] Indeed, some have recommended that before introducing STIC technology into the screening setting, one requirement is that sonologists must be able to acquire clinically valid (ie, acceptable diagnostic quality) volume data sets daily, while also learning how to immediately assess volume quality to discard those inappropriate for diagnostic use.[57] It is clear that for STIC volumes to be informative (ie, ability to display fetal cardiac planes and structures), they should be of high quality.[88,97,98] Thus, methods to determine whether such volumes are appropriate for further analysis are essential.

When STIC volumes are assessed at the patient's bedside (via either the multiplanar display or STICLoop), there are 2 methods of practice: (1) One method is to assess each volume sequentially and then decide whether saving that volume is appropriate. Although this process takes seconds to perform, a disadvantage is that an optimal window of opportunity to collect more volumes may be lost (eg, fetus changes position or begins breathing movements). On the other hand, an advantage of this approach is that appropriate STIC volume(s) may be found, such that it may not be necessary to continue capturing more volumes. (2) The other method is to take advantage of the optimal window of opportunity by capturing and saving as many STIC volumes as possible in rapid succession but without assessing them until the session is finished. The main advantage of this method is that a larger number of volumes may be collected for analysis. However, the disadvantage is that both appropriate and inappropriate STIC volumes will have been saved, and the operator will be assessing this entire group of volumes at the bedside. It is worth noting, however, that both methods (ie, multiplanar display and STICLoop) to evaluate STIC volume data sets can be performed rather quickly and are detailed below. The choice of which method to implement should be based on user preference and the clinical environment. In general, we prefer the second method of capturing and saving as many STIC volumes as possible, with evaluation after the session is completed.

STIC volumes may also be evaluated offline (using the multiplanar display or STICLoop) to determine whether the data sets are appropriate. This process is accomplished through software on desktop or laptop computers, which duplicates the online environment. We will now review the 2 methods of STIC volume display, as well as how to evaluate STIC volumes to determine their appropriateness for analysis.

1. *What Is the Multiplanar Display?*—The dynamic image sequence of a STIC volume data set can be displayed in various formats: (1) multiplanar view; (2) single-plane view; and (3) rendered image. When a volume is displayed in 3 orthogonal planes (representing the transverse, sagittal, and coronal planes of a reference 2D plane within this volume), it is known as the "multiplanar display" or "multiplanar view" (Figure 1 and Video 1). Through STIC technology, dynamic images of the fetal heart in motion can be visualized simultaneously in all 3 orthogonal planes.

a. *Characteristics of 3 planes*: The starting reference plane from which the STIC volume is acquired is referred to as the A plane and is located in the upper left corner (Figure 1 and Video 1). The plane orthogonal to the A plane, but parallel to the ultrasound beam, is termed the B plane (upper right corner). The plane perpendicular to both the A plane and the ultrasound beam is termed the C plane (lower left corner) and is commonly referred to as the coronal plane. Both the B and C planes are perpendicular planes corresponding to the location of the reference dot within the STIC volume.[1]

The multiplanar display of a STIC volume data set provides information on the ROI, as well as the acquisition angle of the volume. Specifically, the A plane displays the size of the ROI box (selected height and width) of the volume, while the B plane demonstrates the acquisition angle of the volume (Figure 1 and Video 1).

It should be noted that when a STIC volume has been acquired from a fetus in a vertex presentation, the heart will be displayed with its left side in the left part of the A plane. At the same time, the fetal head will be on the left side of the screen in the B plane. For a breech presentation, however, the opposite is the case. The left ventricle will appear in the right part of the A plane, while the fetal head will be on the right side of the screen in the B plane.

b. *Image resolution in the planes*: The A-plane image consists of pixels that have the properties of axial and lateral resolution.[92] Accordingly, this plane has the highest resolution, has the best image quality, and is equivalent to a 2D image displayed during sonographic examination. The B and C planes also have axial and lateral resolution. Yet, the resolution in these planes is a function of the transducer beam, as well as the size of the "voxel" (or volume of pixels) that is created from the original STIC volume data set. Both B and C planes have been reconstructed by the system. Therefore, these images are characterized by lower resolution than that of the A plane.[92] The coronal reconstructed plane generally has the lowest resolution of all 3 planes in the multiplanar display. Since the quality of a STIC volume data set can be estimated by directly analyzing the B plane, this step is included when evaluating volumes to determine their appropriateness for further analysis.

c. *Rendered image*: The panel in the right lower corner of the multiplanar display of the STIC volume data set demonstrates the rendered image, which can provide additional information not available from thin 2D image slices.[3] Volume rendering describes the display of either external or internal surfaces of organs with data derived from multiple 2D sections.[86] STIC volumes can be rendered in various display modes (eg, surface rendering,[4,111] minimum mode,[13,15] glass body,[15,53] and inversion[52,54]). Such rendering techniques can be used to visualize any fetal cardiac structure (and provide a depth perspective to structures), as well as optimize the contrast of myocardial borders, septa, and valves.[4,111,112] Realistic 4D images of the structure(s) of interest may also be obtained.[15]

2. *How to Evaluate STIC Volumes to Determine Their Appropriateness for Analysis Using the Multiplanar Display*—Immediately after the STIC acquisition has been completed, the estimated fetal heart rate will appear on the sonographic monitor screen, and the operator should decide whether to cancel/discard or accept/save the volume. In general, the fetal heart rate should be within normal limits to accept the volume. Next, the ultrasound machine can be programmed such that the multiplanar display will appear on the monitor screen. The following steps are recommended:

a. *Reduce cine loop speed to 50%*: The operator can adjust the speed of the STIC cine loop according to his or her preference. We recommend reducing the speed down to 50% because when the cine speed is 100% or higher, detection of true motion artifacts within the STIC volume may become more difficult to discern. Moreover, inherent cardiac motion will appear more pronounced. As a result, one may misinterpret a motion artifact to be present, when the "motion" is actually due to the dynamic image sequence.

b. *Adequate image quality*: The planes of the multiplanar display should demonstrate images of adequate quality (eg, clear visualization of the fetal heart and image neither too bright nor dark). If the image quality is suboptimal, the STIC volume will most likely be uninformative.

c. *Region of interest in A plane*: The A plane displays the size of the ROI box (selected height and width) of the STIC volume, and should be evaluated to ensure that the size is adequate and encompasses the entire fetal chest circumference (Figure 1 and Video 1).

d. *Acquisition angle in B plane*: When an apical 4-chamber view is the acquisition plane, the B plane will depict a sagittal view of the fetal heart (eg, ductal arch; Figure 1 and Video 1). To determine whether the acquisition angle was wide enough, the fetal heart and upper abdomen should be visualized in the B plane (this task can also be accomplished by scrolling through serial parallel frames in the A plane). In theory, for a 4-chamber view acquisition plane, if the operator observed the upper fetal mediastinum and stomach on the monitor screen while the STIC volume sweep was occurring (Video 2), the acquisition angle should be adequate. If the volume demonstrates an acquisition angle that is too narrow, it should be discarded.

e. *Reference dot in cross section of descending aorta in A plane*: The reference dot imaging tool is used to localize the same anatomic structure in all 3 orthogonal planes.[1] As the reference dot is moved around, the corresponding planes will change respectively.[3] The dot should be placed in the cross section of the descending aorta in the A plane, so that the longitudinal descending aorta becomes visible in both the B and C planes (Figure 1 and Video 1). Next, the sagittal view of the fetal heart (B plane) should be evaluated for the presence of: (1) wavy lasagna wall; (2) water dive; (3) piano keys; and (4) staircase spine. The first 3 signs indicate the presence of motion artifact(s) within the STIC volume data set.

f. *Minimal or no motion artifacts observed in B plane*: Any type of motion artifacts or errors in STIC assembly can modify fetal anatomic structure representation[87] and, therefore, are relevant issues when performing 4D sonography with STIC. Indeed, artifacts during STIC acquisition will produce artifacts in the reconstructed planes, with erroneous information contained in the multiplanar display.[26] Specifically, motion artifacts secondary to fetal breathing or gross body movements may be observed in the B plane (sagittal plane) of the multiplanar view. Although much of the fetal anatomy may be affected (Video 8), it is helpful to focus on the wall of the longitudinal descending aorta to evaluate volume quality. In the absence of motion artifact, the wall should appear straight (Figure 11). However, when motion artifact(s) are present, they can affect the characteristics of the longitudinal descending aorta wall in several ways; we have categorized this into 3 types: (1) wavy lasagna wall; (2) water dive; and (3) piano keys. Fetal breathing or gross body movements will also affect the image in the C plane.

Lasagna pasta is a long and broad noodle, which is ideally suited to layering in a baking dish. Although such noodles have a flat shape in Italy, American lasagna noodles tend to be ruffled or wavy along the edges. Similarly, in the presence of regular breathing motion (fetal or maternal), the fetal longitudinal descending aorta wall often appears undulated or wavy at regular intervals. Therefore, we refer to this type of artifact as a "wavy lasagna wall" (Figure 11 and Videos 18 and 19). On the other hand, when there are discrete area(s) of motion artifact seen in the sagittal plane of the multiplanar view, we term this a "water dive" (Video 20). This term refers to the discrete underwater turbulence/motion that develops only in the specific location where a diver enters the water. A water dive artifact usually occurs when there is isolated breathing or gross body movements during the STIC acquisition. Depending on the area(s) of interest, this type of motion artifact may not be an issue. For example, if one is interested in assessing the 3-vessel and trachea view, a water dive motion artifact in the fetal upper abdomen will not pose a problem. The third type of motion artifact occurs in the presence of fetal hiccups. The sagittal plane of the multiplanar view has a very distinctive appearance, similar to that of a pianist sharply pressing and releasing multiple piano keys at fixed intervals apart on the keyboard (ie, corresponding to the regular and episodic nature of hiccups). Therefore, we refer to this appearance as "piano keys" (Video 21). Such a regular pattern may be visualized in an isolated portion of the B-plane image (ie, regular fetal hiccups occurring at a single time point during the volume acquisition), or the pattern may be seen throughout the B-plane image (ie, regular fetal hiccups during the entire volume acquisition, which is more common).

In contrast to most fetal breathing movements, which are regular in nature, gross body movements typically occur at sporadic time points. Yet, because the intensity of body movements tends to be greater than that of fetal breathing movements, the B-plane image is usually noninterpretable in such cases. Although any type of excessive fetal movement will make interpretation of the B-plane image difficult, minimal movement(s) may still preserve the anatomic relationships which are required for diagnosis (Video 9).[3]

Can motion artifacts be identified in the A-plane image of the multiplanar display? In our experience, when there is motion artifact(s) present within the STIC volume data set, it is much easier to identify this in the B plane rather than the A plane. Fetal breathing or movement will not alter the A-plane image unless it is excessive[3] because the A plane contains the original, acquired B-mode images used to construct the B- and C-plane images. Therefore, although fetal breathing will alter the images in the B and C planes, the A-plane image will still be interpretable if the sonologist: (1) evaluates the heart using only this image; and (2) moves through the STIC volume from the beginning to end of the acquisition without rotating the image.[3]

In the presence of excessive fetal breathing or movement, however, the A-plane image may appear to "jump" out of place, or one may observe what we term a "double-vision"

Figure 11. Example of motion artifacts in the wall of the longitudinal descending aorta in a STIC volume data set. The left image shows a straight wall, consistent with absence of fetal breathing during the STIC acquisition. However, the right image shows a wavy lasagna wall, indicating regular fetal breathing during the STIC acquisition. Thus, this volume is not appropriate and should be discarded.

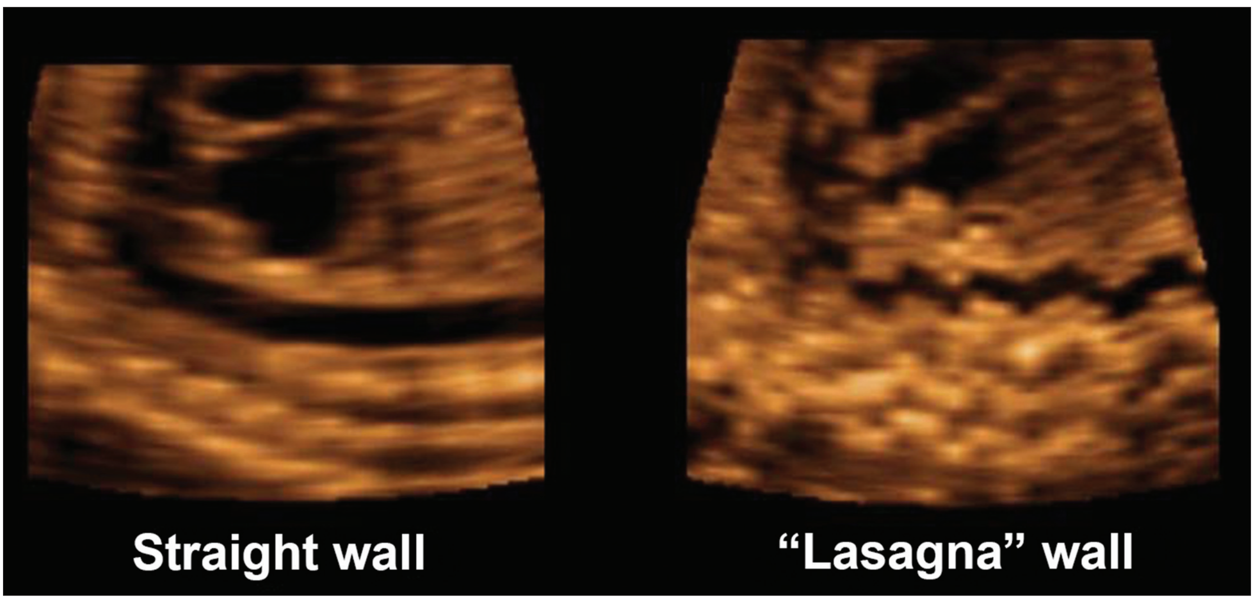


image or "ghost" image in a specific frame(s). A double-vision image (Video 22) occurs when a single object looks like 2 images simultaneously or when 2 images of the same object overlap.[113] In contrast, a ghost image (Video 23) occurs when 2 images are only very slightly separated and not 2 distinct images.[113] In the A plane, the presence of a ghost image, double-vision image, or image jumping out of place will render the STIC volume unacceptable and uninformative.

g. *Staircase spine*: It is optimal to acquire STIC volumes such that the fetal spine appears horizontal (ie, 0°) on the monitor screen, rather than inclined [upstairs spine with the feet raised higher than the head (Figure 10 and Video 16) or downstairs spine with the head raised higher than the feet (Figure 9 and Video 15)]. When the acquisition plane is the 4-chamber view, the orientation of the fetal spine can be evaluated easily in the B plane of the multiplanar display (Figure 9 and Video 15). If there is a mild staircase spine, the STIC volume may still be acceptable. However, a STIC volume with a steep staircase spine should be discarded for the reasons discussed previously. The A plane (transverse plane) in the multiplanar display can also depict a staircase or caterpillar spine. This appearance is recognized when the spinal ossification centers appear stacked on each other like a staircase or caterpillar. Additionally, a coronal view of the curved ribs may also be seen (see "Absence of a staircase spine" above for further explanation; Figure 9 and Videos 15 and 16).

h. *Upper mediastinum and stomach*: Next, the sonologist should scroll through the A plane of the multiplanar display so that one is moving through serial transverse planes from front to back and vice versa. For this action, the location of the reference dot is irrelevant, since a parallel shift movement through transverse planes is occurring. While scrolling through the A plane, both the fetal upper mediastinum (including the transverse aortic arch) and stomach should be included and clearly visible.

i. *Minimal or absent shadowing*: In general, shadowing artifacts should not be observed in either the A or B planes of the multiplanar display. Although it may seem that acoustic shadowing or dropout is not present in the 2D image plane (which is a single slice) during real-time scanning, it may actually be present within the STIC volume because the volume data set comprises thousands of 2D images acquired through the area of interest during the sweep. Therefore, acoustic shadowing or dropout can occur in any of these 2D frames. This issue should be apparent to the sonologist by careful observation during the actual STIC volume sweep. Yet, if acoustic shadowing or dropout has been included within the volume data set, its location influences whether such a volume will be informative. For example, if shadowing or dropout occurs in the fetal abdominal area, it may not be as crucial if it occurs in the upper mediastinum.

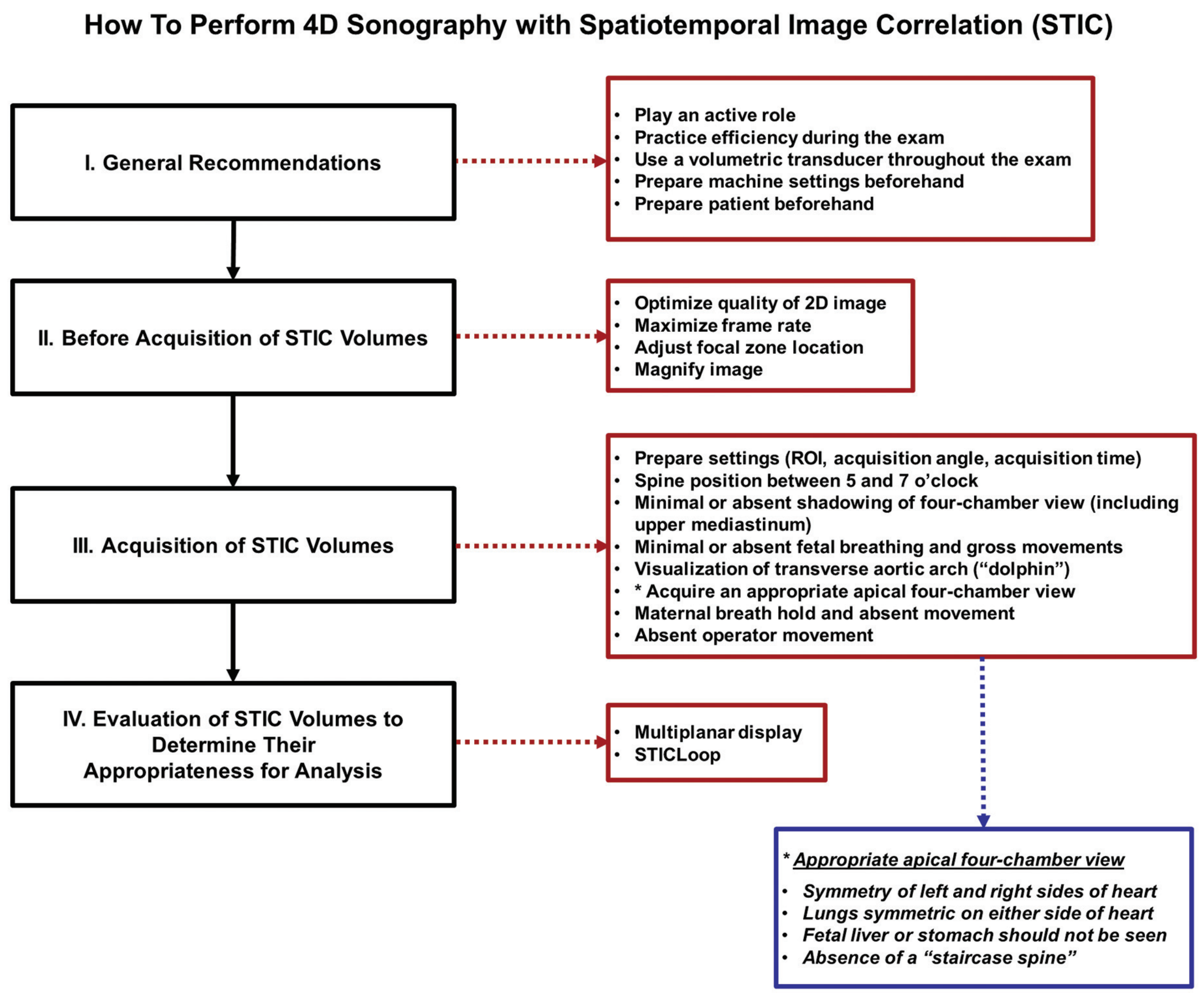
3. *What Is STICLoop?*—This is a 2D cine loop tool developed to aid the user in determining the appropriateness of STIC volume data sets before applying the Fetal Intelligent Navigation Echocardiography (FINE) method to such volumes.[87] Once a STIC volume has been obtained, it is automatically converted into a 2D cine loop that scrolls in a continuous fashion (Video 24).[87] With STICLoop, the image on the screen begins with the initial frame that was obtained by the transducer, and automatic scrolling through all the frames occurs until the last frame acquired in the sweep is reached. Thus, when the acquisition plane is the apical 4-chamber view, serial fetal transverse planes will be depicted in the STICLoop (Video 24). This tool was developed to facilitate detection of: (1) discontinuity or undulating movements that could modify anatomic structure representation and are due to motion artifacts or errors in STIC assembly (Video 25); (2) azimuthal issues (tilted acquisitions); and (3) "drifting spines," in which the spine location migrates on the screen during the automatic STICLoop scroll (Video 26).[87]

How does STICLoop compare to manual navigation through the multiplanar display when evaluating for motion artifacts? With manual navigation, motion artifacts may be hidden or underestimated in the A plane due to speed variability generated when the user operates the mouse.[87] For example, if a fetus has moved quickly during the STIC volume acquisition, a few frames could be displaced from the rest. Yet, we have found that this may not be as noticeable when manually navigating through the A plane and is more likely to be detected by using STICLoop.[87] Observation of the 2D cine loop allows improved detection of issues (eg, undulating movements) compared to the multiplanar display because it is operator independent and runs automatically at a constant speed.[87] Moreover, as previously discussed, fetal breathing or movements will not alter the A-plane image in the multiplanar display unless it is excessive.[3]

4. *How to Evaluate STIC Volumes to Determine Their Appropriateness for Analysis Using STICLoop*—To determine whether STIC volumes are appropriate before applying the Fetal Intelligent Navigation Echocardiography method,[87] the operator should observe that the following criteria are met using STICLoop (Video 24)[87]: (1) fetal spine located between the 5- and 7-o'clock positions (reducing the possibility of shadowing from the ribs or

spine; Figure 2); (2) minimal or absent shadowing (including the 3-vessel and trachea view), which could obscure visualization of cardiac anatomy; (3) adequate image quality; (4) upper mediastinum and stomach included within the volume and clearly visible; (5) minimal or no motion artifacts observed in the STICLoop (ie, smooth sweep without evidence of abrupt jumps or discontinuous movements; Video 25); (6) chest circumference contained within the ROI; (7) sequential axial planes parallel to each other, similar to a sliced loaf of bread (ie, no drifting spine from the 4-chamber view down to the stomach; Video 26); (8) no azimuthal issues observed (ie, atria/ventricles do not appear foreshortened in the 4-chamber view); and (9) minimal or no motion artifacts observed in the sagittal plane. Similarly to evaluation of the B plane (sagittal plane) in the multiplanar display, the sonologist should also evaluate for motion artifact(s) in the sagittal plane of STICLoop [eg, presence/absence of a wavy lasagna wall (Figure 11 and Videos 18 and 19), water dive (Video 20), and piano keys (Video 21)]. In the absence of motion artifacts, the wall of the longitudinal descending aorta should appear straight (Figure 11). It should be noted that the sagittal plane image of STICLoop was designed only to evaluate for motion artifact(s) and not to evaluate cardiac anatomy itself.

Figure 12. Overall practical and stepwise approach to performing 4D sonography with STIC. See text for further details.



In summary, herein we have: (1) described a practical and stepwise approach to performing 4D sonography with STIC (Figure 12); and (2) reviewed the evaluation of STIC volumes to determine their appropriateness for analysis, through use of the multiplanar display or STICLoop (Figure 13). For the readers' convenience, Table 1 lists terms and definitions that are related to 4D sonography with STIC, and Table 2 summarizes important points and tips to remember when performing 4D sonography with STIC.

Conclusions

STIC technology has been a major technological advance in the field of obstetric sonography. Since volumetric sonography of the fetal heart allows the review of all cardiac planes at any time during the cardiac cycle, it could be helpful in cardiac screening and has the potential to increase the detection rate of CHD. Indeed, a large body of evidence suggests that 4D sonography with STIC facilitates examination of the fetal heart and also has the potential to reduce the operator dependency that is associated with conventional 2D sonography. Compared to the latter, 4D sonography with STIC is also characterized by unique features and advantages.

It is our hope that by having reviewed here a pragmatic and stepwise approach to performing STIC, sonologists will find such information useful in clinical practice and, as a result, more widely embrace STIC technology as a valuable tool in the armamentarium of fetal cardiac evaluation.

Figure 13. Two methods to evaluate STIC volumes and determine their appropriateness for analysis (using multiplanar display and STICLoop). See text for further details.

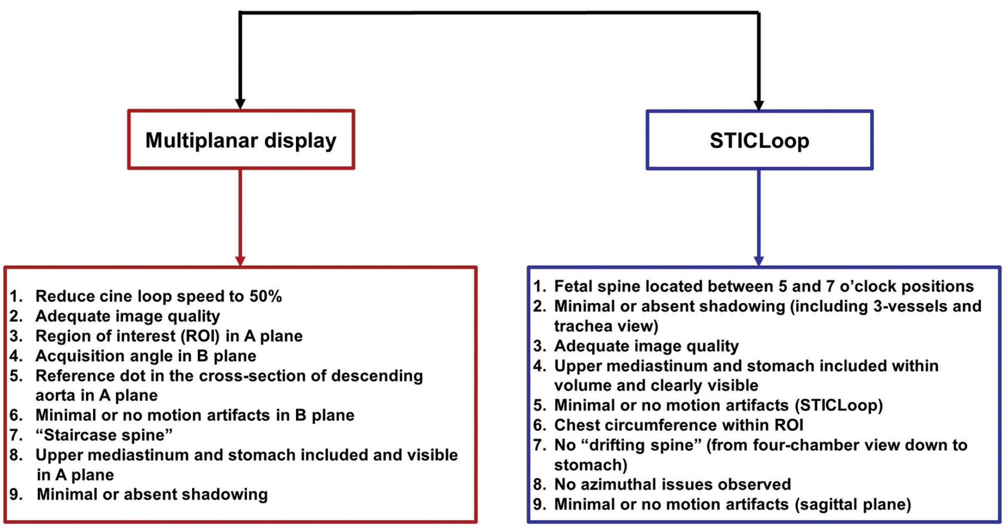


Table 1. Terms and Definitions Related to 4D Sonography With STIC

Term	Definition
Acoustic dropout	Signal loss in the sound path without intervening structures
Acoustic shadowing	Signal loss in the sound path secondary to echogenic structures
Acquisition angle, °	Determines the acquisition depth (amount of information acquired in the z-plane)
Acquisition plane	Starting 2D plane for the volume acquisition Known as the A plane in the multiplanar display
Acquisition time, s	Equivalent to the duration of volume acquisition Determines the speed at which the transducer sweeps the ROI An inverse relationship exists between the acquisition time and sweep speed of transducer
Dolphin	Refers to the fetal transverse aortic arch (appears like a dolphin on sonography)
Double-vision image	Observed in the A plane (multiplanar display) in the presence of excessive fetal breathing or movement When a single object looks like 2 images simultaneously or when 2 images of the same object overlap
Drifting spine	Fetal spine location migrates on the monitor screen during the automatic STICLoop scroll When sequential axial planes are parallel to each other (similar to a sliced loaf of bread), there is no drifting spine
Driving the transducer	Sonographic technique to convert the fetal spine to a posterior position on the monitor screen
Four-dimensional	Volume data sets that incorporate information about the 3 spatial dimensions plus the temporal dimension
Ghost image	Observed in the A plane (multiplanar display) in the presence of excessive fetal breathing or movement When 2 images are only very slightly separated and not 2 distinct images
Multiplanar display or view	Display format of sonographic volumes (eg, STIC) in which there are 3 orthogonal planes (transverse, sagittal, coronal) Allows correlation between image planes that are perpendicular to the main acquisition plane Can be used to determine whether a STIC volume is appropriate for further analysis
A plane	Acquisition plane Displays the size of the ROI box (selected height and width) of volume Located in the upper left corner of the multiplanar display
B plane	Plane orthogonal to the A plane but parallel to the ultrasound beam Demonstrates the acquisition angle of the volume Located in the upper right corner of the multiplanar display
C plane	Plane perpendicular to both the A plane and ultrasound beam Commonly referred to as the coronal plane Located in the lower left corner of the multiplanar display
Piano keys artifact	Characterized by a distinctive appearance in the B plane of the multiplanar display Similar to a pianist sharply pressing and releasing multiple piano keys at fixed intervals apart on the keyboard Occurs in the presence of fetal hiccups
Reference point or dot	Intersection of 3 planes in the multiplanar display Tool can be used to manually navigate through the STIC volume and localize the same anatomic structure in all 3 orthogonal planes
Region of interest (ROI)	Box determines the height (y-plane) and width (x-plane) of the volume data set
Rendered image or display	Contains depth in the z-plane and provides additional information not available from thin 2D image slices Volumes can be rendered in various display modes (eg, surface rendering, inversion) Located in the lower right corner of the multiplanar display
Spatiotemporal image correlation technology	Allows acquisition of a fetal cardiac volume data set and displays a cine loop of a complete single cardiac cycle in motion
Staircase (or caterpillar) spine	Fetus in whom the transverse view of the fetal spine on sonography shows ossification centers stacked on each other like a staircase or caterpillar; coronal view of curved ribs may also be seen Ossification centers are imaged obliquely and appear to move vertically on the monitor screen as the volume is being acquired
Upstairs spine	Fetus is tilted upward (feet raised higher than the head) Exaggerated view of ventricles will be evident in the apical 4-chamber view
Downstairs spine	Fetus is tilted downward (head raised higher than the feet) Left atria may appear foreshortened in the apical 4-chamber view, and Eustachian valve may be visible
STICLoop	2D cine loop to aid the user in determining the appropriateness of STIC volume data sets before applying the FINE method to such volumes Facilitates detection of: (1) discontinuity or undulating movements that could modify anatomic structure representation and are due to motion artifacts or errors in STIC assembly; (2) azimuthal issues (tilted acquisitions); and (3) drifting spines Operator independent and runs automatically at a constant speed
Voxel	Volume of pixels
Water dive artifact	Discrete area(s) of a motion artifact seen in the B plane of the multiplanar display Occurs when there is isolated breathing or gross body movements during volume acquisition
Wavy lasagna wall artifact	Wall of the fetal longitudinal descending aorta (B plane of the multiplanar display) appears undulated or wavy at regular intervals Occurs in the presence of regular breathing motion (fetal or maternal)

FINE indicates Fetal Intelligent Navigation Echocardiography.

Table 2. Performing 4D Sonography With STIC: Important Points and Tips

Many factors that affect the acquisition and quality of STIC volume data sets also pertain to 2D sonography
Success rates of volume acquisition in fetuses with normal hearts range widely (26%–100%) and depend on many factors (eg, operator skill), preset criteria/requirements for acquisition, and the purpose of the study
4 essential steps in performing 4D sonography with STIC include volume acquisition, display, manipulation/postprocessing, and storage of volumes and images
When acquiring volumes and determining whether they are appropriate for further analysis, there are 3 main time points: before acquisition, acquisition, and immediately after acquisition
Volumes may be obtained in each trimester (recommend 19–30 gestational weeks for optimal assessment of fetal cardiac anatomy)
Ask the mother who is lying supine to turn (or roll) laterally onto her side in the same direction that you wish the fetal cardiac apex to turn
Constantly adapt to the fetal “situation” throughout the sonographic examination and take advantage of any proper moments to obtain volumes
If the fetal heart is in an optimal position and conditions are appropriate, immediately acquire multiple volumes in rapid succession
Image quality of volume data sets depends primarily on the original quality of the 2D image
A high frame rate can be achieved by decreasing depth, sector width, and the number of focal zones
Adjust the ROI box size to be as small as possible to maximize the frame rate during acquisition and improve the temporal resolution of the volume data set
Set the acquisition angle at least 5° greater than the gestational age; however, the angle should not be too wide either
The quality of a volume acquisition is reflected by the acquisition time, and volumes should be obtained using the longest possible time (higher image resolution); recommend an acquisition time of at least 10 s, with adjustment based on presence/absence of fetal breathing or movements
When the fetal spine location is between 5 and 7 o’clock, it reduces the possibility of acoustic shadowing from the ribs or spine
Use the technique of driving the transducer to convert the fetal spine to a posterior position on the monitor screen
Fetal breathing and gross body movements during the volume acquisition can lead to motion artifact(s) within the volume data set, with distortion of images and anatomic structures
In most cases, the acquisition plane will be the 4-chamber view
A correct (or appropriate) 4-chamber view should be obtained (ie, true cross section of the thorax with proper alignment in the axial plane)
Sonologists tend to foreshorten the left (vs right) side of the heart when imaging the apical 4-chamber view
Visualizing a fetal staircase spine indicates that a true transverse plane of the fetal chest has not been obtained and therefore should be avoided
In general, sonologists have more difficulty in obtaining an appropriate apical 4-chamber view when the fetus is in a breech presentation (vs vertex)
At the time a volume acquisition begins by pressing a button, the fetal anatomic plane on the monitor screen at that moment will become the acquisition plane
It is very helpful to verbally support and encourage patients throughout the breath hold that occurs during the acquisition
During the actual volume sweep, observe the sequential images within the ROI box on the monitor screen to evaluate for satisfactory or unsatisfactory (eg, fetal movement) conditions
Practicing efficiency during the sonographic examination is immediate awareness of when a volume will be uninformative and needs to be discarded (eg, fetal heart shifts outside the ROI box during the acquisition)
In the presence of an abnormal fetal heart rate (eg, tachycardia, bradycardia), sudden changes in the fetal heart rate, or cardiac rhythm disturbances/arrhythmias, volume acquisitions may not be feasible
2 methods of STIC volume display (multiplanar view and STICLoop) are useful to immediately determine whether the volume is appropriate for further analysis (eg, to obtain fetal cardiac views)
The multiplanar display of a volume data set provides information on the ROI box size (A plane) and the acquisition angle (B plane)
The A-plane image (multiplanar display) has the highest resolution, has the best image quality, and is equivalent to a 2D image displayed during the sonographic examination
Both B and C planes (multiplanar display) are reconstructed planes; therefore, these images are characterized by lower resolution than that of the A plane
The B plane of the multiplanar display may be evaluated for motion artifact(s), such as wavy lasagna wall, water dive, or piano keys
Fetal breathing or movement will not alter the A-plane image unless it is excessive; in this case, the A-plane image may appear to jump out of place, or one may observe a ghost image or double-vision image in a specific frame(s)
Although acoustic shadowing or dropout may seem absent in the 2D image plane during real-time scanning, it may actually be present within the volume
STICLoop is a 2D cine loop tool that aids the user in determining the appropriateness of STIC volume data sets before applying the FINE method to such volumes
STICLoop allows improved detection of issues (eg, undulating movements) vs manual navigation through the A plane

FINE indicates Fetal Intelligent Navigation Echocardiography.

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