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

Part 1

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Four-dimensional sonography with spatiotemporal image correlation (STIC) technology allows acquisition of a fetal cardiac volume data set and displays a cine loop of a complete single cardiac cycle in motion. Part 1 of this 2-part article reviews STIC technology and its features, the importance of operator training/experience, and acquisition of high-quality STIC volumes, as well as factors that affect STIC volume acquisition rates. We also propose a detailed and practical stepwise approach to performing 4-dimensional sonography with STIC and begin herein by providing general recommendations. Part 2 will discuss specifics of the approach, along with how to determine whether such volumes are appropriate for analysis.

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

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Dr Romero has contributed to this work as part of his official duties as an employee of the United States Federal Government. This article is a US Government work and is in the public domain in the United States. This research was supported in part by the Perinatology Research Branch, Division of Intramural Research, Eunice Kennedy Shriver *National Institute of Child Health and Human Development (NICHD), National Institutes of Health (NIH), Department of Health and Human Services; and in part with federal funds from the NICHD, NIH, under contract No. HHSN275201300006C.*

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Abbreviations

CHD, congenital heart disease; 4D, 4-dimensional; ROI, region of interest; STIC, spatiotemporal image correlation; 3D, 3-dimensional; 2D, 2-dimensional

doi:10.7863/ultra.16.01081

Congenital heart disease (CHD) is the most prevalent organ-specific birth defect[1] and the leading cause of infant morbidity and mortality from congenital malformations.[2] Prenatal diagnosis of some CHD types is associated with an improved preoperative condition,[3–7] presurgical mortality rate,[8] survival after surgery,[5,9–12] and long-term neurocognitive function and outcome.[13,14] Yet, despite its importance, sonographic evaluation of the fetal heart is one of the most difficult tasks in prenatal diagnosis.

The detection of CHD is challenging,[15,16] and the sensitivity of sonography remains low (22.5%–52.8%),[17–21] even when more than 90% of women in population-based studies undergo sonographic examination. This situation has been attributed to the complexity of fetal heart anatomy, cardiac motion, and size. Other factors that affect the prenatal detection of CHD include[22,23] gestational age at examination, fetal position, maternal obesity, fetal motion, and abnormal amniotic fluid volume. By far, however, the most important factor is operator skill and expertise.[24–30] Mental reconstruction of a sequence of individual cross-sectional images is required to perform a thorough cardiac examination.[31]

Since volumetric sonography of the fetal heart allows review of all cardiac planes at any time during the cardiac cycle, it could be helpful in cardiac screening.[31] Four-dimensional (4D) sonography with spatiotemporal image correlation (STIC) technology allows the acquisition of a fetal cardiac volume data set and displays a cine loop of a complete single cardiac cycle in motion. Since STIC was first described 13 years ago,[32–34] studies have demonstrated that volume acquisition can be incorporated into the daily practice of ultrasound centers.[35,36] Moreover, a large body of evidence suggests that 4D sonography with STIC facilitates examination of the fetal heart[33,34,37–62] and has the potential to reduce the operator dependency that is associated with conventional 2-dimensional (2D) sonography. Among centers with technical expertise, 4D sonography with STIC has been shown to be an accurate and reliable method for fetal echocardiography in the second trimester,[63] as well as between 14 and 41 weeks' gestation.[64] As a result, STIC technology has been used in the prenatal evaluation and diagnosis of CHD,[31,32,63–81] along with the assessment of fetal cardiac function by combining STIC with Doppler, M-mode, and other postprocessing methods.[48,53,82–88] Several algorithms based on STIC technology have also been developed[34,37,42,45,54,55,61] to aid users in systematically and efficiently interrogating volume data sets to display cardiac planes. Other investigators have reported novel automated and semiautomated algorithms using software applied to fetal cardiac volume data sets to successfully generate standard echocardiographic views.[89–92] This process is especially relevant, since there is a learning curve for the acquisition and analysis of STIC volume data sets.[52,93,94] Such automation technology has the potential to both standardize and simplify sonographic examinations of the fetal heart by decreasing operator dependency.

Although the clinical value and advantages of 4D sonography with STIC over conventional 2D sonography have been demonstrated, many centers have not embraced this modality[95] and use only 2D sonography for fetal cardiac examinations. STIC technology has been widely available on multiple ultrasound platforms in the clinical setting, but it is underused and its value underestimated.

What are the reasons for this? (1) The x, y, and z dimensions are not necessarily intuitive, and therefore, volumetric sonography is perceived to be challenging; (2) there exists the view that one should learn the basics of 2D sonography first, before advancing into other "dimensions"; (3) although 4D sonographic images look artful and impressive, some believe they are mainly for "show" and may not be applicable to one's clinical practice (ie, lack of clinical value); (4) the performance of volumetric sonography is thought to be time-consuming and thus not feasible in a busy clinical practice; (5) there is uncertainty in how to postprocess cardiac volume data sets; (6) not everyone embraces novelty; (7) an unexpressed fear of medical information "hidden" within the volume data set may exist, which could make one vulnerable to blame later; and (8) there is a paucity of training and educational courses on volumetric sonography (especially hands-on).

Although sonologists do not have to be specifically experienced in 3-dimensional (3D) or 4D sonography to acquire high-quality STIC volumes,[36] they should be adequately trained. If there is a lack of standardization in the acquisition of volume data sets, it would be a major limiting step for the effective performance of fetal cardiac examination using 4D sonography with STIC.

Therefore, in this 2-part article, our main objectives are to: (1) review STIC technology and its characteristic features; (2) discuss the importance of operator training/experience and acquisition of high-quality STIC volumes; (3) review factors that affect STIC volume acquisition rates; (4) propose a practical and stepwise approach to performing 4D sonography with STIC; and (5) review the evaluation of STIC volumes to determine their appropriateness for analysis. Part 1 focuses on the first 3 objectives, along with general recommendations on performing 4D sonography with STIC. Part 2[96] provides a detailed and specific approach on steps to be taken before and at STIC volume acquisition, as well as how to determine whether such volumes are appropriate for analysis. We propose that there is a need to demystify 4D sonography with STIC, so that it is no longer perceived as being too challenging to perform. In this way, the technology can be implemented more widely in fetal cardiac examinations.

STIC Technology

The term *4-dimensional* (or *4D*) describes volume data sets that incorporate information about the 3 spatial dimensions and the temporal dimension.[97] Four-dimensional STIC technology allows 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.[32–34,39] It is considered an indirect motion-gated offline scanning mode.[33,34,41,97,98] STIC technology is currently available on multiple ultrasound platforms and is integrated into the system's 3D/4D basic software option. Therefore, no additional software packages for online analysis are required.[33] Moreover, software packages are also available for offline analysis, which duplicate the online environment.

The principles used by the STIC algorithm to synchronize spatial and temporal information in fetal cardiac volume data sets are similar to that of the non-electrocardiographic motion Fourier analysis gating method proposed 20 years ago[99] and have been described in detail elsewhere.[32–34] Nelson et al[99] were able to gate (synchronize) the spatial and temporal information necessary to display 4D images of the beating fetal heart.

Once STIC has been activated, the array within the transducer begins an automatic single sweep over the predetermined volume, or region of interest (ROI).[33,100] The STIC volume display comprises thousands of 2D images acquired through the area of interest during this single automated sweep. The B-mode frame rate during the volume scan can be as high as 150 frames per second[33]; thus, a series of rapidly acquired B-mode images are stacked up behind each other. For example, a 10-second, 25° angle of acquisition would contain 1500 B-mode images.[33,98] Immediately after the STIC volume scan is completed, the system runs a spatial and temporal correlation of the data, detects the systolic peaks, and calculates the fetal heart rate.[32,43] Frames acquired during the same phase of the cardiac cycle (although from a different position in space) are merged into the same volume data set.[101] This process is repeated for all phases of the cardiac cycle. Thus, B-mode images are arranged in order according to their spatial and temporal domains (note the term *spatiotemporal image correlation*). After image rearrangement, an ordered sequence of volume data sets is displayed within seconds on the screen as a continuous cine loop containing all phases of the cardiac cycle, and the data are ready for analysis.[33,34] Although retrospective, gating is performed immediately after the volume scan while the patient is still on the table,[102] allowing its integration into clinical use. The STIC volume may be reviewed while the patient is still present; therefore, volume acquisitions may be repeated as necessary. Such volumes can then be saved to the ultrasound machine or to a network.

Although fetal cardiac volume acquisition can also be achieved by using a nongated static 3D approach, neither the heart rate nor motion is considered during acquisition and rendering. As a result, this technique cannot be used to assess events related to the cardiac cycle, as well as myocardial wall and valvular motion. Moreover, the 3D static sweep captures cardiac structures randomly within the cardiac cycle.[103] Thus, measurements of cardiac and outflow tract dimensions at the end of diastole or systole cannot be performed. In essence, the acquired static 3D volume contains an infinite number of 2D sonographic planes, but without regard to spatial or temporal motion. There are still, however, several beneficial features of static 3D volume acquisition of the fetal heart[52]: (1) rapid acquisition speeds (0.5–2 seconds); (2) the possibility of acquiring large volumes (ROI and acquisition angle), but with minimal artifacts; and (3) such volume data sets may be combined with color Doppler, power Doppler, or B-flow imaging.

Characteristic Features and Applications of 4D Sonography With STIC

Once the image data are analyzed according to their spatial and temporal domains, the dynamic image sequence can be displayed as a multiplanar reformatted view, single plane, and/or rendered image.[33] The following describes the characteristic features and applications of 4D sonography with STIC (Table 1). The interested reader is referred to other articles for further review.[33]

1. *Three Dimensions*—Operators can shift from a 3D mental image reconstruction (which occurs during conventional 2D sonographic examination) to a "true" 3D demonstration of anatomic structures.[104]
2. *Temporal Resolution*—The dynamic image sequence in the multiplanar or surface-rendered display demonstrates improved temporal resolution[33] and is attributed to the increased number of 2D images stored in the STIC volume data set. Thus, a fetal heart that is difficult to image using 2D sonography will become a superior image when viewed with STIC.[33]
3. *Operator Dependency*—When using 4D sonography with STIC, there is reduced dependency on operator experience and skills to image the fetal heart (which is characteristic of 2D sonography).
4. *Cardiac Volume Data Set*—An operator can navigate within the STIC volume, reslice, and produce all the standard image planes necessary for a diagnosis, either during the clinical examination or in the patient's absence.[37,42] Other unique characteristics of a cardiac volume data set include:
   a. *Unlimited number of images*: Anatomic structures can be evaluated in different planes of section other than the original acquisition plane.
   b. *Sequential planes*: Real-time 2D sonography allows the sonologist to focus only on a single plane at a time. However, using STIC technology, an operator can view or scroll through multiple cardiac planes in sequence (even within a specific view, such as the 4-chamber view), since there is a volume with 3D information behind each frame (Video 1). As a result, ventricular septal defects may be identified, for example, which otherwise could have been missed by interrogation of only a single plane of the 4-chamber view.
   c. *Rotation around a 360° axis*: Cardiac anatomic structures may be viewed from multiple perspectives.
   d. *Full independence and control in navigation*: During real-time 2D sonography, the operator is entirely

dependent on any fetal position changes (which affect cardiac views), movements, and the heart rate. All such factors also affect the duration of the sonographic examination. On the other hand, when navigating through a STIC volume data set, the operator has full independence and control over the fetal "position" (and, thus, cardiac views), the speed of the cine loop (which can be adjusted according to user preference), and the duration of the examination. Moreover, fetal movement is absent during navigation through volumes. Such advantages allow an improved assessment of CHD.[64]

5. *Offline Volume Review*—Since volume data sets may be reloaded and reviewed at any time, fetal cardiac examinations can be performed even in the patient's

Table 1. Characteristic Features and Applications of 4D Sonography With STIC

Advantages	Comments
1. Three dimensions	Operators can shift from a 3D mental image reconstruction to a "true" 3D demonstration of anatomic structures
2. Temporal resolution	Resolution is improved due to an increased number of 2D images stored in the STIC volume data set
3. Operator dependency	Reduced dependency on operator experience and skills to image the fetal heart (which is characteristic of 2D sonography)
4. Cardiac volume data set	Operator can navigate within the volume, reslice, and produce all the standard image planes necessary for a diagnosis
a. Unlimited number of images	Anatomic structures can be evaluated in different planes of section other than the original acquisition plane
b. Sequential planes	Can view or scroll through multiple cardiac planes in sequence (even within a specific view, such as the 4-chamber view)
c. Rotation around a 360° axis	Cardiac anatomic structures may be viewed from multiple perspectives
d. Full independence and control in navigation	Operator has full independence and control over the fetal "position" (and, thus, cardiac views), speed of the cine loop (which can be adjusted according to user preference), and duration of the examination
5. Offline volume review	Fetal cardiac examinations can be performed even in the patient's absence
6. Cine loop format	Allows specific phases of the cardiac cycle (end diastole, end systole) to be analyzed
7. Display formats	
a. Multiplanar	Allows correlation between image planes that are perpendicular to the main acquisition plane A reference dot tool can be used to manually navigate through the STIC volume data set and localize the same anatomic structure in the 3 orthogonal planes
b. Rendered	Allows reconstruction of a 3D rendered image of the fetal heart that contains depth in the z-plane and provides additional information not available from thin 2D image slices
8. Virtual planes	Images of the fetal heart not generally accessible or viewed by using a standard 2D sonographic approach may be obtained
9. Repeatability	Cardiac structures and measurements in normal fetal hearts have demonstrated high repeatability between (inter), and within (intra) observers
10. Combination with other applications	STIC technology can be combined with other applications by selecting the appropriate setting before volume acquisition (eg, color Doppler) or can be combined with postprocessing modalities (eg, inversion mode)
11. Congenital heart disease	Can improve the ability to identify complex intracardiac relationships May shorten examination time Accurate in diagnosing most major structural CHD Potential to increase the detection rate of CHD
12. Functional cardiac evaluation	Fetal cardiovascular parameters can be calculated (eg, stroke volume, cardiac output, ejection fraction, TAPSE, ventricular mass, fractional shortening)
13. Counseling	Results in improved understanding of CHD by the family Enhances prenatal counseling and interdisciplinary team consultation/management
14. Education and training	Useful in both medical education and professional training in fetal echocardiography
15. Telemedicine	Review of STIC volume data sets by other examiners or consultative experts can occur at remote sites May improve health care delivery systems by extending the benefits of prenatal cardiac screening

TAPSE indicates tricuspid annular plane systolic excursion.

absence. Moreover, offline review and interpretation of volumes have the potential to improve patient throughput and efficiency of clinical practice.[105]

6. *Cine Loop Format*—STIC technology "mimics" a real-time examination of the fetal heart due to its motion characteristics (Video 2). Moreover, the cine loop may be played in slow motion or stopped at any time for a detailed analysis of specific phases of the cardiac cycle. End-diastolic and end-systolic views can be identified by interrogating the STIC volume frame by frame. The speed of the cine loop may also be adjusted based upon user preference.
7. *Display Formats*
   a. *Multiplanar display*: This format (Figure 1 and Video 2) allows correlation between image planes that are perpendicular to the main acquisition plane (hence, the term *multiplanar*). Since motion information is preserved with STIC technology, multiple planes of the fetal heart in motion can be visualized and examined simultaneously.[50,106–108] Each of the scan planes can also be moved and rotated (eg, on the x-, y-, or z-axis) while maintaining synchronization with the cardiac cycle (Figure 2, A–C, and Videos 3–5). Moreover, in the multiplanar display, the 3 planes intersect at a point. By moving the position of such point (or "reference dot"), the examiner can manually navigate[109] through the STIC volume data set, and the corresponding planes will change respectively

Figure 1. In this STIC volume, the multiplanar display allows correlation between cardiac planes that are perpendicular to the main acquisition plane. The acquisition plane (apical 4-chamber view) is located in the upper left corner. Notice that the reference dot is located in the descending aorta in all 3 planes.

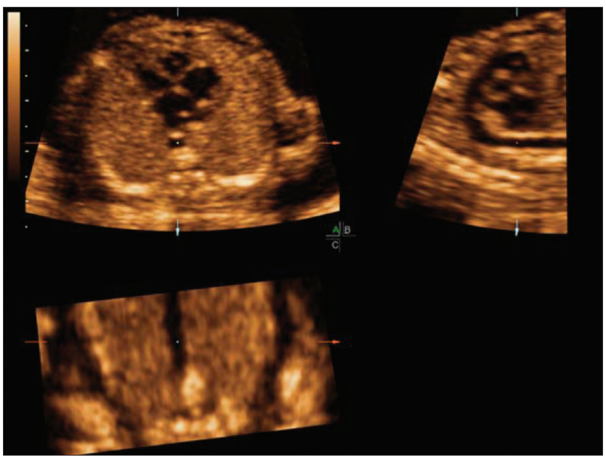
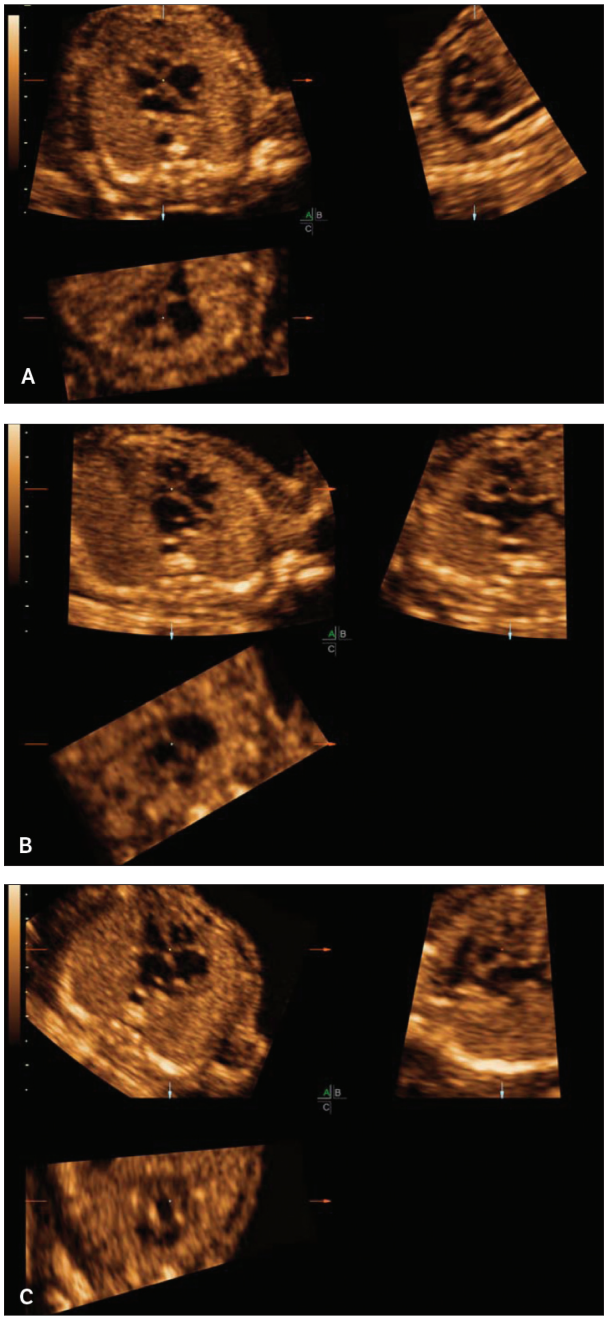


Figure 2. STIC volume of a normal fetal heart. **A**, The reference dot is located in the crux of the fetal heart, and the acquisition plane has been rotated on the x-axis. Notice that simultaneously, the B plane in the upper right corner (ductal arch in this case) is rotated upward. **B**, The reference dot is located in the crux of the fetal heart, and the acquisition plane has been rotated rightward on the y-axis. Notice that simultaneously, the B and C planes have also changed. **C**, The reference dot is located in the crux of the fetal heart, and the acquisition plane has been rotated on the z-axis (like a cartwheel). Notice that simultaneously, the B and C planes have also changed.



(Figure 3 and Video 6).[33] The reference dot can also be used to localize the same anatomic structure in the 3 orthogonal planes (eg, right ventricle; Figure 3 and Video 6). Clinical examples in which the multiplanar display has been shown to be useful include examination of the great vessels[34] and cardiac biometry,[110] once a specific cardiac structure (eg, ventricular septum) has been obtained in all 3 orthogonal planes.

b. *Rendered display:* STIC technology allows reconstruction of a 3D rendered image of the fetal heart that contains depth in the z-plane, providing additional information not available from thin 2D image slices (Figure 4 and Video 7).[33] For example, image depth can be altered by the user, so that with decreasing depth, a slice may be isolated. On the other hand, increased depth allows the posterior wall of the cardiac chambers to be viewed simultaneously with the atrioventricular valves.

8. *Nonconventional or Virtual Planes*—Navigation through a STIC volume allows images of the fetal heart that are not generally accessible or viewed by using a standard 2D sonographic approach (eg, ventricular and atrial septum en face and coronal atrioventricular valve plane[111,112]; Figures 5 and 6 and Videos 8 and 9).

Figure 3. In the multiplanar view, the reference dot can be used to localize the same anatomic structure (here, the right ventricle) in all 3 orthogonal planes.

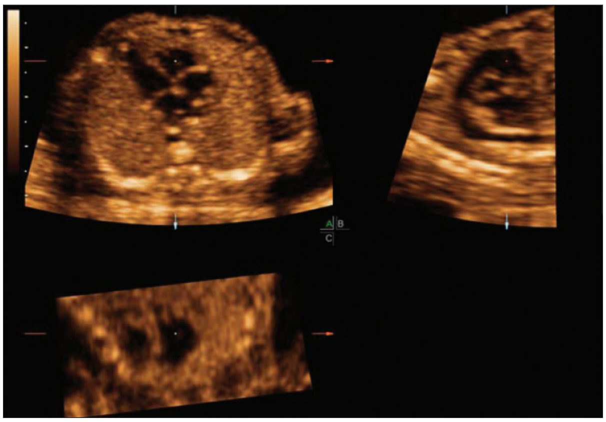


Figure 4. STIC technology allows reconstruction of a 3D rendered image of the fetal heart (here, the 5-chamber view; lower right image) that contains depth in the z-plane. Increased depth allows the posterior wall of the chambers to be viewed simultaneously with the atrioventricular valves.

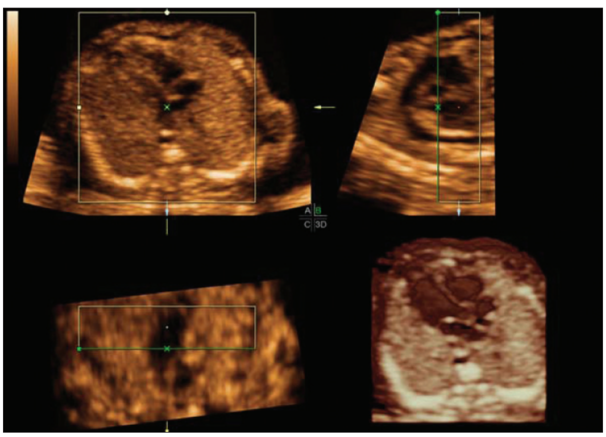


Figure 5. Ventricular septum en face. STIC technology allows visualization of "virtual" planes that are not generally accessible or viewed by using a standard 2D sonographic approach. In the apical 4-chamber view, the green render line is positioned to image the ventricular septum from the right ventricle. The rendered image (ventricular septum en face, triangular in shape) depicted by the white arrow appears realistic, due to the chosen render mode.

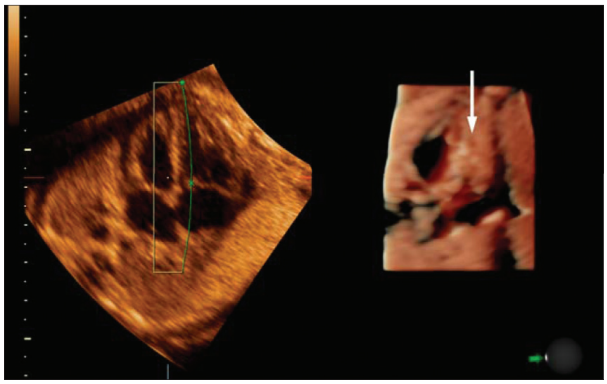
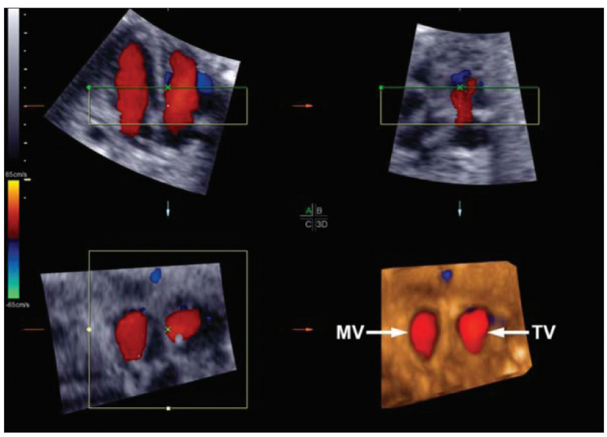


Figure 6. Coronal rendered image of the atrioventricular valves in diastole (STIC volume with color Doppler imaging). In the apical 4-chamber view (upper left corner), the green render line is positioned to image the atrioventricular valves en face from the ventricles. Color Doppler is seen through the open mitral valve (MV) and tricuspid valve (TV).



9. *Repeatability*—Variation in repeated measurements made on the same patient under identical conditions is defined as repeatability of measurements.[113] Using STIC technology, cardiac structures and measurements in normal fetal hearts have demonstrated high repeatability between (inter), and within (intra) observers.[114] Moreover, ventricular volume calculations using STIC combined with postprocessing modalities have also been shown to be repeatable and reproducible.[115]
10. *Combination With Other Applications*—STIC technology can be combined with other applications by selecting the appropriate setting before volume acquisition. These include color Doppler (Figure 7, A and B, and Videos 10 and 11),[39,40,111] power Doppler,[66,116] high-definition flow Doppler (similar to bidirectional power Doppler),[117] and B-flow.[67,118,119] STIC can also be combined with postprocessing modalities, which are not available in the 2D sonographic mode, including surface rendering,[34,112,120] inversion mode,[65,67] and multislice (Figure 8 and Video 12).[42,50,106,107] The end result is a multitude of display modes for STIC volume data sets.
11. *Congenital Heart Disease*—Prenatal assessment and diagnosis of CHD using conventional 2D sonography require an analysis of anatomic structures through a mental reconstruction of their spatial relationships. Four-dimensional sonography with STIC can improve the ability to identify such complex intracardiac relationships (Figure 9 and Video 13) and may also shorten the examination time.[33,43,121] Moreover, fetal cardiac abnormalities undetected during real-time sonographic examination may be detected at the time of STIC volume review.[40] A high degree of accuracy has been demonstrated when using STIC technology to prospectively evaluate fetuses with a wide spectrum of CHD.[64] Even in the first and early second trimesters, STIC volume evaluation has been shown to be accurate in diagnosing most major structural heart defects.[47] Therefore, 4D sonography with STIC has the potential to increase the detection rate of CHD,[33,62] and some have proposed its clinical application in cardiac screening and CHD diagnosis.[64]

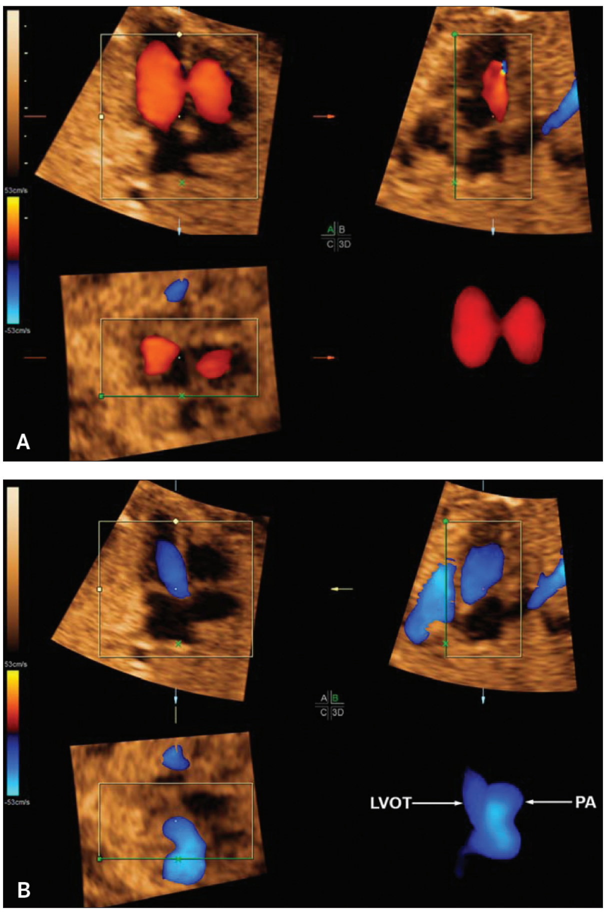


Figure 7. **A**, Apical 4-chamber view in diastole (STIC volume with color Doppler imaging). The rendered image in the lower right corner shows only color Doppler through the mitral (left) and tricuspid valves (right). **B**, Apical 4-chamber view in systole (STIC volume with color Doppler imaging). The rendered image in the lower right corner shows color Doppler through the great vessels only (LVOT indicates left ventricular outflow tract; and PA, pulmonary artery). The normal crisscrossing of the great vessels is visualized.

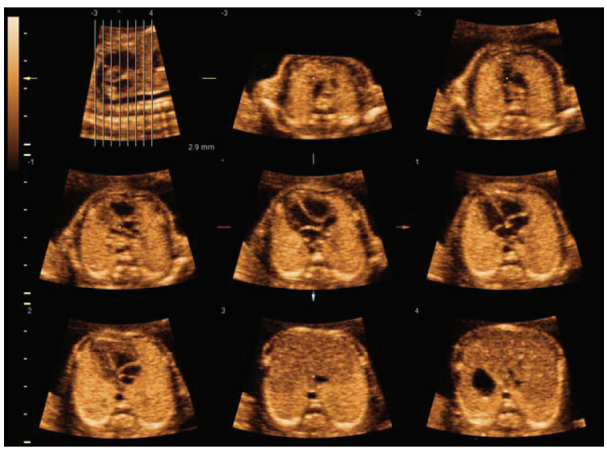


Figure 8. Multislice mode applied to a STIC volume data set from a normal fetal heart. Eight transverse sections from the upper mediastinum to the upper abdomen are displayed. In the overview image (ductal arch), the parallel lines indicate the exact position of the planes of section shown in the 8 subsequent images. Note the transverse aortic arch (–3 image), 3-vessel view (–2 image), 5-chamber view (green asterisk image), 4-chamber view (1 image), and stomach (4 image). Also see Video 12.

12. *Functional Cardiac Evaluation*—Within volume data sets, a specific cardiac phase (end diastole or end systole) can be identified by observing the opening and closing of the atrioventricular and semilunar valves. Therefore, by capturing these time points within the cardiac cycle, ventricular volume measurements may be obtained (Figure 10)[46] and the fetal stroke volume, cardiac output, and ejection fraction calculated.[44,48,53,82–84,86,87] It is generally agreed that 4D ventricular volume quantitation is more accurate than 2D-derived methods because geometric assumptions are avoided, along with magnification of small errors (inherent in the latter modality).[100,122] Thus, 2D echocardiography has limitations in the assessment of fetal cardiac function.[123,124] Other fetal cardiovascular parameters [eg, tricuspid annular plane systolic excursion[59,125] (Figure 11 and Video 14), ventricular mass,[85] and fractional shortening[57] (Figure 12 and Video 15)] have also been calculated using STIC technology.

Figure 9. Multiplanar display of a fetus with coarctation of the aorta. The reference dot is located in the transverse aortic arch, which can be confirmed by viewing both the A (upper left) and B (upper right) planes. Narrowing of the aortic isthmus is apparent (white arrow).

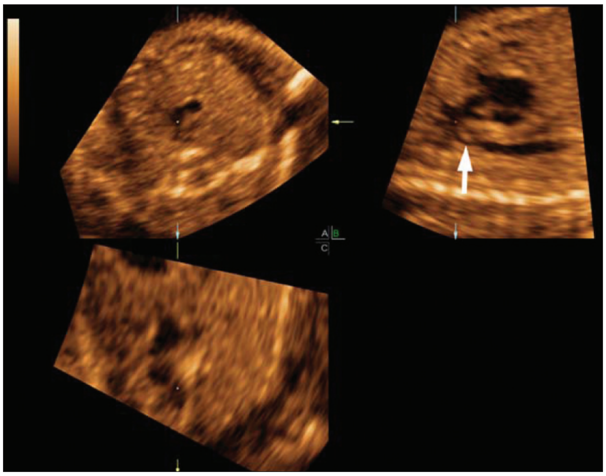


Figure 10. Quantification of fetal left ventricular volume (2.11 mL) during end diastole. The virtual organ computer-aided analysis (VOCAL) trace was performed in the A plane at the level of the 4-chamber view. The lower right image depicts the 3-dimensional model created by the VOCAL tool, which includes the entire traced volume.

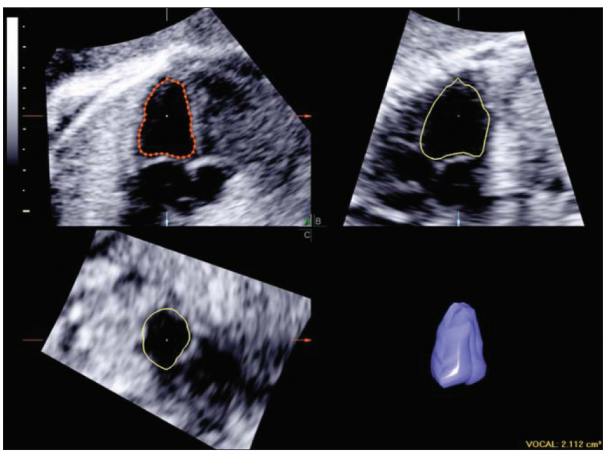


Figure 11. Measurement of STIC M-mode fetal tricuspid annular plane systolic excursion (TAPSE) vertically, parallel to the ventricular septum. The vertical movement of the tricuspid annulus during systole and diastole is derived from measurement (5.7 mm) of the amplitude of the M-mode wave. This measurement is normal for 25 weeks' gestation.[59] RV indicates right ventricle.

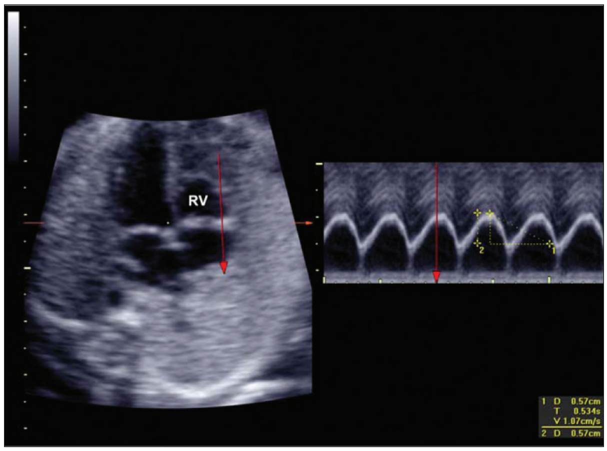
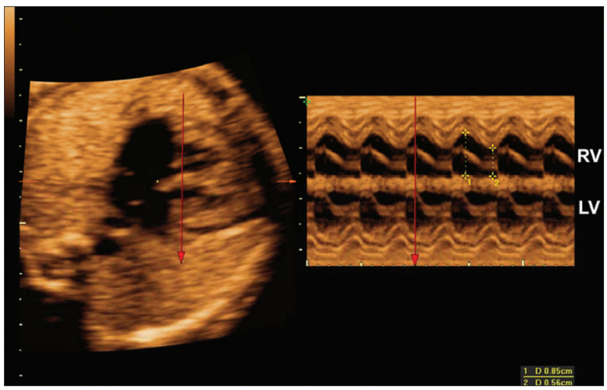


Figure 12. Calculation of fractional shortening using STIC M-mode. The M-mode cursor line is placed perpendicular to the ventricular septum at the level of the mitral and tricuspid valves. From end-diastolic and end-systolic measurements of the ventricles, fractional shortening [(end-diastolic dimension – end-systolic dimension)/end-diastolic dimension)] can be calculated. For the right ventricle, the fractional shortening is 34% (normal). LV indicates left ventricle; and RV, right ventricle.



13. *Counseling*—Four-dimensional sonography with STIC can result in an improved understanding of CHD by family members. Moreover, prenatal counseling, as well as interdisciplinary team consultation and management can be enhanced.
14. *Education and Training*—The study and analysis of STIC volume data sets is useful for both medical education and professional training in fetal echocardiography.
15. *Telemedicine*—Digital storage and review of STIC volume data sets by other examiners or consultative experts can occur at remote sites by transmitting files over networks.[32,68,126] Such offline networking capabilities may improve health care delivery systems by extending the benefits of prenatal cardiac screening to poorly served or underserved areas.[117]

Importance of Acquiring High-Quality STIC Volumes and Influence of Operator Training/Experience

Quality of STIC Volumes

The effective performance of fetal cardiac examination using STIC technology requires 2 essential steps: (1) volume acquisition; and (2) postprocessing.[114] The quality of a STIC volume data set is essential for postprocessing and assessment.[58] When the volume data set is suboptimal, subsequent analysis will be hindered by low image quality and artifacts. Indeed, investigators have demonstrated that: (1) the ability to visualize fetal cardiac structures is correlated with STIC volume quality[127]; (2) a positive correlation exists between the "acquisition condition score" (score assigned to fetal movements, ROI setting, acquisition angle, cardiac apex position, and shadowing) and "quality" of STIC volumes[36]; specifically, the higher the acquisition condition score, the better the volume "quality" (based on the ability to display cardiac structures); and (3) in a multicenter study of 4D fetal echocardiography in the first trimester, centers that reviewed a higher (versus lower) percentage of suboptimal STIC volumes had lower accuracy for identifying CHD.[22]

Therefore, when STIC volume data sets are of high quality, they are more likely to be informative (ie, successful display of cardiac planes and anatomic structures) when analyzed. When the opposite is the case (ie, volume data sets of poor quality), the "garbage in, garbage out" principle used in the fields of computer science and information and communications technology applies.[128] Specifically, computers (since they operate by logical processes) will unquestionably process unintended and even nonsensical input data (garbage in) to produce undesired and often nonsensical output (garbage out).[128] Similarly, a STIC volume data set of suboptimal or poor quality will also produce undesired and uninformative "output." It follows, then, that improving the diagnosis of CHD based on STIC technology cannot occur if the quality of volume data sets is suboptimal or poor.

Criteria for STIC Volume Acquisition

When acquiring STIC volumes using prespecified criteria, the successful generation of information (eg, fetal cardiac views) should be more consistent among examinations than if no protocol were followed. For example, what would be the result if there were no STIC acquisition criteria pertaining to fetal spine location? It is likely that successful visualization of the 3-vessel and trachea view would be greater for a fetus with the spine located at 6 o'clock than at 12 o'clock (due to acoustic shadowing from the spine). Comparing and interpreting the performance of 4D sonography with STIC among studies may also be challenging, since it depends on whether acquisition criteria have been implemented. For example, one group of investigators may report that the rate of obtaining satisfactory fetal cardiac views using STIC technology is poor and therefore conclude that STIC should not be used in clinical practice. Another group might report exactly the opposite findings. However, for the first investigators, were STIC volumes obtained randomly, or were standardized criteria followed during the acquisition process? If the first scenario actually occurred (ie, STIC volumes obtained randomly), an unbeknownst reader will erroneously believe that 4D sonography with STIC has no clinical value. Taken together, if there is a lack of standardization in the acquisition of STIC volume data sets, it would be a major limiting step to effective performance of fetal cardiac examination using 4D sonography with STIC.

Operator Training and Experience

The acquisition of high-quality STIC volumes requires adequate training, and this factor is the key determinant of a successful complete cardiac examination.[127] Moreover, investigators have reported the impact of experience, in which more experienced sonographers have: (1) a significantly higher success rate of STIC volume acquisition than those less experienced (88.4% versus 70.5%; $P = .02$)[36]; (2) significantly less reported fetal movements interfering with STIC volume acquisition (expert versus beginners, 12% versus 62%; $P < .05$); and (3) fewer motion artifacts observed in STIC volumes than in those acquired by beginners (16% versus 42%; $P < .05$).[36] Recently, Novaes et al[129] reported that in normal fetuses, the proportion of STIC volumes considered adequate to demonstrate 5 cardiac views was higher for STIC "specialists" than "nonspecialists" (66.7% versus 36.2%; $P < .001$). The latter group comprised physicians without experience in volumetric sonography.

Other factors besides operator skill and experience influence the quality of STIC volume data sets, such as fetal breathing and movements.[32–34,130] It is noteworthy, however, that such factors also influence image quality in 2D sonography; therefore, these are not unique to 4D sonography with STIC. Indeed, it is important to clarify the relationship between these two sonographic modalities. A prevailing myth that should be abolished is that STIC technology is immune to some of the limitations inherent in 2D sonography. For example, we have been asked how to avoid acoustic shadows from being introduced into STIC volume data sets when the fetal spine is anteriorly located. STIC technology is just as susceptible to limitations in scanning windows[36] as 2D sonography; thus, such issues cannot be resolved.

What Is the Success Rate of STIC Volume Acquisition, and Are Such Volumes Informative?

An important issue is the success rate of STIC volume acquisition when examining fetuses with normal hearts. These rates range widely from 26% to 100%[32,35,36,39,45,47–49,77,84,85,92,114,115,129,131–134] (Table 2) and depend on many factors, such as operator training and skill, route of examination (transabdominal versus transvaginal), gestational age, maximum duration of the examination allowed, patient ambulation, and number of STIC volume acquisitions per patient. Yet, probably the most important factors influencing the volume acquisition rate are the preset criteria/requirements for acquisition, as well as their degree of rigor.[92] These criteria may include specifics about fetal movement and breathing, fetal position, acoustic shadowing, and which anatomic structures should be visualized before volume acquisition begins.[92] For example, at one end of the spectrum, if a transducer is simply placed over the fetal heart without any specifications, and the success rate of STIC acquisition is defined as just "obtaining a volume," the rate will be 100%. In contrast, if there are stringent criteria required for obtaining a STIC volume data set, the success rate is likely to be lower.

The criteria set forth by investigators to acquire STIC volumes will vary, depending on the area(s) being studied. For example, if color Doppler velocimetry is combined with STIC to evaluate flow through the atrioventricular valves, it is acceptable for the fetal spine to be located anteriorly. When STIC M-mode is used to obtain fetal cardiac dimensions,[57] assess ventricular fractional shortening,[135] or measure ventricular wall and interventricular septal thickness,[58] a lateral insonation of the fetal heart (ie, spine located laterally) is obtained (Figure 12 and Video 15). This situation is also the case when evaluating fetal pulmonary veins (STIC combined with B-flow)[136] or the outflow tracts.[37] However, when the goal is to assess fetal cardiac views, the spine should ideally be located posteriorly to minimize acoustic shadowing.[116]

Acquisition rates and/or the definition of an "acceptable" STIC volume data set are also influenced by the purpose of study (eg, to visualize cardiac views and structures or to calculate ventricular volumes and indices of cardiac function). For example, if the objective is to visualize the 4-chamber view only, the rate of acceptable STIC volumes should be high. On the other hand, if clear demarcation of ventricular endocardial borders and absence of shadowing artifacts in multiple planes is required for evaluating fetal cardiac function, the rate of acceptable STIC volumes will be lower.[84]

Collectively, it is therefore important to keep these concepts in mind when reviewing reports on the success rates of STIC volume acquisition. In general, the greater the number and rigor of preset criteria/requirements, the lower the success rate will be.[92] A far more crucial issue, however, is whether STIC volume data sets are informative (ie, ability to display cardiac planes and structures), which occurs only if they are of high quality.[36] Just because a volume data set has been obtained, it does not necessarily translate into one that is clinically useful. Thus, there may not be a direct relationship between the STIC acquisition rate and the quality of information that can be derived from such volumes. For example, the acquisition rate may be 100%, but due to suboptimal STIC quality, volumes may be uninformative. The flip side is that stringent acquisition criteria may lead to lower STIC volume acquisition rates, but volumes may be very informative.

In some cases, acquisition of an appropriate STIC volume will not be possible despite multiple attempts (eg, secondary to an uncooperative fetus or maternal obesity). Yet, these factors are no different from those of conventional 2D sonography, in which a successful fetal cardiac examination may not always be possible.

Table 2. Rates of STIC Volume Acquisition in Fetuses With Normal Hearts

First Author, Year, Reference	Fetal Population, n	Gestational Age, wks	Characteristics of STIC Volumes and Acquisition	Criteria for STIC Volume Acquisition (2D Mode)	Success Rate of STIC Volume Acquisition and Volumes Not Discarded	Clinical Information Provided From Analysis of STIC Volumes
1. Viñals, 2003[32]	100	18–37	2D mode Acquired by 1 general obstetrician 1–2 volumes	Adequate 4CH view (apical and lateral) Angle 30° (always) Avoid shadows, inconvenient fetal lie, transient bradycardia, movements Extra time allowed for fetus to change to a more favorable position (if necessary)	100% acquisition However, 30 acquisitions did not meet criteria of a proper 4CH view and were not considered well visualized (but in most cases, the multiplanar view allowed proper recognition of structures and views)	94.2% rate of visualizing different structures and views of the fetal heart (using STIC sweep alone) and 96.2% (by adding multiplanar examination) Stomach could not be visualized (n = 19)
2. Chaoui, 2004[39]	35	20–term	2D mode Color Doppler 1–3 volumes (color Doppler) stored for each exam	Dorsoposterior position, allowing either an apical, right-sided, or left-sided insonation of heart Transverse cardiac sweep Did not acquire volumes only with a strict apical view	100% acquisition However, 11.5% (4/35) had an incomplete exam using color Doppler STIC due to a perpendicular insonation in 1 of 3 planes of interest	90% visualization of 4CH view, 5CH view, 3VT view
3. Rizzo, 2008[45]	119	19–23	2D mode	4CH view Dorsoposterior position, allowing either apical, right-sided, or left-sided insonation of heart	95% (113/119)	Used “3-steps” technique Adequate views of 4CH view and outflow tracts obtained in >80% volumes
4. Viñals, 2008[131]	32	11–13.6	2D mode Color Doppler Acquired by 1 general obstetrician 1–6 volumes	4CH view (apical, 63%; lateral, 37%) 15° acquisition angle, 7.5-s acquisition time Time limit of 20 min	70% (32/46) In fetuses >12 wk, volumes were acquired in 86%	Volumes reviewed by 2 individuals Checklist of 18 structures and views Recognition of most structures/views necessary to assess cardiac anatomy with a high degree of interobserver concordance Good/very good concordance ($\kappa > 0.6$) in 14/18 cardiac structures and views

Table 2. (continued) Rates of STIC Volume Acquisition in Fetuses With Normal Hearts

First Author, Year, Reference	Fetal Population, n	Gestational Age, wks	Characteristics of STIC Volumes and Acquisition	Criteria for STIC Volume Acquisition (2D Mode)	Success Rate of STIC Volume Acquisition and Volumes Not Discarded	Clinical Information Provided From Analysis of STIC Volumes
5. Uittenbogaard, 2008[36]	148	For 112 cases, the mean was 21 wk	2D mode Brief training in 3D/4D sonography Acquired by 4 sonographers (1 with substantial experience in STIC and 3 without)	Transverse plane through fetal thorax Optimal position was fetal spine between 5 and 7 o'clock (apex between 10 and 2 o'clock) No additional time given (30-min slots) Not allowed to make more than 4 attempts	75.7% (112/148) Experienced sonographers, 88.4% (vs less experienced sonographers, 70.5%); *P* = .02	Acquisition condition score[a] STIC quality rated as insufficient, sufficient, high[b] Of analyzed volumes, 64.8% (68/105) were high or sufficient quality STIC quality and render ability correlated strongly with acquisition conditions High-quality volumes successfully rendered the septa in 84.6% Coronal atrioventricular plane was rendered in 46.2% of high-quality volumes High-quality volumes were more likely to display any given cardiac anatomic structure than those of sufficient quality Positive correlation between acquisition condition score and quality of volumes was found in 3 quality groups (the higher the score, the better the volume quality)
6. Turan, 2009[49]	107	11–13.6	2D mode Color Doppler TA (91.6%) and TV (8.4%) sonography Volume acquisition repeated as necessary to get 3 high-quality images (minimum of 3 volumes per patient)[c]	4CH view identified via color Doppler Fetal spine clearly seen, minimizing shadowing from ribs or spine Minimal or no motion artifacts in sagittal plane All scans were completed within the normal scan time	100% (107/107)	Volumes evaluated by TUI Ability to visualize 12 anatomic landmarks using 2D mode and color Doppler assessed (4CH view, cardiac axis, size and symmetry, atrioventricular valves, great vessels, descending aorta, forward flow in aortic and ductal arches) Individual anatomic landmarks identified in 89.7%–99.1% Visualization of all 12 landmarks in a single panel in 85%
7. Uittenbogaard, 2009[48]	63	12–30	2D mode Mean number of volumes per fetus, 3 (range, 1–6) Multiple volumes taken (longitudinal study design)	"Well-performed STIC acquisitions without movement or shadow artifacts"	71% (205/287) 202 volumes used in final analysis Increased failure rate of volume acquisition after 29 wk	Ventricular volume measurements obtained using 3D Slice method Established reference values for left and right ventricular volumes and indices of cardiac function (SV, EF, CO)

Table 2. (continued) Rates of STIC Volume Acquisition in Fetuses With Normal Hearts

First Author, Year, Reference	Fetal Population, n	Gestational Age, wks	Characteristics of STIC Volumes and Acquisition	Criteria for STIC Volume Acquisition (2D Mode)	Success Rate of STIC Volume Acquisition and Volumes Not Discarded	Clinical Information Provided From Analysis of STIC Volumes
8. Hamill, 2009[115]	44	18–36.6	2D mode 2 volumes acquired from each of 44 fetuses (maximum time, 30 min) Each STIC had ventricular volumes calculated twice (for agreement and reliability)	4CH view Volumes accepted if no shadowing, dropout, motion artifacts Data set accepted for analysis if ventricular septum, ventricular walls, atrioventricular valves visible throughout each rotational step Excluded if suboptimal fetal position	75% (33/44) had 2 successful volume acquisitions	Ventricular volumes evaluated by VOCAL Ventricular volumes were reproducible with negligible differences in agreement, and good reliability Bias between volume acquisitions was minimal STIC and VOCAL allows repeatable and reproducible calculation of ventricular volumes
9. Bennasar, 2009[47]	58	11.1–15.5	2D mode Color Doppler TV sonography 2–6 volumes acquired from each patient	4CH view, preferably apical When fetal position was not favorable, patient asked to return in 30 min Acquisition stopped if significant fetal movements (although numbers of stopped attempts were frequent, they were not recorded)	100% (58/58) However, after volume evaluation, 5 were classified as unsatisfactory and were excluded from analysis	90% rate of full cardiac examination from 12 wk onward Accuracy, 95.3%; sensitivity, 90.9%; specificity, 96.2%; PPV, 83.3%; NPV, 98.1% STIC is reliable for early reassurance of normal anatomy and to diagnose most major CHD
10. Bennasar, 2010[114]	150 11 excluded, leaving a study population of 139	1st–3rd trimesters	2D mode Color Doppler 1 or more volumes	4CH view, preferably apical approach (apical, 59%; lateral, 30%; basal, 11%) Maximum time, 25 min	98% (147/150)	14 cardiac structures and 5 measurements were evaluated Complete cardiac examination was possible in 95% cases (132/139) evaluated by observer 1 and 91% cases (126/139) evaluated by observer 2 Cardiac examination from volumes showed high repeatability between and within observers in each trimester
11. Dan-dan, 2011[132]	1062 normal 43 CHD without VSD 58 with VSD	21–36	2D mode Volumes acquired 3 times (normal heart)	Fetal spine was "away from probe," and the best quality STIC was used to evaluate clinical feasibility (normal heart) Limited time for STIC acquisition (normal heart)	70.1% (744/1062)	Volumes assessed by multiplanar slicing, TUI, inversion mode, rendering 1 case diagnosed as normal by 2D echocardiography confirmed to have VSD by STIC Misdiagnosis rate of VSD by STIC was 0.17% There is advantage and value of STIC in the prenatal diagnosis of VSD

Table 2. (continued) Rates of STIC Volume Acquisition in Fetuses With Normal Hearts

First Author, Year, Reference	Fetal Population, n	Gestational Age, wks	Characteristics of STIC Volumes and Acquisition	Criteria for STIC Volume Acquisition (2D Mode)	Success Rate of STIC Volume Acquisition and Volumes Not Discarded	Clinical Information Provided From Analysis of STIC Volumes
12. Messing, 2011[85]	121	21–38	2D mode	"Acquisition performed with the abdomen uppermost"	87.6% (106/121)	Myocardial volume measurements performed using VOCAL and inversion mode Cardiac ventricular mass quantified, and mass measurements shown to be reliable and reproducible
13. Rizzo, 2011[35]	495	18–24	2D mode 1-d training program on STIC acquisition Sonographers with experience in routine obstetric sonography but not with fetal echo 5 sonographers examined 500 consecutive pregnancies (each sonographer acquired volumes during the 1st 100 consecutive exams)	4CH view Chest anterior or anterior/oblique position	94.7% (469/495)	2 reviewers assessed the rate of satisfactory images in 5 views: 1. 4CH (91.5% and 93%) 2. LVOT (85% and 86.2%) 3. RVOT (83.9% and 84.5%) 4. 3VT (85.2% and 84.5%) 5. Abdominal (92.4% and 93.6%) Volumes were high enough quality to allow satisfactory diagnostic cardiac views in 80%–90%
14. Simioni, 2012[133]	290 216 study population (108 male, 108 female)	20–34.6	2D mode	Axial level of 4 heart chambers Fetal back between 3 and 9 o'clock Fetuses with "dorsal anterior (between 11 and 1 hour)" and excessive fetal movements were excluded, along with other exclusion criteria	88.3% (256/290)	Ventricular volumes assessed by VOCAL Ventricular volumes, CO, EF compared between male and female fetuses (no significant differences found)
15. Hongmei, 2012[77]	31	18–39	B-flow	Transverse and longitudinal sweeps of anterior chest wall	93.5% (29/31)	In 29 fetuses, the aorta, pulmonary artery, ductus arteriosus, IVC, DV could be detected on reconstructed images In 7 fetuses, 4 pulmonary veins were successfully demonstrated on a reconstructed view

Table 2. (continued) Rates of STIC Volume Acquisition in Fetuses With Normal Hearts

First Author, Year, Reference	Fetal Population, n	Gestational Age, wks	Characteristics of STIC Volumes and Acquisition	Criteria for STIC Volume Acquisition (2D Mode)	Success Rate of STIC Volume Acquisition and Volumes Not Discarded	Clinical Information Provided From Analysis of STIC Volumes
16. Schoonderwaldt, 2012[84]	84	20–34	2D mode On average, 4–6 volumes	4CH view Spine dorsal position BMI < 25 kg/m^2 Maximum scan duration of 20 min Only volumes without motion artifacts and a clear demarcation of endocardial borders were accepted for analysis	Inclusion of patients proceeded until 6 adequate volumes were obtained for each gestational age period Overall 35.7% (30/84) According to gestational age: 20–22 wk (55% [6/11]) 23-25 wk (40% [6/15]) 26-28 wk (26% [6/23]) 29-31 wk (32% [6/19]) 32-34 wk (38% [6/16])	Ventricular volumes assessed by VOCAL and Simpson's rule (method of discs) LV volume, SV, EF calculated STIC allows reproducible measurements of LV volume and SV Large percentage of poor-quality STIC volumes and wide limits of interobserver agreement are obstacles for clinical application of this technique
17. Rocha, 2015[134]	90	21.4–30.6	2D mode	No information provided on criteria for STIC acquisition Patients excluded if spine located between 11 and 1 o'clock, high BMI, polyhydramnios or oligohydramnios, CHD	56% (50/90)	54% rate of satisfactory cardiac views for 4 planes (4CH view, RVOT, LVOT, 3VT view) and 14% rate for 6 planes (4CH, RVOT, LVOT, 3VT view, aortic arch, ductal arch) Rate of satisfactory cardiac views for screening: 4CH view, 100%; RVOT, 70%; LVOT, 66%; 3VT view, 82%; aortic arch, 16%; ductal arch, 44%
18. Garcia, 2015[92]	207	19–30	2D mode	Fetal spine located between the 5- and 7-o'clock positions Minimal or absent shadowing (including a clearly visible transverse aortic arch) Absent fetal breathing, hiccups, movement Adequate image quality	72.5% (150/207)	9 fetal echocardiographic views generated using a combination of diagnostic planes and/or VIS-Assistance in 98-100% of cases (Fetal Intelligent Navigation Echocardiography [FINE])
19. Novaes, 2016[129]	64 (74 ultrasound exams)	20–34	2D mode Brief explanation about STIC software Acquired by 4 STIC specialists or 8 nonspecialists 3 or more volumes	Acquisition of volumes independent of fetal position and maternal habitus 20°–40° acquisition angle, 7.5–15-s acquisition time Allowed 20 min to obtain volumes	Overall 97.3% (72/74) STIC specialist, 100% (vs nonspecialist, 95%) 80.7% (197/244) volumes were properly acquired and saved	Volumes reviewed by 2 individuals 5 axial views (4CH view, RVOT, LVOT, 3VT view, abdominal situs) were seen in 49% of volumes: STIC specialist, 67% of volumes Nonspecialist, 36% of volumes

3VT, indicates 3-vessel and trachea; BMI, body mass index; CO, cardiac output; DV, ductus venosus; EF, ejection fraction; 5CH, 5-chamber; 4CH, 4-chamber; IVC, inferior vena cava; LV, left ventricle; LVOT, left ventricular outflow tract; NPV, negative predictive value; PPV, positive predictive value; RVOT, right ventricular outflow tract; SV, stroke volume; TA, transabdominal; TV, transvaginal; TUI, tomographic ultrasound imaging; VIS-Assistance, Virtual Intelligent Sonographer Assistance; VOCAL, virtual organ computer-aided analysis; and VSD, ventricular septal defect.

[a]Acquisition condition score = summation of scores for each of the following categories: fetal movements, region of interest setting, acquisition angle, apex position, and shadowing. Scores assigned for each of the 5 categories were 0, 1, or 2 (2 was the best condition).

[b]STIC quality (insufficient, sufficient, or high) was determined according to the ability to display cardiac structures (eg. 4-chamber view).

[c]For 80% of patients, the first 3 volumes were high quality; for 20% of patients, up to 9 volumes were required due to fetal movement.

How to Perform 4D Sonography With STIC

There are 4 essential steps when performing 4D sonography with STIC: (1) volume acquisition; (2) volume display; (3) volume manipulation/postprocessing; and (4) storage of volumes and images. After STIC volume acquisition, standardization of the multiplanar view, volume interrogation to obtain cardiac views and/or rendering of the volume is performed. In this article, we will review concepts pertaining to STIC volume acquisition and display only.

Three main time points deserve focus when acquiring STIC volume data sets and determining their appropriateness for analysis: (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[90]).

It is noteworthy that the specific approach described herein pertains to STIC volumes acquired through a transabdominal approach, using B-mode sonography, and via a transverse acquisition plane of the fetal chest (level of the 4-chamber view). We recognize that not every aspect of this approach will apply to all clinical situations and will vary depending on the primary goal. Our intent is to describe an overall practical method to serve as a guide. Moreover, if the described technique is not followed, it does not necessarily mean that the STIC volume data set will be uninformative. Indeed, clinically useful information can still be obtained from STIC volumes derived by using a variety of approaches, provided that they are of high quality.

At what gestational ages should STIC volumes be obtained? In general, we recommend that volumes be acquired between 19 and 30 weeks' gestation for optimal assessment of fetal cardiac anatomy.[92] High-quality STIC volumes tend to become more difficult to acquire after this gestational age range, due to fetal positioning and acoustic shadowing. Indeed, authors have reported that only a few high-quality STIC volumes can be acquired beyond 29 weeks' gestation.[48] It is noteworthy, however, that volumes of superior quality can still be obtained throughout the third trimester, even up to 39 weeks' gestation.[90] Moreover, in the first and early second trimesters, a detailed evaluation of both normal and abnormal fetal hearts using STIC technology can be performed.[22,47,49,127,131,137] This fact is clinically relevant, due to the increasing role of first-trimester fetal cardiac examination[138–143] (eg, increased nuchal translucency thickness in the presence of a normal fetal karyotype). However, the challenges of performing 4D sonography with STIC in the first trimester include frequent fetal motion and the size of cardiac structures. Transvaginal sonography may be used to obtain volumes in early pregnancy.[22,47,49,127]

General Recommendations

We propose the following general recommendations when performing 4D sonography with STIC:

1. *Play an Active Role*—If possible, sonologists should proactively get the fetus into a more optimal position and/or move fetal parts out of the imaging field of view. For example, the following actions can be performed: (1) 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. For example, let us assume that a vertex fetus has the cardiac apex located at 7 o'clock (transverse plane of the chest) on the monitor screen. If the desired effect is movement of the fetal cardiac apex to an 11-o'clock position (a "clockwise roll"), the mother also should be asked to roll in a clockwise direction, so that she comes to rest on her left side. In our experience, frequently changing the maternal position (eg, rolling to either or both lateral sides, ambulating, going to the restroom, or sitting up) will usually change the fetal position successfully into the desired one. (2) Gently "move" the fetus into the desired position by placing one's hands on the maternal abdomen. (3) Gently tap on the maternal abdomen or ask the mother to cough, so that fetal parts (eg, an extremity) move out of the field of view. (4) Change the tilt and position of the examination bed. Understandably, women often prefer the upper part of the bed to be raised at an angle for comfort. However, when the entire bed is tilted upward (head higher than the feet), or the bed is "jackknifed" or bent at the midway point of the bed (and, thus, the maternal waist), maneuvering the probe around the maternal abdomen is sometimes suboptimal and awkward because sonologists may have to bend their wrists backward to obtain optimal images. Therefore, when possible, we prefer to scan patients lying completely supine to "flatten" their abdomen or with the entire bed tilted downward (feet higher than the head). In our experience, this position allows easier maneuvering and tilting of the transducer, and sonologists are able to bend their wrist forward to scan.
2. *Practice Efficiency During the Sonographic Examination*—Success in STIC volume acquisition can be achieved by constantly adapting to the fetal situation. Using this approach is particularly relevant when imaging the fetal heart, since examination of this organ is highly dependent on fetal position, and fetuses can move frequently. A few examples of practicing efficiency during the sonographic examination include

the following: (1) Recognize when there is an optimal moment to image the fetal heart and acquire STIC volume data sets. If the fetal spine is anteriorly located at first, but the fetus suddenly flips to a supine position, one should immediately focus on cardiac examination. If the fetal heart is already in an optimal position, and conditions are appropriate (eg, absence of fetal breathing or movement), the sonologist should take advantage of this opportunity by immediately acquiring multiple STIC volumes in rapid succession. Such a chance may not occur again. (2) In the presence of a suboptimal fetal position, instead of trying repeatedly and unsuccessfully to image cardiac structures, one can examine other fetal organs, obtain biometric measurements, etc, to allow time for the fetus to change into a more optimal position. While doing so, the sonologist should frequently check back to see whether the fetal heart can now be imaged successfully using STIC. Thus, in summary, one should always be "on the lookout" throughout the sonographic examination and take advantage of any proper moments to obtain STIC volumes.

3. *Use a Volumetric Transducer Throughout the Examination*—If the sonologist plans to acquire STIC volume data sets during the sonographic examination, it is advantageous to use a volumetric transducer throughout the study. This use avoids having to switch back and forth between a probe used for 2D imaging and a volumetric transducer, all of which takes time, requires setting changes, and is inefficient when practiced frequently. Fortunately, next-generation volume transducers have been designed to be lighter than previous versions, for the purpose of reducing user fatigue.
4. *Prepare the Machine Settings Beforehand*—Since capturing STIC volume data sets can occur at any time during the examination, it is helpful to "prepare" the acquisition settings on the ultrasound machine beforehand (eg, adjust the ROI size, decrease the depth, and set the acquisition angle and time). Such measures are helpful because if conditions suddenly become optimal for STIC acquisition (eg, fetal spine moves to a 6-o'clock position), the settings have already been programmed, and one can immediately proceed with the acquisition. If this preparation has not occurred beforehand, sometimes while the operator spends time adjusting the settings, fetuses will change position or commence breathing movements, and the chance becomes lost. Of course, despite all preparations, adjustments are sometimes necessary (eg, change the depth) due to a dynamic fetal environment.
5. *Prepare the Patient Beforehand*—It is helpful to explain to patients ahead of time that there may be attempt(s) throughout the sonographic examination to obtain STIC volumes; therefore, her participation is encouraged (eg, maintain a breath hold and remain motionless). The purpose of 4D sonography with STIC and how it is performed should be discussed with the patient. In general, we have found such a practice to be invaluable because patients are informed, prepared ahead of time, and more likely to be cooperative.

Conclusions

Prenatal diagnosis of CHD is important, since it is the leading organ-specific birth defect and the leading cause of infant morbidity and mortality from congenital malformations. However, sonographic evaluation of the fetal heart is one of the most difficult tasks in prenatal diagnosis, and the detection of CHD remains challenging. Since STIC technology was first described 13 years ago, a large body of evidence suggests that it facilitates examination of the fetal heart and has the potential to reduce the operator dependency associated with conventional 2D sonography. Four-dimensional sonography with STIC has also been used to successfully evaluate and diagnose CHD, as well as assess fetal cardiac function. Yet, despite the advantages of 4D sonography with STIC over conventional 2D sonography, the former has been underused and its value underestimated.

STIC volume acquisition can be incorporated into the daily practice of ultrasound centers. However, using such technology to examine the fetal heart requires an important prerequisite: the training of sonologists to acquire high-quality volume data sets so that they are informative. Here we have described general recommendations on the performance of 4D sonography with STIC. In part 2 of this article,[96] we discuss a detailed and practical stepwise approach for STIC volume acquisition, along with methods to determine whether such volumes are appropriate for analysis.

Our overall goal is to demystify an imaging modality that is considered by many to be too complicated and challenging to perform. By doing so, the objective is to encourage sonologists to embrace STIC technology as an additional and valuable tool for examining the fetal heart. Since the sensitivity of 2D sonography for CHD has not improved over the last decade,[20] there is a need to address this long-standing problem and offer a solution that could improve detection rates. Bringing high-quality ultrasound screening to all pregnant women is essential, and 4D sonography with STIC should move to the forefront of this solution. In doing so, the first steps include education and training each other.

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