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# Prospective evaluation of the fetal heart using Fetal Intelligent Navigation Echocardiography (FINE)

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**KEYWORDS:** 4D; cardiac; fetal heart; prenatal diagnosis; spatiotemporal image correlation; STIC; ultrasound; Virtual Intelligent Sonographer Assistance; VIS-Assistance®

## ABSTRACT

***Objective*** *To evaluate prospectively the performance of Fetal Intelligent Navigation Echocardiography (FINE) applied to spatiotemporal image correlation (STIC) volume datasets of the normal fetal heart.*

***Methods*** *In all women between 19 and 30 weeks' gestation with a normal fetal heart, an attempt was made to acquire STIC volume datasets of the apical four-chamber view if the following criteria were met: (1) fetal spine located between 5- and 7-o'clock positions; (2) minimal or absent shadowing (including a clearly visible transverse aortic arch); (3) absence of fetal breathing, hiccups, or movement; and (4) adequate image quality. Each STIC volume successfully acquired was evaluated by STICLoop™ to determine its appropriateness before applying the FINE method. Visualization rates of fetal echocardiography views using diagnostic planes and/or Virtual Intelligent Sonographer Assistance (VIS-Assistance®) were calculated.*

***Results*** *One or more STIC volumes (365 in total) were obtained successfully in 72.5% (150/207) of women undergoing ultrasound examination. Of the 365 volumes evaluated by STICLoop, 351 (96.2%) were considered to be appropriate. From the 351 STIC volumes, only one STIC volume per patient (*n = *150) was analyzed using the FINE method, and consequently nine fetal echocardiography views were generated in 76–100% of cases using diagnostic planes only, in 98–100% of cases using VIS-Assistance only, and in 98–100% of cases when using a combination of diagnostic planes and/or VIS-Assistance.*

***Conclusions*** *In women between 19 and 30 weeks' gestation with a normal fetal heart undergoing prospective sonographic examination, STIC volumes can be obtained successfully in 72.5% of cases. The FINE method can be applied to generate nine standard fetal echocardiography views in 98–100% of these cases using a combination of diagnostic planes and/or VIS-Assistance. This suggests that FINE could be implemented in fetal cardiac screening programs. Published 2015. This article is a U.S. Government work and is in the public domain in the USA.*

## INTRODUCTION

Congenital heart disease (CHD) is the most common group of malformations affecting both fetuses and newborn infants[1]. Up to 90% of cases of cardiac defects occur in pregnancies with no high-risk features[2]. This provides the impetus to perform a comprehensive screening examination of the fetal heart in all pregnant women, to maximize the detection of heart defects[3–6]. Yet, even when more than 90% of women in the population undergo a prenatal ultrasound examination, studies report low sensitivity (22.5–52.8%) for the detection of CHD[7–10]. This has been attributed mainly to operator expertise and experience[1,2,5,10–14].

A thorough sonographic examination of the fetal heart has traditionally relied on obtaining standard anatomic planes, including the four-chamber view, left and right outflow tracts and the three-vessels and trachea view (3VT)[15–26]. Moreover, five 'short-axis views' have been proposed as a screening method for comprehensive fetal echocardiography[27]. A large body of evidence now

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indicates that four-dimensional (4D) sonography with spatiotemporal image correlation (STIC) can facilitate examination of the fetal heart[28–56] and may also be used to evaluate CHD[57–82]. STIC technology enables acquisition of a volume dataset of the fetal heart, and displays a cine loop of a complete, single cardiac cycle in motion. Such volume datasets allow cardiac planes to be extracted and displayed in any orientation. This is conventionally performed through interrogation and analysis of three orthogonal planes in the multiplanar display mode. However, this process is highly challenging and operator dependent. Indeed, some have suggested the presence of a learning curve for the manipulation and analysis of STIC volume datasets[45,83,84].

Recently, we developed and reported a novel method known as Fetal Intelligent Navigation Echocardiography (FINE), which generates nine standard fetal echocardiography views automatically in normal hearts by applying 'intelligent navigation' technology to STIC volume datasets[85]. Such a method can simplify examination of the fetal heart and reduce operator dependency[85]. Along with other unique features, FINE allows demonstration of nine cardiac diagnostic planes and spontaneous navigation of the anatomy surrounding each of these planes (through Virtual Intelligent Sonographer Assistance, or VIS-Assistance®). After the initial development phase of FINE, we tested the method on a new group of 50 STIC volume datasets of normal fetal hearts that came from our collection[85]. Each volume was first evaluated using STICLoop™ to determine its appropriateness before the FINE method was applied[85]. In such cases, nine fetal echocardiography views were generated in 98–100% of cases using a combination of diagnostic planes and/or VIS-Assistance.

We conducted this study to determine prospectively the success rate of STIC volume acquisition between 19 and 30 weeks' gestation in women with normal fetal hearts undergoing sonographic examination and to evaluate the performance of the FINE method when applied to such volume datasets.

## METHODS

### Subjects

All women undergoing sonographic examination at the Detroit Medical Center/Wayne State University and the Perinatology Research Branch of NICHD, NIH, DHHS between 19 and 30 weeks' gestation were approached prospectively to undergo 4D ultrasound examination with STIC volume acquisition if they had a fetus with a normal heart. For the purpose of this study, STIC volumes were not acquired in the presence of congenital anomalies, suspected congenital heart defects, arrhythmias or anhydramnios/oligohydramnios. All women had been enrolled in research protocols approved by the institutional review board of NICHD, NIH and by the Human Investigation Committee of Wayne State University. All participants provided written informed consent for the sonographic images to be used for research purposes.

### Acquisition of STIC volumes

Using STIC technology (Voluson E8 Expert, GE Healthcare, Milwaukee, WI, USA), 4D volume datasets of the fetal heart were acquired from an apical four-chamber view using hybrid mechanical and curved array transducers (2–5 and 4–8 MHz) by transverse sweeps through the fetal chest. Patients were asked to momentarily suspend breathing during the STIC acquisition. An attempt was made to acquire one or more STIC volume datasets per patient only if the following criteria were met: 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 or movement; and adequate image quality. Acquisition times ranged from 7.5 s to 12.5 s, depending on fetal movement, while the angle of acquisition ranged between 20° and 35°, depending on gestational age. No additional time was taken during the ultrasound examination to attempt to and actually acquire STIC volumes.

Volumes were subsequently saved onto the hard drive of the ultrasound machine only if the following criteria were met, based upon review of the multiplanar display: (1) fetal heart rate within normal limits; (2) upper fetal mediastinum and stomach included and clearly visible in the volume; (3) minimal or no motion artifacts observed in the sagittal plane (depicted after placement of the reference dot in the cross-section of the descending aorta in the acquisition plane; 50% speed in Auto Cine); (4) minimal or absent shadowing; and (5) adequate image quality.

### STICLoop evaluation

All saved STIC volumes were imported into a software system (SONOCUBIC FINE™; Version 2013.06.13; Medge Platforms, Inc., New York, NY, USA), which was installed on a Dell OptiPlex 990 desktop computer (Dell Inc., Round Rock, TX, USA) using the Operative System Microsoft Windows 7 PRO 64-bit Service Pack (Microsoft Corp., Redmond, WA, USA). Once a STIC volume is loaded onto this software system it is converted into a two-dimensional cineloop that scrolls automatically in a continuous fashion (i.e. STICLoop)[85]. This tool aids the user in determining the appropriateness of STIC volume datasets before implementation of the FINE method. With STICLoop, the image on the screen begins with the initial frame that was obtained by the mechanical probe, and automatic scrolling through all frames occurs until the last frame acquired in the sweep is reached. We used a cine rate of 8–12 loops/min to evaluate all STIC volumes. Using STICLoop, volumes were deemed appropriate if all of the following nine criteria were met[85]: (1) fetal spine located between the 5- and 7-o'clock positions (reducing the possibility of shadowing from the ribs or spine); (2) minimal or absent shadowing (including 3VT); (3) adequate image quality; (4) upper

mediastinum and stomach included within the volume; (5) minimal or no motion artifacts observed in the loop (i.e. smooth sweep without evidence of abrupt jumps or discontinuous movements); (6) chest circumference contained within the region of interest; (7) sequential axial planes parallel to each other, similar to a sliced loaf of bread (i.e. no 'drifting spine' from the four-chamber view down to the stomach); (8) no azimuthal issues observed (i.e. atria/ventricles do not appear foreshortened in the four-chamber view); and (9) minimal or no motion artifacts (observed in the sagittal plane).

From all the STIC volumes determined to be appropriate by STICLoop, only a single volume per patient was chosen for analysis using the FINE method.

### Testing of the FINE method

Seven anatomical structures of the fetal heart, described previously[85], were marked using the feature Anatomic Box® to generate a geometrical model of the heart. These structures (in sequential order) are: (1) cross-section of the aorta at the level of the stomach; (2) cross-section of the aorta at the level of the four-chamber view; (3) crux; (4) right atrial wall; (5) pulmonary valve; (6) cross-section of the superior vena cava; and (7) transverse aortic arch. After marking had been completed, the following nine standard fetal echocardiography views were generated automatically and displayed by FINE (as diagnostic planes and/or VIS-Assistance)[85]: (1) four chamber; (2) five chamber; (3) left ventricular outflow tract; (4) short-axis view of great vessels/right ventricular outflow tract; (5) 3VT; (6) abdomen/stomach; (7) ductal arch; (8) aortic arch; and (9) superior and inferior venae cavae. Fetal echocardiography views are displayed simultaneously in a single template as nine diagnostic planes. VIS-Assistance may also be activated for each cardiac diagnostic plane to improve the success of obtaining the fetal echocardiography view of interest and to allow operator-independent sonographic navigation and exploration of surrounding structures in the diagnostic plane[85]. This tool was developed because the complex anatomy of the fetal heart and its anatomic variations may require additional interrogation of a given diagnostic plane[85]. VIS-Assistance 'scans' the STIC volume in a purposeful and targeted manner (in the form of a videoclip) with the goal of visualizing specific structures (i.e. a 'virtual' sonographer)[85].

Visualization rates for the nine fetal echocardiography views using diagnostic planes and/or VIS-Assistance were calculated. When necessary, the adequacy of a given echocardiography view was determined by comparison with the gold standard (view obtained by expert manual navigation of the STIC volume using 4D View (GE Healthcare)). In four cardiac VIS-Assistance views (3VT, left ventricular outflow tract, short-axis view of great vessels/right ventricular outflow tract and abdomen/stomach), we pre-specified that certain anatomical structures should also be visualized, in order to consider the VIS-Assistance as being successful in depicting the echocardiography view, as follows[85]: (1) 3VT: three-vessel view, pulmonary valve and transverse aortic arch view[86]; (2) left ventricular outflow tract: mitral valve, aortic valve, and ventricular septum; (3) short-axis view of great vessels/right ventricular outflow tract: pulmonary valve and tricuspid valve; and (4) abdomen/stomach: stomach and four-chamber view (to determine situs).

For the four-chamber view VIS-Assistance, we recorded how often the atrial septum (both septum primum and septum secundum) and pulmonary veins could be visualized when compared with the four-chamber view diagnostic plane. For each STIC volume dataset we also calculated the maximum number of fetal echocardiography views that were obtained successfully through diagnostic planes or VIS-Assistance and the success rate in obtaining four specific fetal echocardiography views (four chamber, left ventricular outflow tract, short-axis view of great vessels/right ventricular outflow tract and abdomen/stomach) through diagnostic planes or VIS-Assistance.

## RESULTS

### Acquisition of STIC volumes and evaluation by STICLoop

Of the 225 women undergoing sonographic examination between 19 and 30 weeks' gestation, 18 (8%) were excluded owing to: patient declining STIC volume acquisition or uncooperative ($n = 9$); suspected CHD or arrhythmia ($n = 4$); congenital anomaly ($n = 2$); anhydramnios/oligohydramnios ($n = 2$); and twin gestation ($n = 1$). Therefore, STIC acquisition of the apical four-chamber view was attempted in 207 pregnancies with a normal fetal heart (Figure 1). The median (interquartile range) gestational age for this group was 23.3 (20.6–26.2) weeks. Despite an attempt, 13% ($n = 27$) of women did not have a STIC volume acquired; the most common reason (81.5%; 22/27) was the fetal spine not being located between the 5- and 7-o'clock positions. Another 30 (14.5%) women had STIC volumes acquired that were subsequently discarded; the most common reason (36.7%; 11/30) was poor image quality secondary to maternal obesity. As a result, one or more STIC volumes ($n = 365$ total) were obtained successfully in 72.5% (150/207) of women undergoing ultrasound examination. A flowchart of the study population is given in Figure 1.

All 365 STIC volumes were saved onto the hard drive of the ultrasound machine and then evaluated by STICLoop. The number of volumes obtained per patient ($n = 150$) was: one, $n = 36$; two, $n = 42$; three, $n = 50$; four, $n = 17$; five, $n = 3$; and six, $n = 2$. Only 14 (3.8%) STIC volumes were determined to be inappropriate for FINE analysis, the most common reason being a 'drifting spine' visualized on STICLoop. From the 351 (96.2%) volumes determined to be appropriate, only a single volume per patient was selected for analysis using the FINE method (Figure 1). When multiple appropriate volumes were available per fetus, the volume dataset considered to be of highest

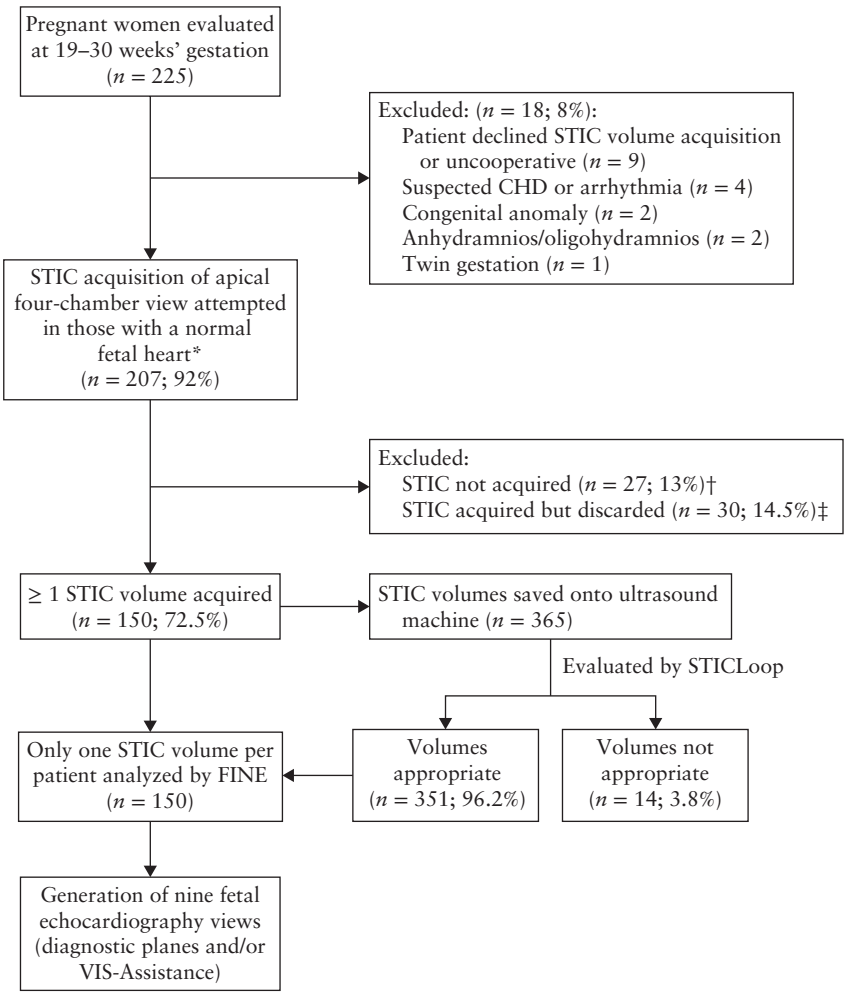


**Figure 1** Flowchart of study population. STICLoop™ aids user in determining appropriateness of spatiotemporal image correlation (STIC) volume datasets before implementation of Fetal Intelligent Navigation Echocardiography (FINE) method. *STIC acquisition attempted only if following criteria were met: fetal spine located between 5- and 7-o'clock positions; minimal or absent shadowing (including a clearly visible transverse aortic arch); absent fetal breathing, hiccups, or movement; and adequate image quality. †Most common reason was fetal spine not located between 5- and 7-o'clock positions. ‡Most common reason was poor image quality due to maternal obesity. CHD, congenital heart disease; VIS-Assistance, Virtual Intelligent Sonographer Assistance.

quality was chosen. Therefore, 150 STIC volumes of fetuses with normal hearts comprised the final study group. The majority of volumes ($n = 139$; 92.7%) in the study group had been obtained in an acquisition time of 10 s, while eight (5.3%) and three (2.0%) volumes were obtained in acquisition times of 12.5 s and 7.5 s, respectively. Twenty-five percent (38/150) of such fetuses were in breech presentation, so that the cardiac apex was originally pointing to the right side of the monitor screen.

### Performance of FINE in generating fetal echocardiography views

Testing the performance of the FINE method consisted of evaluating 1350 diagnostic planes (150 STIC volumes × 9) and 1350 VIS-Assistance videoclips (150 STIC volumes × 9), for a total of 2700 images. FINE was able to generate nine fetal echocardiography views in 76–100% of cases using diagnostic planes, 98–100% of cases using VIS-Assistance and 98–100% of cases using a combination of diagnostic planes and/or VIS-Assistance (Table 1). Figure 2 shows an example of the nine cardiac diagnostic planes in a single template with the additional feature of automatic labeling through intelligent navigation in a fetus at 19.4 weeks' gestation[85]. Such labeling occurs for the nine fetal echocardiography views (i.e. diagnostic planes), left and right side of the fetus, cranial and caudal ends, as well as the atrial chambers, ventricular chambers, great vessels (aorta and pulmonary artery), superior and inferior venae cavae and stomach. Videoclip S1 demonstrates the same nine cardiac diagnostic planes but without automatic labeling activated.

The maximum number of fetal echocardiography views successfully obtained through diagnostic planes or VIS-Assistance for each normal STIC volume dataset ($n = 150$) is shown in Table 2. For diagnostic planes, 130 (86%) STIC volumes demonstrated either eight ($n = 56$; 37%) or all nine ($n = 74$; 49%) echocardiography views, while 18 (12%) demonstrated seven views. For

**Table 1** Fetal Intelligent Navigation Echocardiography (FINE): success rates of obtaining nine fetal echocardiography views after applying intelligent navigation to 150 normal spatiotemporal image correlation (STIC) volume datasets using diagnostic planes and/or Virtual Intelligent Sonographer Assistance (VIS-Assistance)

| *Fetal echocardiography view* | *Diagnostic plane (n = 150)* | *VIS-Assistance (n = 150)* | *Diagnostic plane and/or VIS-Assistance (n = 150)* |
|---|---|---|---|
| Four-chamber | 148 (99) (95–99.9) | 150 (100) (97–100) | 150 (100) (97–100) |
| Five-chamber | 142 (95) (90–97) | 150 (100) (97–100) | 150 (100) (97–100) |
| LVOT | 150 (100) (97–100) | 150 (100) (97–100) | 150 (100) (97–100) |
| Short-axis view of great vessels/RVOT | 145 (97) (92–99) | 150 (100) (97–100) | 150 (100) (97–100) |
| 3VT | 124 (83) (76–88) | 147 (98) (94–99.6) | 147 (98) (94–99.6) |
| Abdomen/stomach | 150 (100) (97–100)* | 150 (100) (97–100)† | 150 (100) (97–100) |
| Ductal arch | 114 (76) (69–82) | 150 (100) (97–100) | 150 (100) (97–100) |
| Aortic arch | 145 (97) 92–99 | 150 (100) (97–100) | 150 (100) (97–100) |
| SVC/IVC | 133 (89) (82–93) | 150 (100) (97–100) | 150 (100) (97–100) |
| SVC | 144 (96) (91–98) | — | — |
| IVC | 138 (92) (86–95) | — | — |

Data are given as *n* (%) (95% CI). Wald method was used to calculate two-sided CIs for proportions expressed in the table; as the true proportion cannot exceed 100%, upper CIs were truncated at 100%. *Visualization of stomach in diagnostic plane. †Visualization of both stomach and four-chamber view in VIS-Assistance (to determine situs). 3VT, three-vessels and trachea; IVC, inferior vena cava; LVOT, left ventricular outflow tract; RVOT, right ventricular outflow tract; SVC, superior vena cava.

VIS-Assistance, 147 (98%) STIC volumes demonstrated all nine echocardiography views, while the remaining three (2%) demonstrated eight views.

For each normal STIC volume dataset ($n = 150$), the success rate of obtaining the four-chamber view, left ventricular outflow tract view, short-axis view of the great vessels/right ventricular outflow tract and abdomen/stomach view was 95% ($n = 143$) using diagnostic planes and 100% ($n = 150$) using VIS-Assistance.

### Comments about diagnostic planes and VIS-Assistance in normal fetuses

One of the anatomical structures to be marked in Anatomic Box is the right atrial wall. This is accomplished by clicking on the crux of the fetal heart, and then placing the preconfigured line (which appears next) over the ventricular septum[85]. The inferior portion of this line is angled towards the right atrial wall for subsequent marking by the operator. However, to improve the success rate of obtaining the left ventricular outflow tract in the diagnostic plane, we designed an alternative straight (as opposed to angled) line to mark the atrial wall[85]. In only 3% ($n = 4$) of the 150 cases described herein, we employed the straight line. When using either the straight or the angled line for marking the atrial wall, the left ventricular outflow tract diagnostic plane was obtained successfully in 100% ($n = 150$) of cases (Table 1). When using the angled line only to mark the right atrial wall, VIS-Assistance was able to demonstrate the left ventricular outflow tract successfully in 100% ($n = 150$) of cases (Table 1).

Figure 3 and Videoclip S2 show a fetus in which the ductal arch could not be obtained successfully using the diagnostic plane; however this view was obtained successfully using VIS-Assistance.

An advantage of the four-chamber view VIS-Assistance is that it allows visualization of the atrial septum (both septum primum and septum secundum) and pulmonary veins[85]. Both the septum primum and septum secundum were seen in 39% ($n = 59$) of cases in the four-chamber view diagnostic plane, but in 99% ($n = 149$) when VIS-Assistance was employed. However, the five-chamber view diagnostic plane was able to demonstrate the septum secundum successfully in the one case in which the four-chamber view VIS-Assistance did not. The pulmonary veins were seen in 63 (42%) cases in the four-chamber view diagnostic plane, but in 150 (100%) cases when VIS-Assistance was employed. For the abdomen/stomach VIS-Assistance, both the stomach and the four-chamber view were visualized in 100% ($n = 150$) of cases, so that situs could be determined (Table 1).

## DISCUSSION

### Principal findings of the study

The principal findings of this study are: (1) one or more STIC volumes of normal fetal hearts were successfully obtained in 72.5% (150/207) of women undergoing ultrasound examination between 19 and 30 weeks' gestation; (2) 351 (96.2%) STIC volumes evaluated by STICLoop were determined to be appropriate; (3) nine fetal echocardiography views were generated by the FINE method using a combination of diagnostic planes and/or VIS-Assistance in 98–100% of cases; (4) for each STIC volume dataset, 86% of volumes demonstrated either eight or all nine echocardiography views via diagnostic planes, while 98% of volumes demonstrated all nine echocardiography views via VIS-Assistance; and (5) for each STIC volume dataset, the success rate of obtaining four views (four chamber, left ventricular outflow tract, short-axis view of great vessels/right ventricular outflow tract, abdomen/stomach) was 95% and 100% using diagnostic planes and VIS-Assistance, respectively.

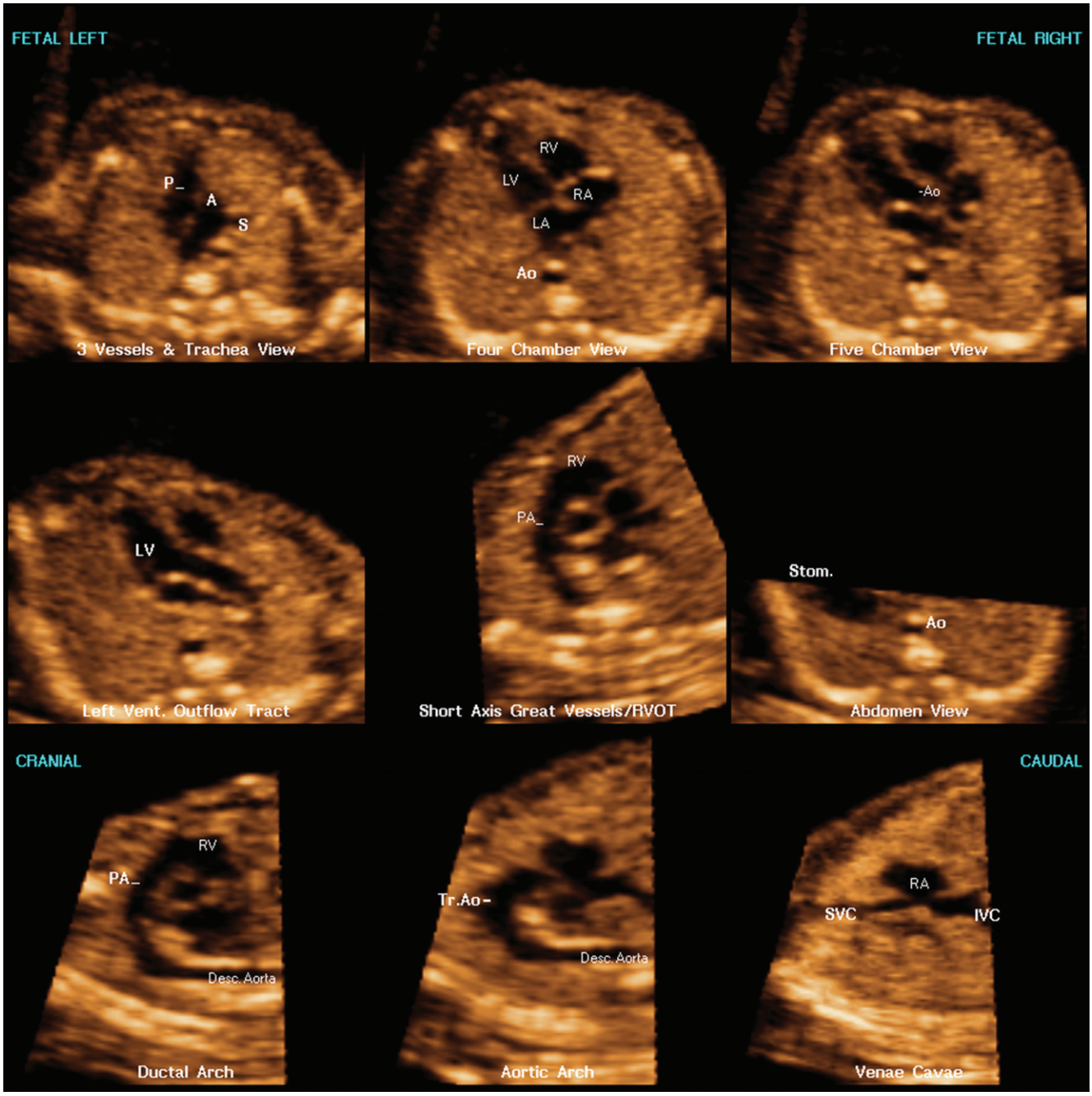


**Figure 2** Spatiotemporal image correlation (STIC) volume dataset of the fetal heart showing nine cardiac diagnostic planes with automatic labeling (through intelligent navigation) of each plane, anatomical structures, fetal left and right sides and cranial and caudal ends (also see Videoclip S1). The labeling is distinctive because it stays with the corresponding anatomical structure(s), even as the image is increased in size (zoomed). A, transverse aortic arch; Ao, aorta; Desc., descending; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; P, pulmonary artery; PA, pulmonary artery; RA, right atrium; RV, right ventricle; RVOT, right ventricular outflow tract; S, superior vena cava; Stom., stomach; SVC, superior vena cava; Tr., transverse; Vent., ventricular.

## Acquisition of STIC volumes: an important first step

STIC technology allows the acquisition of a complete volume dataset of the fetal heart, and displays a cine loop of a complete, single cardiac cycle in motion. However, to be an effective tool in fetal cardiac screening, 4D sonography with STIC should meet the following criteria: there should be appropriate *acquisition* conditions (e.g. fetal position) for STIC volumes to be successfully acquired and analyzed; volume datasets should be of *high quality* (i.e. informative); and volume acquisition must be *feasible* in clinical practice[87,88]. Moreover, 4D sonography with STIC should be accessible to operators, readily learned and acceptable to patients.

In this study, we report that, of women undergoing ultrasound examination between 19 and 30 weeks' gestation, STIC volume acquisition of normal fetal hearts is feasible almost 75% of the time. Moreover, no extra examination time was required. Various investigators have reported their success rate in obtaining STIC

 

**Table 2** Number of fetal echocardiography views obtained successfully through diagnostic planes or Virtual Intelligent Sonographer Assistance (VIS-Assistance) for each normal spatiotemporal image correlation (STIC) volume dataset ($n = 150$)

| *Number of views obtained (maximum = 9)* | *Diagnostic planes* (n = *150)* | *VIS-Assistance* (n = *150)* |
|---|---|---|
| 5 | 1 (1) | — |
| 6 | 1 (1) | — |
| 7 | 18 (12) | — |
| 8 | 56 (37) | 3 (2) |
| All 9 views | 74 (49) | 147 (98) |
| Total | 150 (100) | 150 (100) |

Data are given as *n* (%).

volume datasets in normal fetuses, and this ranged widely from 26% to 100%[32,39,41,42,48,57,75,87,89–97]. Such success rates depend on many factors (e.g. gestational age). However, probably the most important factor affecting the acquisition rate is the preset criteria/requirements for acquisition, and their degree of rigor. Such criteria may include specifics about fetal position, fetal movement and breathing, acoustic shadowing and what anatomical structures should be visualized before acquisition occurs.

STIC acquisition rates and/or the definition of an acceptable STIC are also affected by the aim of the study. For example, Schoonderwaldt *et al.*[96] evaluated fetal cardiac function and only accepted STIC volumes for analysis if they demonstrated clear demarcation of endocardial borders and there was absence of shadowing artifacts in all six planes. As a result of these rather strict criteria, many volumes were discarded, and the STIC acquisition rate ranged from only 26% to 55%, depending on the gestational-age window. In general, the greater the number and rigor of preset criteria/requirements, the lower the success rate will be.

We have defined here a set of criteria for acquiring STIC volumes to successfully generate nine fetal echocardiography views (an ambitious task). Yet, despite such criteria, our success rate for obtaining STIC volumes was still 72.5%. This is similar to the results of the study of Uittenbogaard *et al.*[87], who investigated the feasibility of incorporating STIC technology into a tertiary fetal echocardiography program. In cases in which an attempt was made, STIC volume acquisition was successful in 75.7% (112/148). Our STIC volume acquisition rate was accomplished within the normal timeframe specified for sonographic examination. Yet, if further time had been allowed, it is possible that the rate would have been higher, as others have shown[92]. Of course, it is expected that STIC volume datasets cannot be obtained successfully in all patients, therefore algorithms based upon 4D sonography with STIC would not be applicable in such cases.

Collectively, although studies certainly suggest that acquisition of STIC volume datasets is feasible, our view is that adequate and rigorous training should be implemented as an initial step. Such training should occur, regardless of the reasons that 4D sonography with STIC is being performed. This is because a far more critical issue is whether the STIC volume dataset is informative (i.e. ability to display various cardiac planes and structures), which can only occur if they are of high quality[87].

## Quality of STIC volume datasets

Acquiring an appropriate STIC volume is a requirement for its successful display and analysis[87], and proper

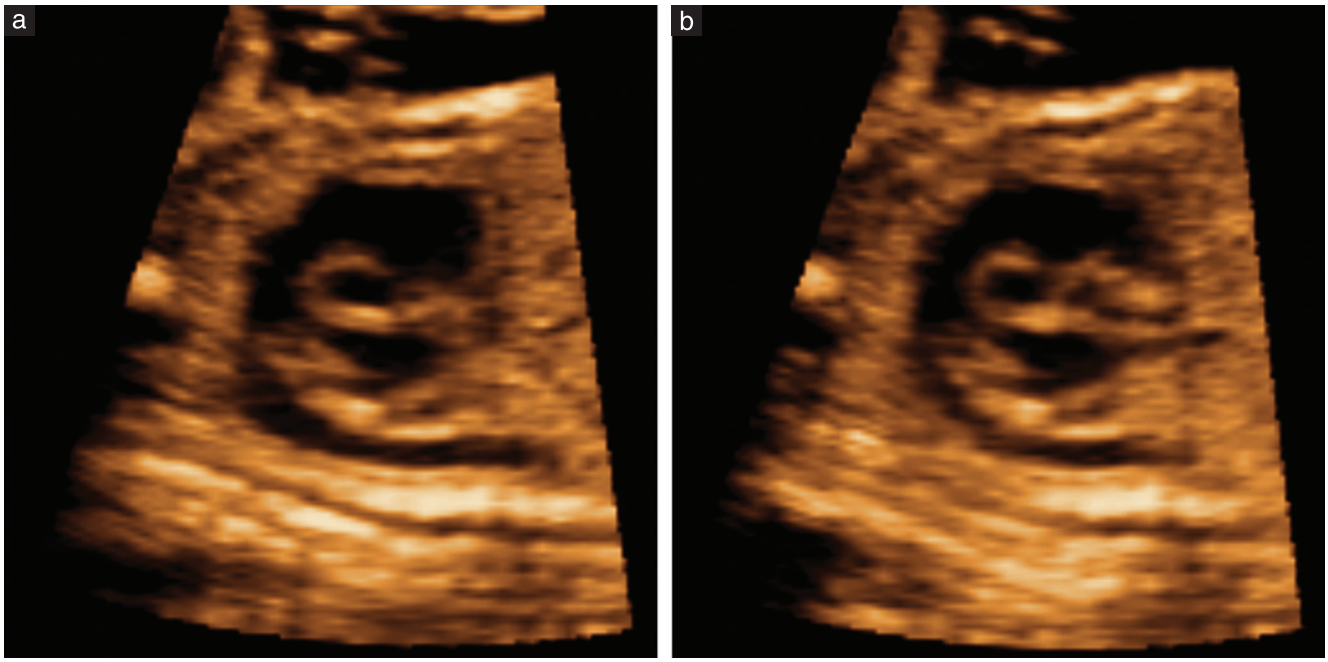


**Figure 3** Spatiotemporal image correlation (STIC) volume dataset of the fetal heart showing ductal arch view through the FINE method. Due to some overlap with the aortic arch, the ductal arch was not obtained successfully using the diagnostic plane (a), but was obtained successfully (automatically) using Virtual Intelligent Sonographer Assistance (VIS-Assistance) (b). See Videoclip S2.

acquisition is essential for performing FINE[85]. For our study, we developed a set of criteria to be met before considering that a STIC acquisition was 'successful'. The purpose was to allow the highest quality volume datasets to be captured. Indeed, of 365 STIC volumes saved, an overwhelming majority (96.2%) were determined to be appropriate using STICLoop. This is beneficial because immediate feedback as to whether a volume is appropriate is provided to the operator. Indeed, Viñals[84] reported that various factors influence the success of a protocol for STIC volume acquisition, one of which is whether there is a standardized acquisition technique with feedback regarding technical errors.

### Are STIC volume datasets informative?

The FINE method has been proposed as an aid for examining the fetal heart in the population at large[85]. Thus, it follows that we would implement strict criteria for STIC acquisition, maximizing the chance that volumes are informative (i.e. demonstrate nine fetal echocardiography views). Indeed, this is reflected in our results, in which FINE generated nine echocardiography views in 76–100% of cases using diagnostic planes, and in 98–100% of cases using VIS-Assistance, from volumes obtained prospectively during sonographic examination. This is very similar to our initial report on the FINE method, which was tested on previously obtained volume datasets in our collection[85]. Our results were achieved by carefully following preset criteria to acquire and select STIC volumes, marking anatomical structures appropriately using Anatomic Box, and recognizing cardiac anatomy.

Analysis of STIC volume datasets by manually using controls to interrogate and retrieve the cardiac views required for prenatal diagnosis is highly operator dependent and challenging. To address this, investigators have developed algorithms to examine such volume datasets so that information can be retrieved both systematically and efficiently[29,30,36,39,43,47,49]. Abuhamad *et al.*[98] were the first to describe an algorithm for the automatic display of diagnostic cardiac planes from a three-dimensional static or STIC volume dataset following initial standardization in the acquisition plane. Such technology can standardize and simplify sonographic examination of the fetal heart by decreasing operator dependency.

By applying intelligent navigation technology to STIC volume datasets of normal fetal hearts, the FINE method successfully results in the display of nine standard fetal echocardiography views in the second and third trimesters. It also allows operator-independent sonographic navigation and exploration of the surrounding structures in each of the nine cardiac diagnostic planes (VIS-Assistance). Other unique features of the method (e.g. automatic labeling of anatomical structures) have been described extensively elsewhere[85].

Although the current study did not focus on CHD, we have reported previously that in such cases, the FINE method demonstrates abnormal fetal cardiac anatomy (evident in multiple cardiac views simultaneously in a single template)[85]. Future studies should further elucidate the value of the FINE method in other cases of complex CHD.

### Conclusion

In conclusion, STIC volumes may be obtained successfully in approximately 75% of pregnancies with normal fetal hearts undergoing sonographic examination. By applying the FINE method to such volumes, nine standard fetal echocardiography views can be generated using a combination of diagnostic planes and/or VIS-Assistance in 98–100% of patients, suggesting that FINE could be implemented in fetal cardiac screening programs. Whether implementation of the method described here translates into improving the prenatal detection of CHD is an important question, and remains to be determined.

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An application for a patent ('Apparatus and Method for Fetal Intelligent Navigation Echocardiography') has been filed with the US Patent and Trademark Office and the patent is pending. Dr Lami Yeo and Dr Roberto Romero are co-inventors, along with Mr Gustavo Abella and Mr Ricardo Gayoso. The rights of Dr Yeo and Dr Romero have been assigned to Wayne State University, and NICHD/NIH, respectively. None of the authors has a financial relationship with either GE Healthcare, Milwaukee, WI or Medge Platforms, Inc., New York, NY.

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## SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:

**Videoclip S1** Nine cardiac diagnostic planes displayed automatically in a single template by Fetal Intelligent Navigation Echocardiography (FINE) (see Figure 2).

**Videoclip S2** Ductal arch view (VIS-Assistance). The panel on the left shows that, due to some overlap with the aortic arch, the ductal arch was suboptimally obtained using the diagnostic plane. VIS-Assistance is then activated, and through automatic navigational movements, the ductal arch was successfully obtained (see Figure 3).

 