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REVIEW ARTICLE

4D Fetal Echocardiography in Clinical Practice

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ABSTRACT

Spatiotemporal image correlation (STIC) is a technique that acquires the fetal cardiac volumes, and then analyzes it offline in both multiplanar and rendered modes, using both static and moving images from a four-dimensional (4D) cine sequence simulating a full cardiac cycle. Spatiotemporal image correlation makes it possible to evaluate cardiac structures and their vascular connections, is less operator dependent, and allows cardiac volumes to be sent to specialists in tertiary centers for examination. Spatiotemporal image correlation can be combined with other software techniques, such as virtual organ computer-aided analysis (VOCAL) and automatic volume calculation (SonoAVC), to calculate cardiac function parameters. It can also be used in association with Omniview® in order to obtain standard echocardiographic planes using simple targets arterial rendering (STAR) and four-chamber view and swing technique (FAST). Recently, fetal intelligent navigation echocardiography (FINE), acquired from 3D STIC volumes, has made it possible to automatically obtain nine standard echocardiographic planes. In this article, we review the chief applications of 4D echocardiography using STIC technique in clinical practice.

Keywords: Automatic volume calculation, B-flow imaging, Congenital heart disease, Fetal intelligent navigation echocardiography, HDlive, Inversion mode, Omniview®, Spatiotemporal image correlation, Tomographic ultrasound imaging, Virtual organ computer-aided analysis.

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INTRODUCTION

Congenital heart disease (CHD) is one of the most frequent forms of congenital malformations, affecting 0.3 to 1.2% of all live births.[1,2] It has been proven that prenatal CHD diagnosis improves postnatal prognosis because pregnant women are referred to tertiary centers with specialized cardiac and neonatal cardiac surgery teams.[3] Because most CHD cases arise in low-risk groups,[4] CHD screening during the second-trimester ultrasound examination is very important so that positive cases can be referred for conventional bidimensional echocardiography, the gold standard for prenatal CHD diagnosis.[4] However, echocardiography is a complex examination that is performed by few professionals and is operator dependent. These limitations have led to a constant search for new and simpler diagnostic methods that would be accessible to a larger number of professionals and are less operator-dependent.[5]

The introduction of three- and four-dimensional (3D/4D) ultrasound in obstetric practice led to a new method for assessing fetal cardiac anatomy: spatio-temporal image correlation (STIC), a new technique for acquiring images of the fetal heart. Cardiac volumes can be acquired in three or four dimensions and stored for later reconstruction and detailed anatomical analysis. Images are displayed in multiplanar and render modes, showing the position of the blood vessels and their intimate relationship with cardiac cavities (atria and ventricles). Cardiac movements can also be evaluated using the cine loop technique.[6-8]

Spatiotemporal image correlation also uses some existing conventional ultrasound applications, such as grayscale and color Doppler. Grayscale offers a better view of the left and right ventricular outlets and the aortic and ductal arches,[6] whereas color Doppler offers a better view of the location and extent of interventricular septal defects.[9] New techniques, such as the inversion mode and B-flow imaging, have been developed along with 3D technology to improve tracking of certain CHDs.[10,11]

Spatiotemporal image correlation also allows cardiac function to be assessed by measuring ventricular volume, because this measurement can provide important information about anatomical and functional aspects of CHDs. Spatiotemporal image correlation permits the calculation of stroke volume, ejection fraction, and cardiac output.[12-14] Recently, the STIC-M-mode technique (STIC-M) has also been applied to assess fetal cardiac function using the shortening fraction and tricuspid annular plane systolic excursion (TAPSE).[15,16]

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Recently, STIC's diagnostic capabilities have been evaluated for use in CHD. Spatiotemporal image correlation combined with other techniques, such as color Doppler, tomographic ultrasound imaging (TUI), B-flow imaging, and HDlive, has yielded better assessment of cardiac anatomy compared to conventional bidimensional echocardiography.[17-21] Moreover, new technologies, such as Omniview® (General Electric Medical Systems, Zipf, Austria), by using simple targets arterial rendering (STAR) and four-chamber view and swing techniques (FAST),[22,23] and fetal intelligent navigation echocardiography (FINE)[24,25] are available in the clinical practice.

This chapter aims to describe the STIC technique and its applications in the evaluation of cardiac function, diagnosis of CHD, and other applications in fetal cardiology.

Acquiring Fetal Cardiac Volumes using the STIC Technique

Only a few ultrasound devices with 3D/4D technology feature STIC software; these are fitted with convex transducers with automatic scanning. Volumes may be acquired through endovaginal or transabdominal scans. It should be stressed that early in the pregnancy, particularly in obese patients, endovaginal scanning is indicated to improve the sensitivity of the examination.[26]

The four-chamber plane is preferred for the scans, performed in the transversal section of the fetal thorax and abdomen. In order to obtain a superior-quality cardiac image, the fetal spine should ideally be positioned at 6 o'clock in an apical four-chamber plane. If the fetus' back is facing forward, sections where the spine is between 11 o'clock and 1 o'clock should be avoided, because this position increases the acoustic shadow over the heart. Instead, the transversal four-chamber plane should be used.

The angle of image acquisition may vary from 10 to 45° depending on the gestational age at which the study is performed; 20 to 25° is more appropriate for the 2nd trimester, and 35 to 40° for the 3rd trimester. The scanning time for acquiring the volume varies from 7.5 to 15 seconds. A slower capture tends to produce better image quality, but when the fetus is active, a shorter time ensures better image resolution.[27] When acquiring cardiac volume, the mother should be asked to hold her breath for a few moments, and the operator should wait for less fetal movement, which will ensure better quality in the cardiac volumes acquired.

For storing the acquired cardiac volumes, a standard procedure has been devised so that the physician responsible for offline analysis is aware of the actual position of the cardiac chambers relative to the fetal axis and the right and left sides. According to Paladini,[28] whenever the fetus is in a vertex or cephalic position, one should consider that the side of the heart corresponds to that side in the fetus, as opposed to a fetus in breech position, where the sides are reversed.

After capturing the four-chamber section, the device automatically provides the image in the three orthogonal planes (axial, sagittal, and coronal) in the multiplanar mode. In the axial plane (plane A, located in the upper left), the four-chamber section itself is viewed, while the other cardiac sections are viewed in the sagittal plane (plane B, in the upper right) and in the coronal plane (plane C, in the lower left). In render mode, cardiac texture can be evaluated, including the valves and the relationship between the chambers and their vessels (Fig. 1). Cardiac movement can also be analyzed for an entire cycle when the cine loop function is activated.[6-8] Measurements of cardiac vascularization, particularly the outflows of the left and right ventricles, the aortic and ductal arches, can also be obtained when the x, y, and z axes are rotated. Additionally, through TUI all of the heart's axial planes can be viewed on the screen, from the upper abdomen to the top of the thorax (Fig. 2). In order to acquire images of the outlets of great vessels, the following steps should be performed: (1) the volume should be rotated around the z axis so that the base of the heart is located at 6 o'clock and the point of reference is shifted to the crux of the heart; (2) the volume should be rotated 30° to the right on the z axis; (3) the point of reference should be displaced to the midpoint of the ventricular septum; (4) plane A should be slightly rotated around the y axis; this will open continuity between the

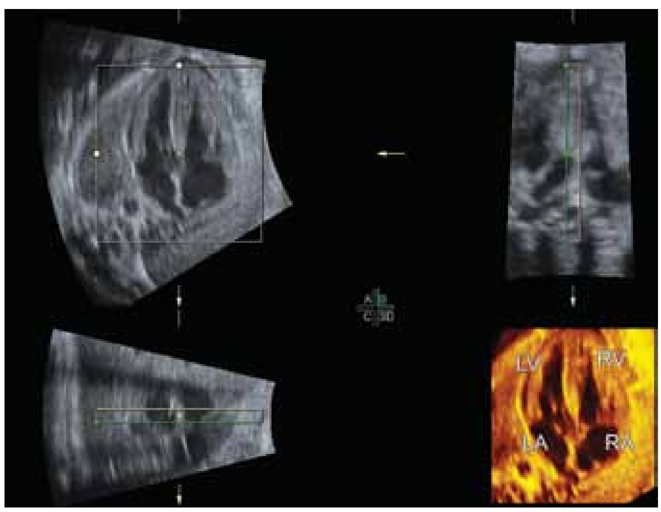


Fig. 1: Technique for obtaining a rendering of the cardiac chambers using spatiotemporal image correlation: after capturing volume in the four-chamber plane, the ROI (green line) should be positioned in plane B in a thin slice from right to left, automatically obtaining the rendered image of the four cardiac chambers (RA: Right atrium; RV: Right ventricle; LA: Left atrium; LV: Left ventricle)

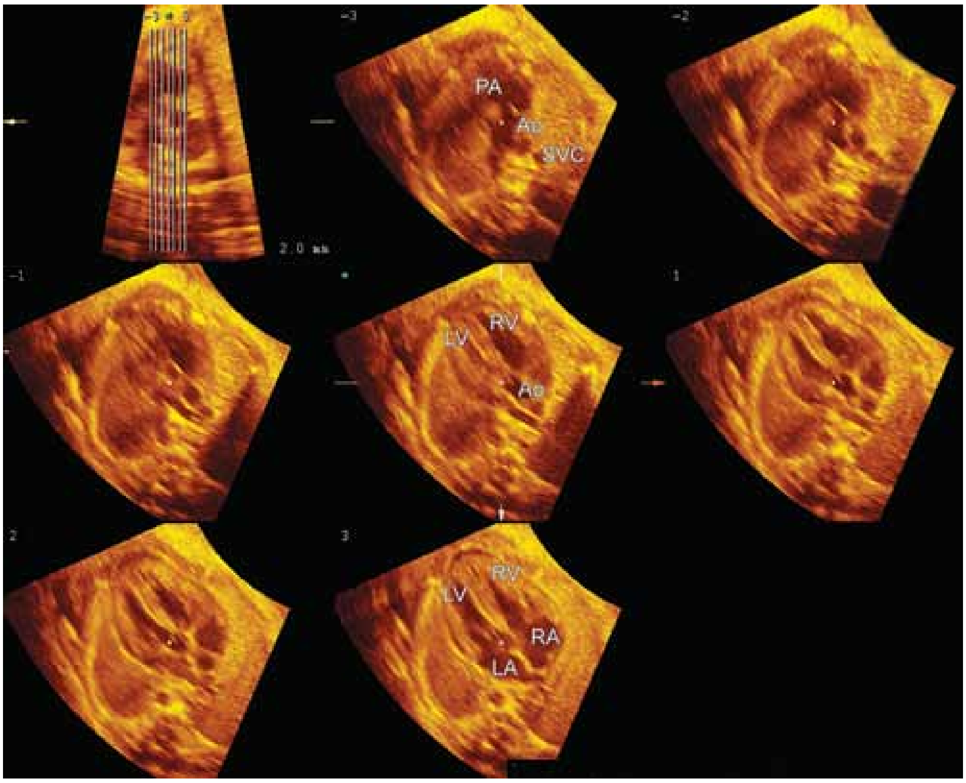


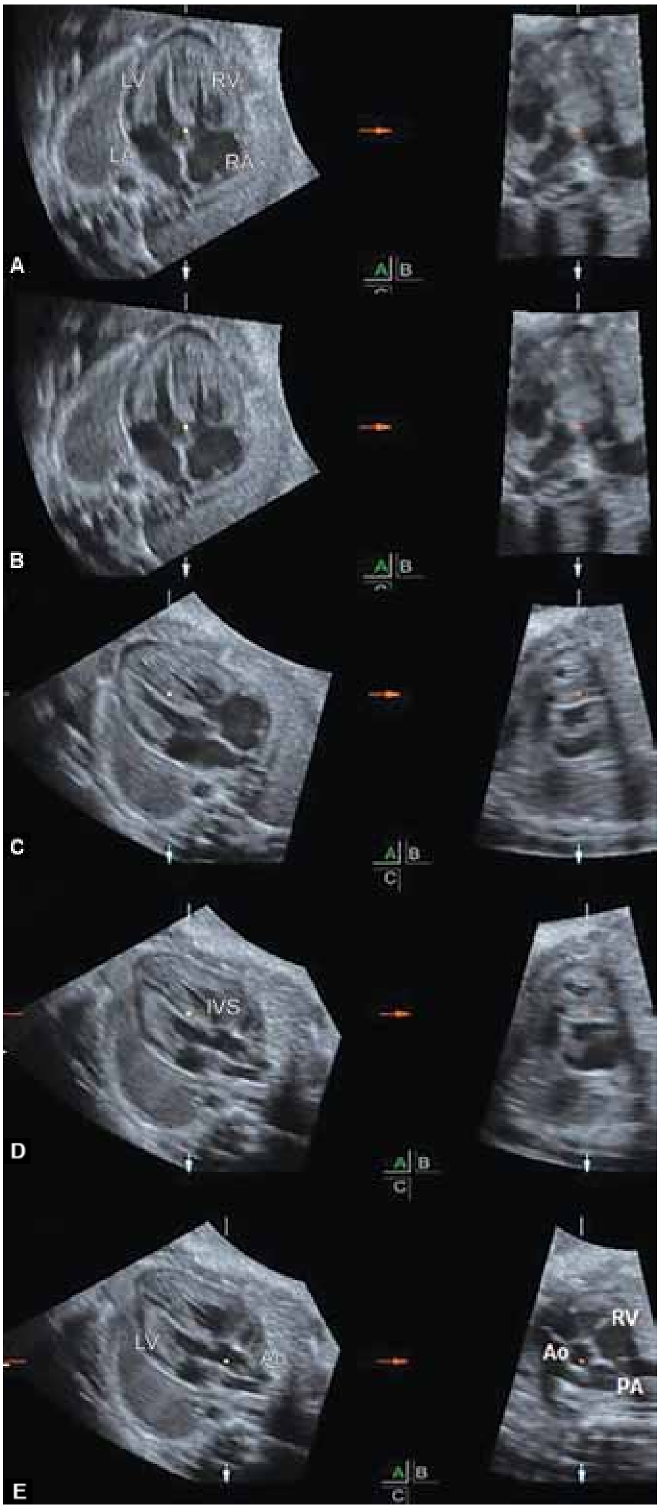
Fig. 2: Technique for obtaining standard echocardiographic planes using the tomographic ultrasound imaging (TUI) method. The plane of the ductal arch is used for reference (overview image). The plane marked with an asterisk (*) is placed in the middle point of the ascending aorta. Six new planes are defined: three to the right and three to the left of the plane marked with an asterisk (*), each spaced 2.0 mm from the other. Seven new echocardiographic planes are automatically obtained, such as three vessels plus trachea, left ventricle outlet, and four chambers (PA: Pulmonary artery; Ao: Aorta; SVC: Superior vena cava; LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium)

ventricular septum and the anterior wall of the aorta; (4) the reference point should be displaced to below the aortic valve. This will obtain the outflow of the aorta in plane A and the outflow of the pulmonary artery in plane B (Figs 3A to E). In order to evaluate the aortic and ductal arches, the following steps should be performed: (1) align the crux of the heart with the aorta and relocate the point of reference to the crux of the heart; (2) relocate shift the point of reference to the center of the aorta, which will automatically place the aortic arch in plane B (Fig. 4A); (3) after the point of reference is relocated to the center of the aorta, this structure is positioned longitudinally; by slightly rotating plane C in the z axis so that the aorta is positioned horizontally, the ductal arch appears in plane B (Figs 4B and C). In order to view the crossing of the major vessels using color Doppler, the volume capture must be performed with this feature activated; later, the region of interest (ROI, green line) positioned in plane B is selected in the anterior-to-posterior direction (from the pulmonary artery to the aorta and ventricles). The rendered image will then show the crossing of the major vessels at the base (Fig. 5). In order to render the cardiac structures, after the capture the ROI should be positioned in plane A as a thin slice. Figure 6 shows a front-facing view of the mitral and tricuspid valves.

Inversion Mode and B-flow Imaging

Inversion mode is a postprocessing technique that inverts the grayscale (i.e. echogenic voxels become anechoic) to evaluate liquid structures. The reconstructed volumetric image can be rotated in different viewing perspectives, with a more detailed anatomical view. Inversion mode provides a new way of evaluating the spatial relationships between liquid structures, which may be difficult to characterize by only reviewing a few image planes.[29]

A study by Espinoza et al[30] evaluated inversion mode for viewing the spatial relationships in fetal venous connection abnormalities (interruption of the inferior vena cava with azygos or hemiazygos continuation, associated or not with heterotaxic syndromes). These authors examined three fetuses with interruption of the inferior vena cava and azygos continuation and one fetus with no cardiac abnormalities. A sagittal volumetric acquisition plane of the thorax and upper abdomen was used. The ROI was positioned in the anteroposterior projection of the sagittal plane, with a threshold filter between 70 and 90. The images showed the azygos vein ascending to the right of the aorta, the arch of the azygos vein entering the superior vena cava, and the spatial relationship between the azygos vein, the aortic arch, the descending aorta, the



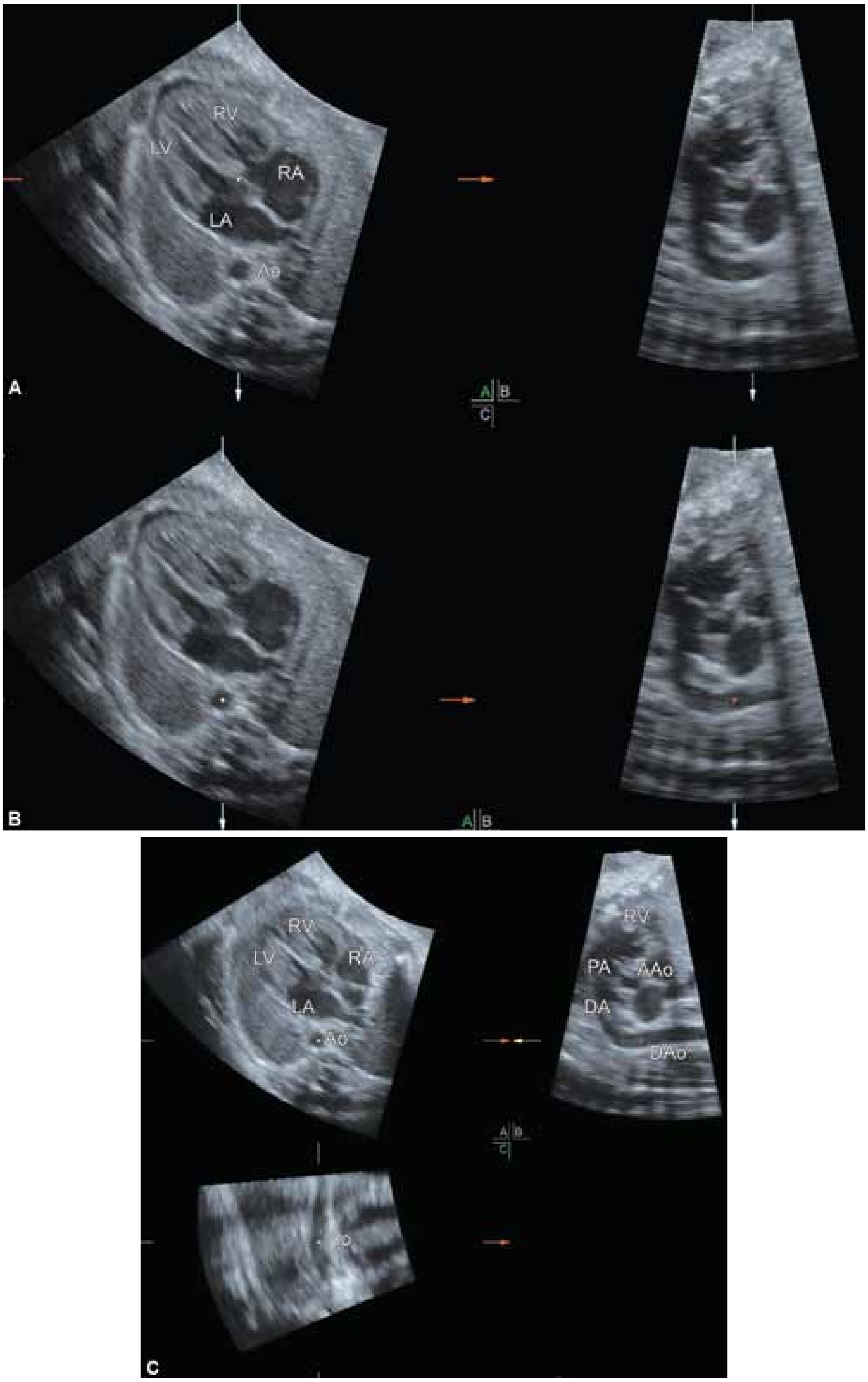
Figs 3A to E: Technique for obtaining the outlets of the major vessels in the fetal heart using spatiotemporal image correlation: (A) the volume should be rotated around the z axis so that the base of the heart is positioned at 6 o'clock and the reference point is shifted to the crux of the heart; (B) the volume should be rotated 30° from the z axis to the right; (C) the reference point should be shifted to the midpoint of the ventricular septum; (D) plane A should be slightly rotated on the y axis; this will create continuity between the ventricular septum and the front wall of the aorta; (E) the reference point should be shifted to below the aortic valve; this will display the aortic outlet in plane A and the pulmonary arterial outlet in plane B (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; IVS: Interventricular septum; Ao: Aorta; PA: Pulmonary artery)

right atrium, and the fetal spine. The ultrasound findings were postnatally confirmed during surgical correction of pulmonary stenosis. The authors concluded that inversion mode provided a view of the dilated azygos and hemiazygos veins, as well as their spatial relationship with the descending aorta, aortic arch, superior vena cava, right atrium, and fetal spine in cases of interruption of the inferior vena cava, whether this was associated or not with heterotaxic syndromes.

Ghi et al[31] reported a case of an isolated muscular-type defect of the ventricular septum in a 21-week fetus, using STIC with inversion mode. Volume acquisition was performed by a transversal scan at the level of the four-chamber plane. The diastolic blood flow between the ventricles through the defect was viewed as a hyperechogenic flap bridging. By measuring the diastolic depth of the bridge, the area of the septal defect was obtained (0.057 mm^2) (Fig. 7).

B-flow imaging is a technique that features better resolution with a high frame rate in grayscale. The periphery of the small vessels can be shown because the signals reflected by the blood cells are directly visible.[11] B-flow enhances the weak signals reflected by blood cells, while also suppressing the strong signals from neighboring tissue. Because this technology does not use Doppler methods, it is not angle-dependent, and does not interfere with the frame rate as do color and power Doppler. Because of its high sensitivity and angle independence, B-flow is potentially better than Doppler techniques for viewing the major vessels and venous return to the heart.[11] B-flow's chief applications are in evaluating the cardiac chambers, the outlets, the aortic and ductal arches, and fetal venous return.[32]

Volpe et al[32] analyzed whether B-flow imaging associated with STIC added any important information to bidimensional ultrasound findings in prenatal diagnosis of isolated total anomalous pulmonary venous connections. Seven fetuses with isolated total anomalous pulmonary venous connections were examined: three using only grayscale and color Doppler bidimensional echography, and four via echocardiography with STIC and B-flow imaging. Echocardiography alone did not permit a diagnosis of isolated total anomalous pulmonary venous connections in two of the seven cases. In the three cases examined by echocardiography and re-examined by STIC with B-flow, the course and individual measures of each pulmonary vein could be clearly viewed, as well as the confluence of the pulmonary veins and the vertical ascending and descending veins originating from these veins. Spatiotemporal image correlation with B-flow revelead the detailed anatomy of the anomalous venous return trajectory, providing additional information that was more than echocardiography alone (Fig. 8).



Figs 4A to C: Technique for obtaining the aortic and ductal arches in the fetal heart using spatiotemporal image correlation: (A) align the crux of the heart with the aorta and relocate the point of reference to the cross of the heart; (B) relocate the reference point to the center of the aorta, which will automatically place the aortic arch in plane (B and C) after the reference point is relocated to the center of the aorta, the latter is positioned longitudinally; slightly rotating plane C in the z axis so that the aorta is positioned horizontally, the ductal arch appears in plane B (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; Ao: Aorta; AAo: Ascending aorta; DAo: Descending aorta; DA: Ductus arteriosus; PA: Pulmonary artery

Evaluation of Cardiac Function using STIC

The first study that aimed to determine fetal cardiac function by measuring ventricular volume with STIC was performed by Messing et al.[12] The authors used virtual organ computer-aided analysis (VOCAL) as the volumetric technique, associated with inversion mode. A 100 fetuses aged between 20 and 40 weeks were examined, their ventricular volumes obtained by

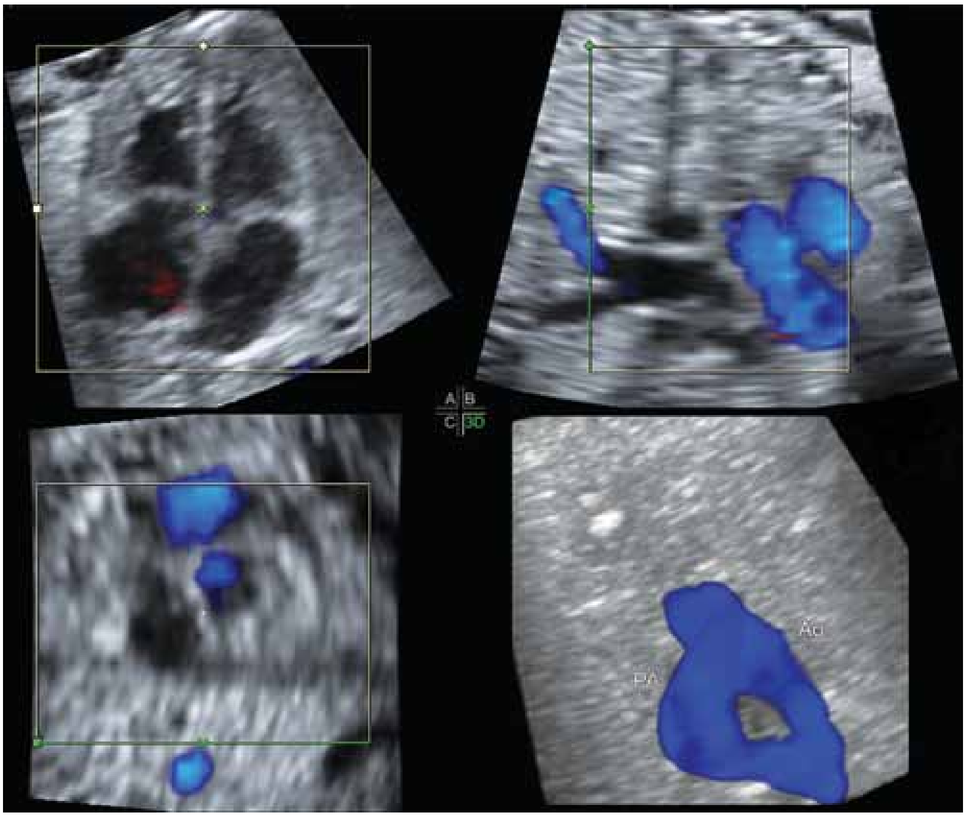


Fig. 5: Technique for obtaining the crossing of the great vessels using color Doppler with spatiotemporal image correlation: the volume capture should be performed with this feature on; later, the region of interest (ROI, green line) positioned in plane B is selected in the anterior to posterior direction (from the pulmonary artery to the aorta and ventricles). The rendered image will then show the crossing of the great vessels of the base (Ao: Aorta; PA: Pulmonary artery)

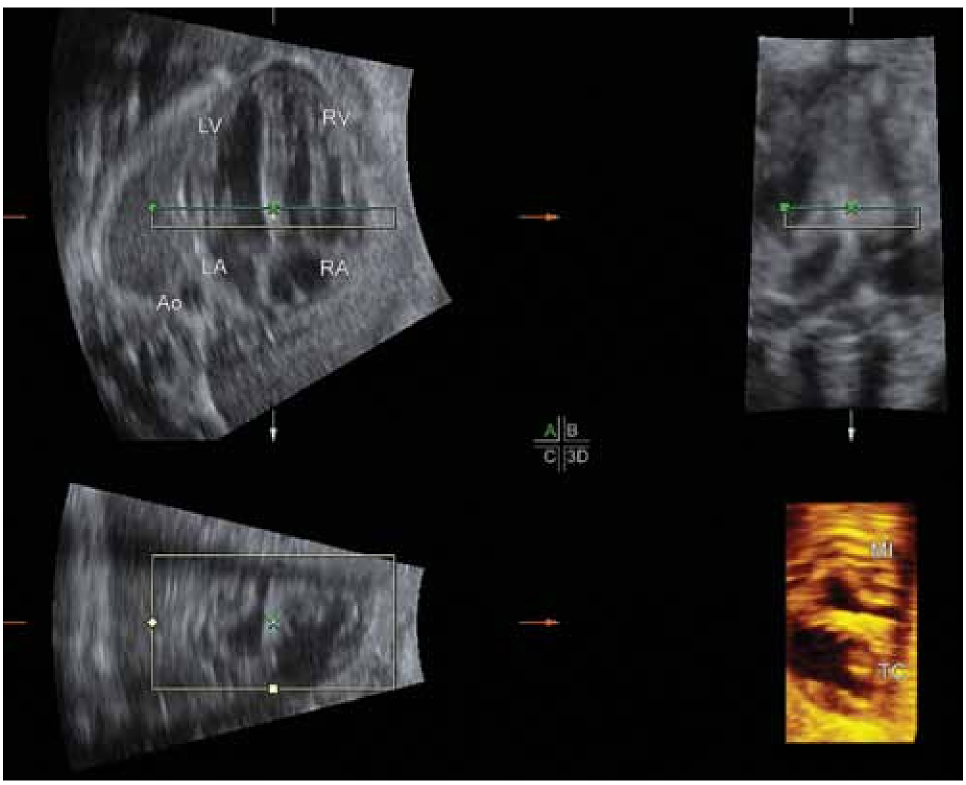


Fig. 6: Front-facing view of the fetal mitral and tricuspid valves using spatiotemporal image correlation, in rendering mode. Plane A (four chambers) is selected for reference and rotated around the z axis so that the apex is positioned at 12 o'clock. The region of interest (ROI, green line) is positioned in a thin slice from the ventricles at the level of the crux of the heart, automatically obtaining the rendered image of the mitral and tricuspid valves (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; Ao: Aorta; MI: Mitral valve; TC: Tricuspid valve)

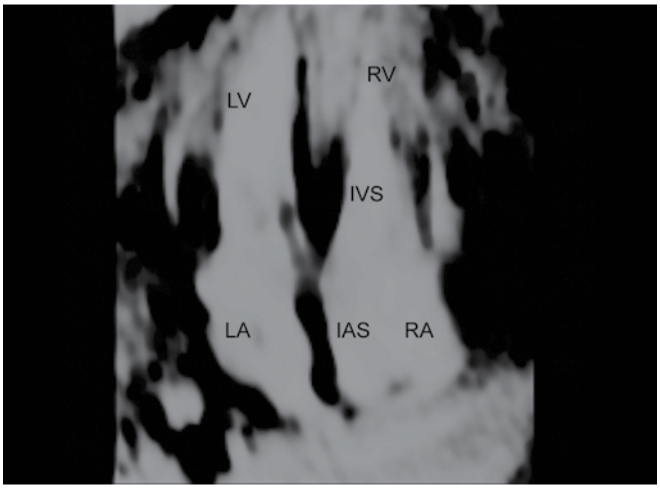


Fig. 7: Four-chamber image obtained by spatiotemporal image correlation, with inversion mode postprocessing. Note that due to the grayscale inversion, the blood present in the cardiac chambers becomes hyperechogenic, while the interatrial and interventricular septa become anechoic (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; IVS: Interventricular septum; IAS: Interatrial septum)

the combined use of these techniques, and the volumes used to calculate ejection fraction and cardiac output. For VOCAL, a 15° rotation angle was used; the ventricles were manually delimited, including the myocardium, and inversion mode provided the cavity volume. The ventricles were measured in both systole and diastole. The authors observed a mean final diastolic volume for the left ventricle between 0.53 cm^3 in the first half of pregnancy (20–24 weeks) and 3.96 cm^3 at term (36–40 weeks); the mean final systolic volume varied between 0.17 cm^3 and 1.56 cm^3. For the right ventricle, mean final diastolic volume varied from 0.68 cm^3 in mid-pregnancy to 5.44 cm^3 at term; mean final systolic volume varied from 0.26 cm^3 to 2.29 cm^3 at term. Mean total systolic volume varied from 0.78 cm^3 to 5.5 cm^3. All these parameters strongly correlated with gestational age and estimated fetal weight; however, ejection fraction remained relatively stable throughout pregnancy.

In another study, Molina et al[13] determined reference values for systolic volume and cardiac output with STIC, using VOCAL as the volumetric method and a 30° angle (Fig. 9). The authors evaluated 140 single pregnancies with normal fetuses between 12 and 34 weeks. Each ventricle was manually outlined, and the volume of both right and left ventricles was determined, in both systole and diastole. The systolic volume was determined for each ventricle by subtracting the volume obtained at the end of diastole from that obtained at the end of systole. Cardiac output was defined as the product of the systolic volume and fetal heart rate. The values for both left and right systolic volume and cardiac output exponentially increased as pregnancy progressed, with respective means of 0.02, 0.01, 2.39, and 1.80 ml/min in the 12th week; 0.30, 0.32, 43.46, and 46.72 ml/min in the 20th week; and 2.07, 2.67, 284.71, and 365.99 in the 34th week.

Simioni et al[33] performed a transversal section study on 265 normal pregnant women to evaluate fetal cardiac function using STIC. Virtual organ computer-aided analysis was used as the volumetric technique for measuring the ventricles, with a 30° rotation angle. The mean left and right total systolic volumes varied respectively from 0.211 to 0.220 ml in the 20th week and from 1.925 ml to 2.043 ml in the 34th week. The mean left and right cardiac output varied respectively from 30.25 ml/min to 31.52 ml/min in the 20th week, and from 268.49 ml/min to 287.80 ml/min in the 34th week. Both left and right ejection fractions remained constant, around 0.63 throughout the pregnancy.

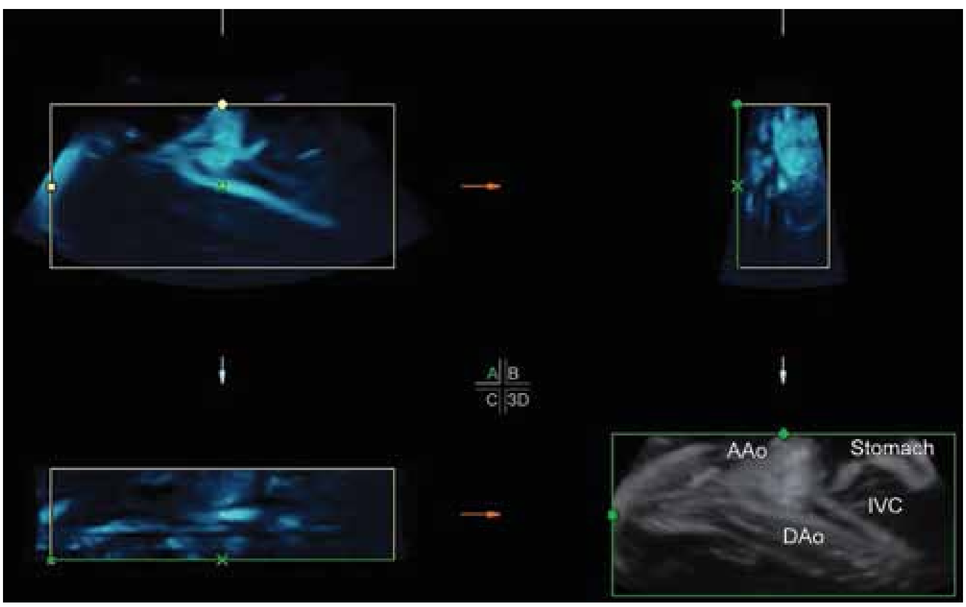


Fig. 8: Reconstruction of the fetal heart and its vascular connections using B-flow imaging (AAo: Ascending aorta; DAo: Descending aorta; IVC: Inferior vena cava)

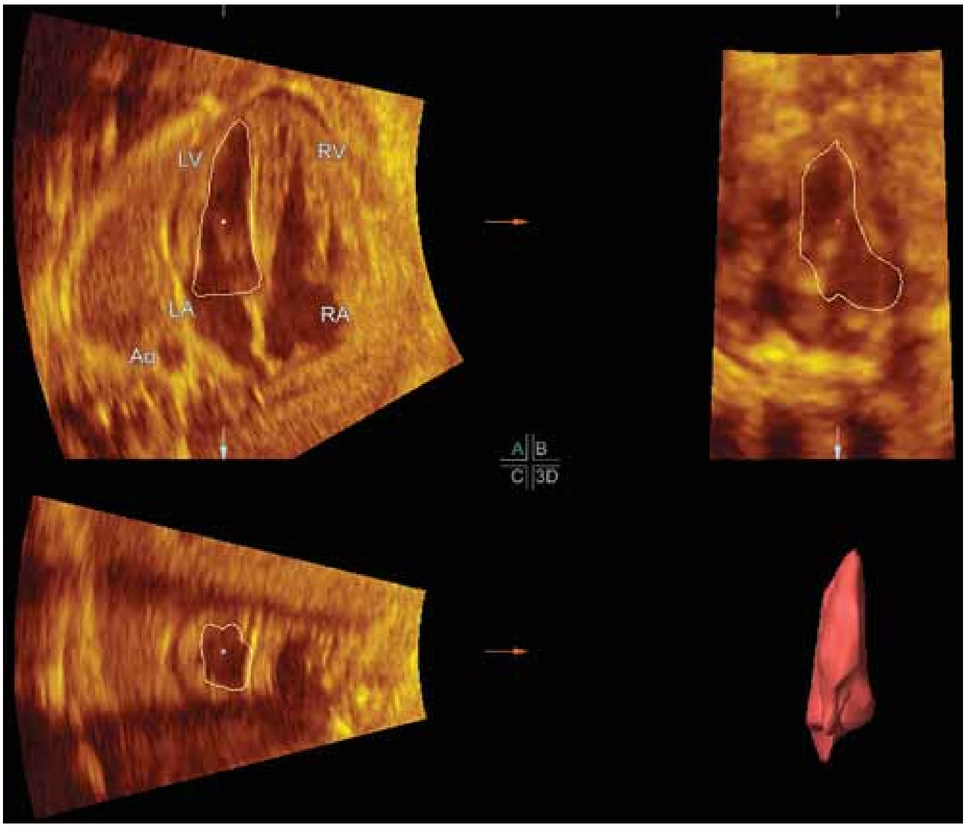


Fig. 9: Evaluation of left ventricular volume at the end of diastole by the virtual-organ computer-aided analysis method, with a 30° rotation. The measurement calibrators are positioned at the apex and the base of the ventricle, with the latter's outer surface manually delimited. After delimiting six sequential and adjacent planes, the device provides the reconstructed image of the structure as well as its volume

Rizzo et al[34] performed a study comparing fetal ventricular volume using the VOCAL and automatic volume calculation (SonoAVC) methods. These authors examined 45 fetal hearts, 30 of which were normal and 15 had congenital anomalies, with gestational ages between 19 and 32 weeks. Cardiac volumes were acquired using STIC, with the four-chamber plane as reference and angles between 20 and 25°. The total systolic volume was obtained by subtracting the volume at the end of diastole from that at the end of systole. For the VOCAL method, a 15° rotation angle was used. For SonoAVC, the smallest possible ROI was used, and the 'separation' and 'growth' parameters were moderated for all measurements. It was possible to obtain all volumes using both techniques. Systolic and diastolic volumes measured by VOCAL were significantly greater than those measured by SonoAVC. However, total systolic volumes were not significantly different. The time needed to obtain the total systolic volume was significantly shorter with SonoAVC than with VOCAL. Both techniques were highly reproducible by both intra- and interobservers.

When evaluating fetal cardiac function using STIC associated with M-mode (STIC-M), two parameters stand out: shortening fraction and TAPSE. Tongsong et al[15] proposed that reference curves be built for shortening fraction using STIC-M. This study examined normal fetuses and others with hydrops fetalis secondary to Bart hemoglobinopathy (alpha thalassemia) or CHD. The authors found different shortening fraction values when they compared fetuses with hydrops fetalis resulting from diseases that cause low cardiac output CHD to fetuses with hydrops resulting from diseases that cause high cardiac output (fetal anemia). Fetuses with CHD presented a greater degree of contractile function impairment when compared to fetuses with anemia. The authors concluded that myocardial dysfunction and cardiac decompensation are the primary causes of hydrops fetalis in fetuses with CHD, but that hypervolemia is the leading factor for the appearance of hydrops in fetuses with anemic conditions.

Tricuspid annular plane systolic excursion is a measurement of systolic ventricular function that quantifies the contraction of the right ventricle. Messing et al[16] established reference values for TAPSE in the second half of pregnancy and compared STIC and STIC-M in performing such measurements. These authors concluded that TAPSE values increased with gestational age. Tricuspid annular plane systolic excursion proved to be a highly reproducible measure of cardiac function, both in M-mode and with STIC-M, and an important tool for studying fetuses with CHD, arrhythmias, and diseases that affect preload and afterload, such as fetal growth restriction, hydrops, and feto-fetal transfusion syndrome (Fig. 10).

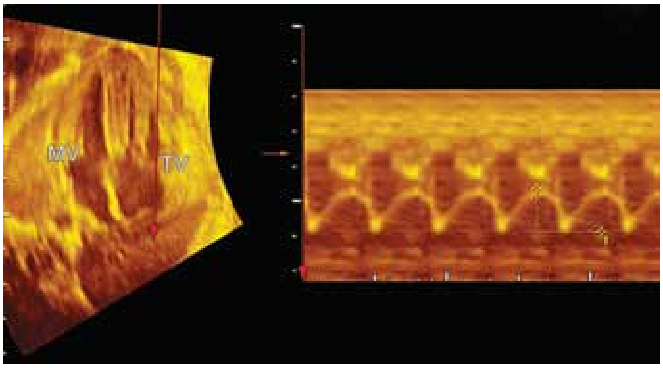


Fig. 10: Calculation of tricuspid annular plane systolic excursion (TAPSE) by spatiotemporal image correlation associated with M-mode (STIC-M). The STIC-M cursor is positioned parallel to the interventricular septum and adjacent to the tricuspid valve. The program automatically traces M-mode. The measure key is activated, and M-mode and generic measurement by slope are enabled (MV: Mitral valve; TV: Tricuspid valve)

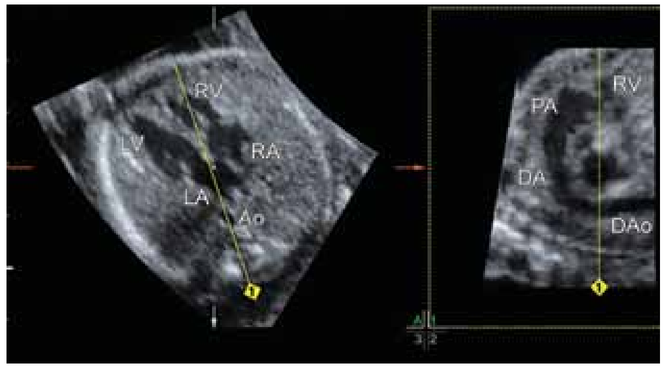


Fig. 11: Obtaining the plane of the ductal arch by the simple targets arterial rendering (STAR) technique of Omniview® software (General Electric Medical Systems, Zipf, Austria). Using the four-chamber plane as a reference, a yellow straight line is positioned through the right ventricle, the crux of the heart, the left atrium, and the descending aorta. The plane of the ductal arch is automatically obtained (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; Ao: Aorta; PA: Pulmonary artery; DA: Ductus arteriosus; DAo: Descending aorta)

STAR and FAST Techniques obtained with STIC and Omniview®

The simple targets arterial rendering (STAR) technique consists of drawing three independent lines with Omniview® software (General Electric Healthcare, Zipf, Austria) when viewing the four-chamber plane. This simultaneously shows three independent planes, such as: the ventricular septum with the major vessels (aorta and pulmonary), the pulmonary artery continuing from the ductal arch, and the left ventricular outlet along the long axis (Fig. 11). Yeo et al[22] demonstrated some cases of CHD diagnosed using the STAR technique in which the four-chamber plane window appeared normal, such as a case of transposition of the great vessels in a 20-week gestation and a case of tetralogy of Fallot in a 38-week gestation. Using the disproportionate four-chamber view in a 29-week fetus, the STAR technique showed severe pulmonary artery hypoplasia, with dilation of the aorta. Using the STAR technique with analysis of the four-chamber plane, a case of interventricular communication was also seen. The authors concluded that STIC complemented with STAR optimized image quality and increased the diagnostic accuracy.

The four-chamber view and swing technique (FAST) technique consists of obtaining standard echocardiographic planes by orienting lines obtained with Omniview® in the plane of the ductal arch in fetal cardiac volumes obtained with STIC. Three lines are positioned to provide standard planes: line 1: three vessels plus trachea, line 2: left ventricular outlet, and line 3: four chambers (Fig. 12). Yeo et al[23] evaluated the cardiac volumes of 50 normal fetuses and 5 with CHD. In the normal cases, the FAST technique showed 100% success in obtaining the standard planes, except the three-vessel plus trachea plane that had a 98% success rate. In the CHD cases, FAST showed alterations compared to the planes obtained in the normal cases.

STIC in the Evaluation of Congenital Heart Disease

As experience with using STIC technology has grown in recent years, several authors have evaluated this technology's contribution to CHD diagnosis. These studies have demonstrated that STIC adds important information to bidimensional echocardiography and can effectively contribute to increased accuracy in CHD diagnosis.

Bennasar et al[18] evaluated the accuracy of STIC in diagnosing CHD in high-risk populations. This study evaluated 363 pregnant women carrying fetuses suspected to have CHD, with gestational age varying between 14 and 41 weeks. Spatiotemporal image correlation acquisitions were performed in the four-chamber plane, both in grayscale and in color Doppler. All of the women underwent conventional echocardiography, independent from STIC. The accuracy of the latter with echocardiography was evaluated by comparison with the results of the postnatal diagnostic confirmation, or the autopsy in cases of miscarriage and perinatal death. Offline STIC evaluations were performed at least 1 year after the volumetric acquisitions. Spatiotemporal image correlation evaluation was possible in 98% of cases. Of the total of 363 pregnancies, 21 cases were lost from follow-up, 167 had normal hearts, and 175 had CHD. Accuracy, sensitivity, specificity, and positive and negative predictive value were 91.6, 94.9, 88.1, 89.7, and 94.0%, respectively. Spatiotemporal image correlation had a 73.4% absolute agreement with the final diagnosis of confirmed cases, compared to 81.7% for bidimensional echocardiography.

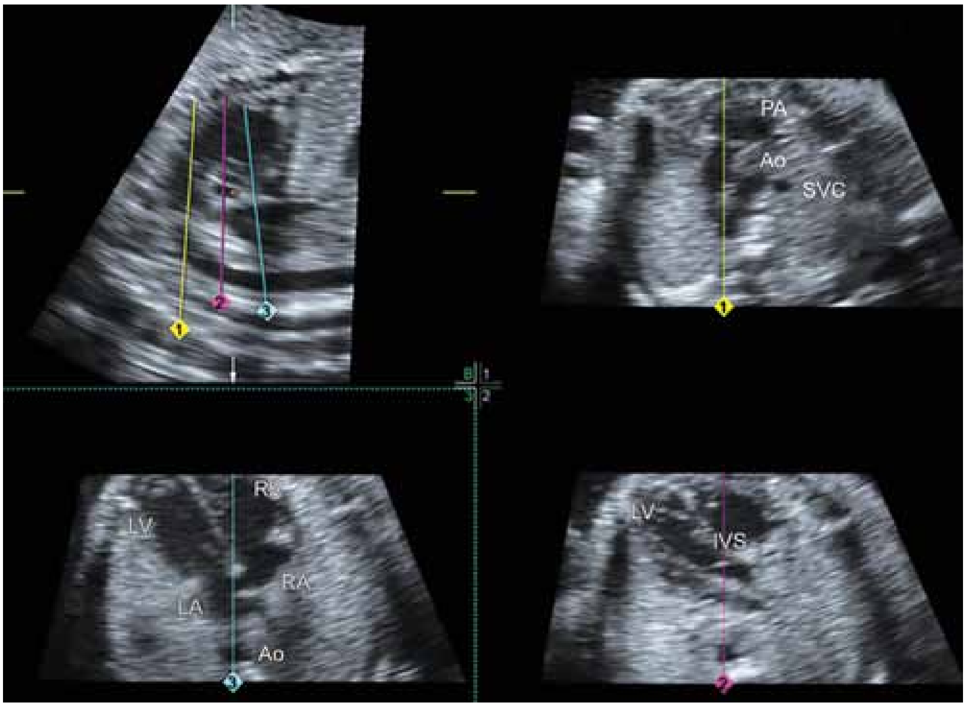


Fig. 12: Obtaining standard echocardiographic planes by four-chamber view and swing technique (FAST) of Omniview® software (General Electric Medical Systems, Zipf, Austria). Taking the plane of the ductal arch as a standard, three straight lines are positioned. The first line (yellow) goes through the center of the pulmonary artery; the second line (pink) goes through the center of the aorta, and the third line (blue) is adjacent to the outer edge of the aorta. The program automatically provides the three-vessel plus trachea plane (upper left), the five-chamber plane (lower left) and the four-chamber plane (lower right) (LV: Left ventricle; RV: Right ventricle; LA: Left atrium; RA: Right atrium; Ao: Aorta; PA: Pulmonary artery; SVC: Superior vena cava; IVS: Interventricular septum)

In another study, Yagel et al[19] evaluated the value added by 3D/4D ultrasound to offline analysis and CHD diagnosis. The authors evaluated 181 fetuses with CHD, with both bidimensional echocardiography and STIC. The evaluation protocol included echocardiography's five-plane axial section, examination of the ductus venosus, and a longitudinal evaluation of the aortic arch. The examinations included grayscale two-dimensional (2D) ultrasound, color Doppler, STIC alone, STIC with color and power Doppler, and STIC with B-flow imaging, both abdominally and transvaginally. Diagnoses were confirmed by pathological examination in the cases of miscarriage, and by neonatal echocardiography. Two-dimensional ultrasound examinations, with or without color Doppler using cine loops, as well as the 4D volumes, were stored and separately reviewed later to compare with the diagnosis. The authors observed that STIC increased diagnostic accuracy in 12 cases, because 12 cases had diagnostic errors and no false positive results were observed. Overall, 3D/4D ultrasound added diagnostic information to only 6.6% of diagnosed cases of CHD. The authors concluded that in their study, the diagnostic value of 3D/4D ultrasound is only moderately encouraging (Figs 13 and 14).

Fetal Intelligent Navigation Echocardiography

Fetal intelligent navigation echocardiography (FINE) (Medge Platforms Inc., New York, NY, USA) applies intelligent navigation technology to STIC volume datasets to automatically generate fetal echocardiography standard views. Once a correct volume is acquired STIC, intelligent navigation has a role in obtaining the target diagnostic planes automatically, minimizing the intraoperator variability and examination duration. After activation of anatomical box, the examiner should apply seven landmarks to obtain nine fetal echocardiography standard views: three vessels and trachea; four-chamber view; five-chamber view; left ventricle outflow tract; right ventricle outflow tract; abdomen view; ductal arch; aortic arch and venae cavae. The program also permits labels to be added in each of the fetal echocardiography standard views, facilitating the correct understanding of fetal cardiac structure and the standard views (Figs 15A to I).[25]

Yeo and Romero[24] described and tested the FINE technique in STIC volumes for 50 normal fetal hearts (18.6–37.2 weeks) and four with CHD (aortic coarctation at 25 weeks, tetralogy of Fallot at 25 weeks, transposition of the major vessels at 28 weeks, and pulmonary atresia with intact ventricular septum at 29 weeks). In the normal cases, FINE was able to show the nine standard echocardiographic planes in 78 to 100% of cases (mean: 76%, n = 38) of STIC volumes showed either eight or nine planes, whereas 18% (n = 9) showed seven planes. By contrast, in CHD cases, FINE showed evidence of abnormality in standard planes in all cases.

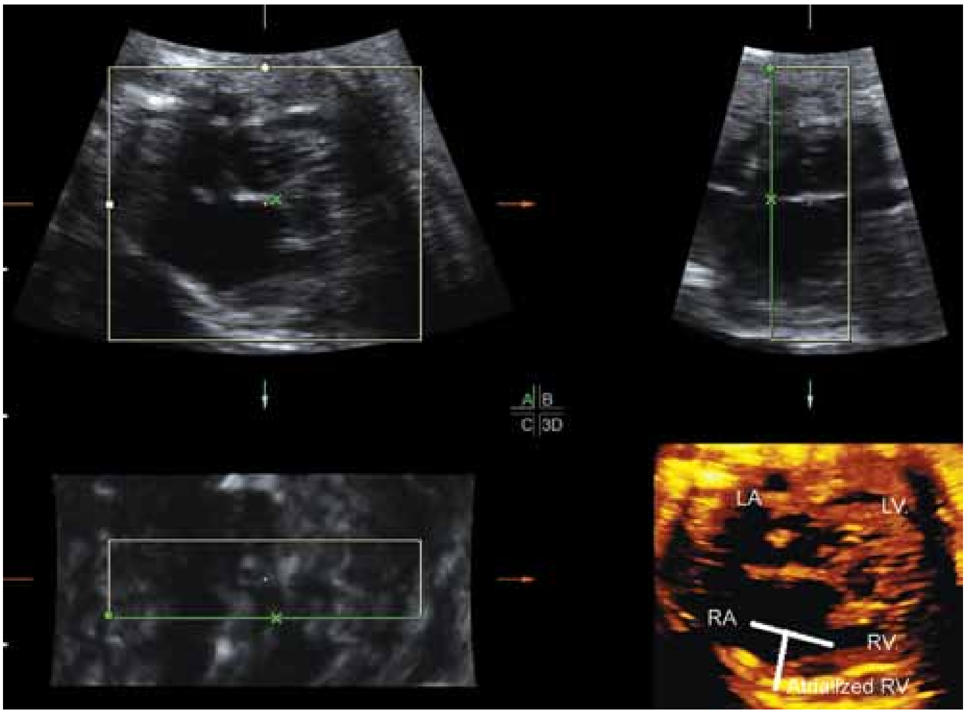


Fig. 13: Ebstein's anomaly in the 27th week of pregnancy, as seen with spatiotemporal image correlation. After volumetric capture in the four-chamber plane, the ROI (green line) should be positioned in plane B in a thin slice from right to left, automatically obtaining the rendered image of the four cardiac chambers. Note a more apical insertion of the tricuspid valve's leaflets relative to the annulus. The proximal portion of the right ventricle continues into the true right atrium and forms the 'atrialized' portion of the right ventricle (RA: Right atrium; RV: Right ventricle; LA: Left atrium; LV: Left ventricle)

Other STIC Applications

Spatiotemporal Image Correlation Rendering

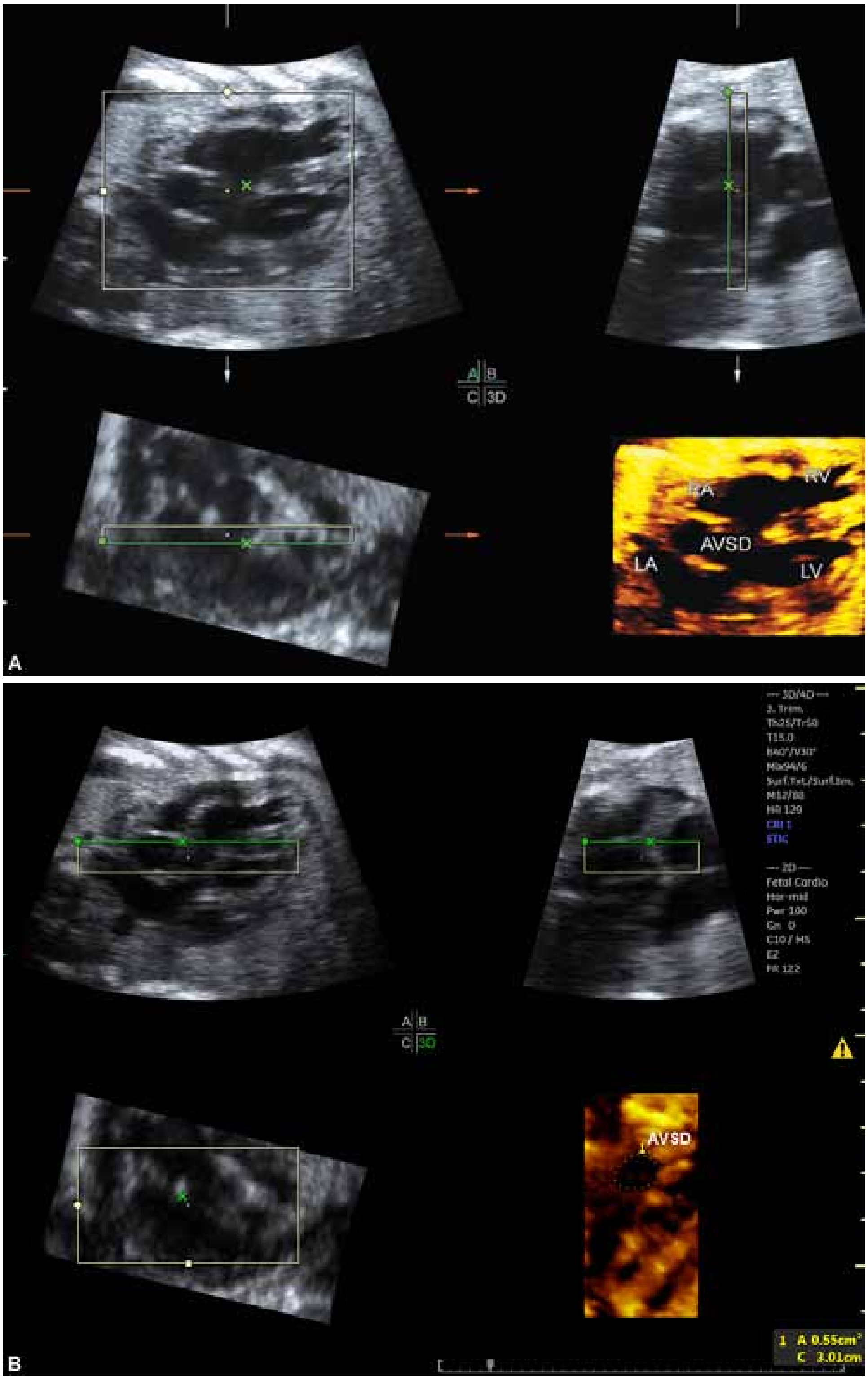
According to Yagel et al,[35] STIC rendering mode allows virtual planes of the interatrial and interventricular septa to be seen, as well as the annulus of the atrioventricular valves in both normal and pathological fetal hearts, permitting a better understanding of anatomical defects and potentially optimizing management by the multidisciplinary team. Using a low level of transparency, STIC rendering can be applied to the fetal heart by using the interface between the cardiac cavities and walls, providing cardiac views that cannot be obtained by 2D ultrasound.[36]

Nardozza et al[37] determined a reference curve for the area of the interventricular septum using STIC rendering mode. The active line (ROI) was positioned at the outer edge of the septum, which was manually delimited. The authors transversally evaluated 328 unique pregnancies between 18 and 33 weeks. A correlation was observed between the area of the interventricular septum and gestational age (r = 0.81), with the mean area increasing from 0.47 ± 0.1 cm^2 in the 18th week to 2.42 ± 1.13 cm^2 in the 33rd week. Rolo et al[38] determined reference values for the annulus of the fetal mitral and tricuspid valves with STIC rendering mode. The active line (ROI) was positioned from the atria with the reference point at the level of the crux of the heart. The mean area of the mitral and tricuspid valves varied from 0.19 ± 0.08 cm^2 and 0.20 ± 0.10 cm^2 in the 18th week to 0.93 ± 0.31 cm^2 and 1.06 ± 0.39 cm^2 in the 33rd week.

Rolo et al[39] determined the viewing rate and the reference values for the area of the papillary muscles of the atrioventricular valves in the fetal heart. The authors transversally evaluated 310 single pregnancies between 18 and 34 weeks. The viewing rate for all of the papillary muscles was 89.3%. The area of all the papillary muscles (anterolateral and posteromedial for the mitral valve, and anterosuperior, inferior and septal for the tricuspid valve) corresponded to gestational age. Recently, Barros et al[40] determined reference values for the area of the fetal myocardium using the STIC rendering method. These authors performed a prospective transversal study of 371 single pregnancies between 20 and 33 weeks. The area of the myocardium was obtained by positioning the green line (ROI) in the sagittal plane with the reference point at the midpoint of the interventricular septum. The mean area of the myocardium varied from 0.86 ± 0.23 cm^2 in the 20th week to 2.75 ± 0.69 cm^2 in the 33rd week (Fig. 16).

HDlive

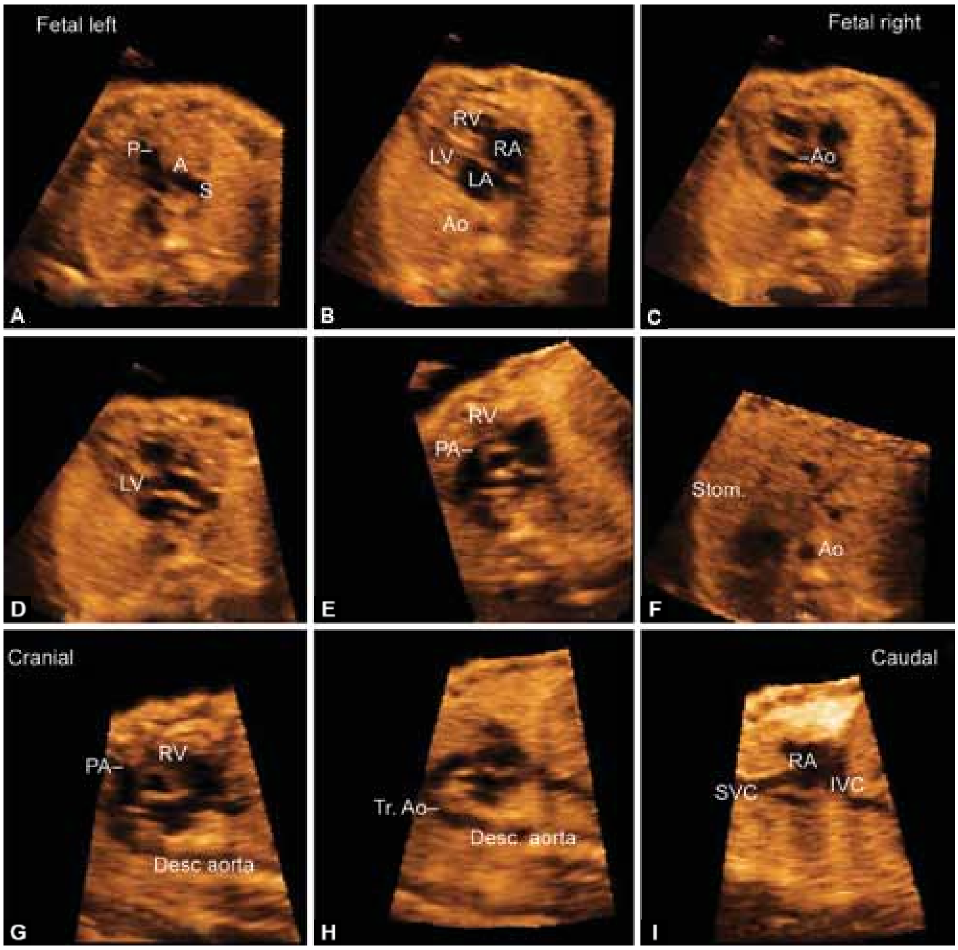
HDlive is a new software technique for drawing surfaces. The operator adjusts the lighting to create depth effects by optimizing the light and shadow of the images.[41] This technique allows standard echocardiographic planes to be obtained, such as four-chamber and ventricle outlets,



Figs 14A and B: Balanced atrioventricular septal defect (AVSD) in the 32nd pregnancy week, as seen with spatiotemporal image correlation. (A) After volumetric capture in the four-chamber plane, the ROI (green line) should be positioned in plane B in a thin slice from right to left, automatically obtaining the rendered image of the four cardiac chambers. (B) The ROI is positioned in the four-chamber plane at the AVSD level in a thin slice, automatically obtaining the front-facing image of the AVSD. By activating the measure key, the area of the transversal section of the septal defect can be obtained. Note the complete absence of the crux of the heart (RA: Right atrium; RV: Right ventricle; LA: Left atrium; LV: Left ventricle)

and also permits the reconstruction of the fetal heart and its vascular connections.[42]

HDlive associated with STIC (STIC-HDlive rendering) was first described by Hata et al.[21] Those authors evaluated four normal fetuses and three with CHD (Ebstein's anomaly, hypoplastic left heart syndrome, and tetralogy of Fallot) between the 25th and 35th week of pregnancy. In the normal cases, STIC-HDlive rendering made it



Figs 15A to I: Fetal intelligent navigation echocardiography (FINE) showing the seven standard echocardiographic planes: (A) three vessels plus trachea, (B) four-chamber view, (C) five-chamber view, (D) left ventricle outlet, (E) right ventricle outlet, (F) abdomen view, (G) ductal arch, (H) aortic arch and (I) venae cavae

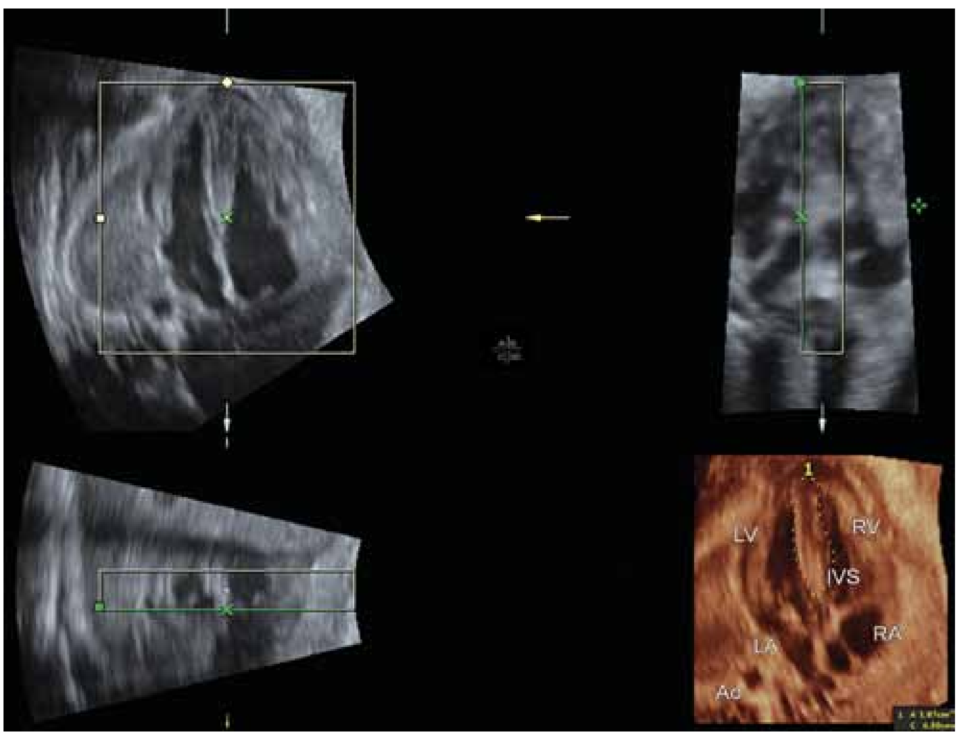


Fig. 16: Technique for obtaining rendered images of fetal cardiac chambers by spatiotemporal image correlation: Volumetric capture in the four-chamber plane, the ROI (green line) should be positioned in plane B in a thin slice from right to left, automatically obtaining the rendered image of the four heart. By activating the measure key, the area of the interventricular septum can be obtained (RA: Right atrium; RV: Right ventricle; LA: Left atrium; LV: Left ventricle; Ao: Aorta; IVS: Interventricular septum)

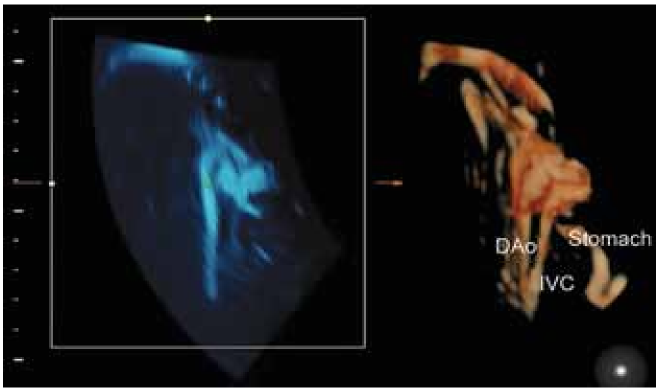


Fig. 17: HDlive associated with spatiotemporal image correlation (STIC-HDlive rendering), showing a reconstruction of the fetal heart and its vascular connections (DAo: Descending aorta; IVC: Inferior vena cava)

possible to realistically view the dynamic movement of the flap of the foramen ovale and the atrioventricular valves. In the case of Ebstein's anomaly, the STIC-HDlive rendering produced a realistic anatomical image of the tricuspid valve's most apical insertion, in addition to the atrialization of the left ventricle. In the case of hypoplastic left heart syndrome, tricuspid thinning and pulmonary valve dysplasia were evident. In the case of tetralogy of Fallot, the over-riding aorta and the interventricular septal defect were realistically demonstrated (Fig. 17).

CONCLUSION

Spatiotemporal image correlation is a software technique that allows acquiring fetal cardiac volume and viewing cardiac structures as a 4D cine sequence, containing information from a full cardiac cycle. Spatiotemporal image correlation uses an algorithm based on synchronizing temporal and spatial information, and is evaluated in multiplanar and rendered mode. Additionally, this technique can be used in association with color and power Doppler, TUI, inversion mode, B-flow imaging, and HDlive, allowing for complete evaluation of the fetal heart and its vascular connections. In some cases, it also increases the accuracy of bidimensional echocardiography for diagnosing CHD. Spatiotemporal image correlation also permits more reliable evaluation of cardiac function by measuring the volume of the ventricles and calculating total systolic volume, ejection fraction, and cardiac output. Recently, FINE software has come on the scene, a resource which requires fewer skills on the part of the examiner to obtain standard echocardiographic planes for screening of CHD.

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