Four-dimensional imaging by spatio-temporal image correlation (STIC)

In STIC technology, an automated device incorporated into the ultrasound probe performs a slow sweep acquiring a single three-dimensional (3D) volume. This volume is composed of a great number of two-dimensional (2D) frames. As the volume of the fetal heart is small, appropriately regulating the region of interest allows a very high frame rate (in the order of 150 frames per second) during 3D volume acquisition. For example, an acquisition time of 10 seconds and a sweep angle of 25° would lead to the recording of 1500 2D frames. During the acquisition time there will be approximately 20-25 cardiac cycles. Therefore, among the 1500 frames, 20-25 will show a systolic peak (Figure 1).

It is of paramount importance to set the smallest possible region of interest, so the heart will occupy the maximum proportion of the image acquired. Ideally, moving structures should represent 30% to 50% of the whole image.

Figure 1. Principles of STIC acquisition

Maternal and fetal movements (either gross body or breathing movements) are a possible source of interference, in particular causing artifacts in planes B and C, which can affect volume reconstruction. In relation to gestational age, the successful application of STIC technology between 13 and 40 weeks has been described in the literature.
Acquisition plane
The acquisition plane is the starting section from which the volume will be acquired, symmetrically upwards and downwards. Given the geometry of the fetal heart, and the need to analyze its anatomy according to a segmentary approach, starting from the abdomen to the upper mediastimum, the acquisition section for four-dimensional (4D) fetal echocardiography corresponds to the four-chamber view (Figure 2). Image definition will be maximal for plane A—corresponding to the original acquisition plane—and lower for planes B and C, which are reconstructed.

In the case of a conventional transverse acquisition, the fetus will ideally be lying with the spine at 6 o’clock. In practice, good image quality can be obtained with any position except for spine anterior (spine between 11 o’clock and 1 o’clock), where acoustic shadowing from the vertebrae hides cardiac structures. To better visualize the interventricular septum it is also advisable to avoid an apical four-chamber view. Conversely this is the best choice if color Doppler is used, as it allows the user to optimize for diastolic ventricular filling.

Region of interest (ROI)
The 3D-4D ROI box determines the height and width of the volume acquired. As a general rule, it is better to set the smallest possible ROI including the cardiac apex and corresponding vertebral body and a width including both ventricles (Figure 3).

Acquisition angle
The acquisition angle determines the acquisition depth (i.e. how much above and below the acquisition plane will be acquired). This generally depends upon the size of the fetus. In the first and second trimesters, an angle of 20 to 25 degrees is usually sufficient, while in the third a trimester 35 to 40 degree angle is often required. During the acquisition, the operator will notice if the angle is adequate to visualize the stomach bubble at one extreme of the sweep and the three-vessel view at the other.

Acquisition time
Acquisition time is inversely proportional to the speed at which the transducer acquires the volume. The shorter the acquisition time, the higher the speed of the sweep that the transducer will perform. A short acquisition time implies a lower image resolution, but results in a lower chance of artifacts due to fetal movements. Acquisition time usually varies between 7.5 and 15 seconds. Correct setting of the acquisition time, also in relation to the acquisition angle, is of the greatest importance to obtain good volumes.
**Acquisition with color and power Doppler**

For cardio-STIC, the volume acquisition can be performed with either color or power Doppler turned on. Power Doppler, due to its relative angle-independence, is mainly useful for the visualization of the arches. As explained earlier, a sagittal acquisition plane is better to optimize the imaging of these structures.

On the contrary, superimposed color Doppler is particularly useful to study intracardiac hemodynamics and the outflow tracts (Figure 4a-b). Once the volume is acquired, it is possible to visualize the images with or without the superimposed Doppler signals. However, in the latter case the quality of the pure gray scale image is understandably inferior compared with a similar acquisition without Doppler. Therefore, if it is necessary to store volumes with Doppler information, it is recommended to perform at least two volume acquisitions: one without Doppler, and one with superimposed color or power Doppler.

**Fetal cardiac volumes analysis: multiplanar approach**

Cardiac volumes are represented as a cardiac cycle in real time, and can be reproduced in a clip. Images can be displayed at different velocities or stopped to perform detailed analyses of specific phases of the cardiac cycle.

All scanning planes can be moved or rotated maintaining its synchronization with the cardiac cycle so that four chambers, long axes and all the different scanning planes can be visualized both as clips and as still images.

Cardiac volumes can be analyzed using different modalities: scrolling technique, spin technique and automatic slicing.

With the multiplanar reconstruction mode (MPR), the intersection of the three planes is represented as a dot; by moving this point it is possible to navigate through the volume (Figure 5).

**Figure 4.** STIC acquisition with color Doppler of four-chamber view (a) and the outflow tracts (b).

**Figure 5.** Representation in STIC mode: multiplanar representation
1. Image (a) acquired with the sweep STIC
2. Vertical plane (b) perpendicular to scanning plane (a)
3. Horizontal plane (c) perpendicular to scanning plane (a)
Bottom right corner shows the reciprocal spatial arrangement of the three planes.
Scrolling
This modality is based on cranial and caudal scroll starting from the four-chamber view without using rotations and it allows visualization of situs, left ventricular outflow tract, right ventricular outflow tract, and the three-vessel view.

Starting from the acquired volume, the four-chamber view is optimized modifying resolution, zoom and the clip velocity (between 25% and 50% of the original fetal heart rate).

Moving the y axis in plane B from left to right or vice versa, it is possible to check the situs and the position of the stomach and the left ventricular outflow tract. Further cranially, it is possible to visualize the pulmonary artery, the three-vessel view with thymus, and trachea.

Spin technique
This is based on different rotations (spin) on y and z axes to visualize the outflow tracts (Figure 6).

Figure 6. After optimization of the four-chamber view, the cardiac apex is positioned at 9 o’clock (a).

Scrolling cranially on the B plane allows visualization of the left ventricular outflow tract (b).

The reference point is then placed inside the aorta, a rotation on the y axis shows the ascending aorta (c).

Then the reference point is moved into the right pulmonary artery which appears below the aortic arch in the transverse view. A rotation on the y axis shows the pulmonary artery with its branches in the B plane. A further rotation on the z axis in the A plane shows the full length of the main pulmonary artery and its bifurcation into the right and left pulmonary arteries (d).

In the following steps it is necessary to go back to the four-chamber view and then scroll cranially to display the three-vessel view (e).

Moving the reference point inside the aorta and rotating on the z axis to align y axis with the aorta, displays the aortic arch in B. In a similar way, aligning the y axis in plane A with pulmonary artery displays the ductus arteriosus (f).
Automatic approach: iSlice

Automatization of multiplanar reconstruction is faster and less operator-dependent compared with the process previously described. This mode of representation displays images from ultrasound in the same fashion as CT or MR.

Once the data has been acquired the volume can be represented through a series of parallel planes. This mode can be integrated with color Doppler too. The first step is the acquisition of a STIC volume, followed by optimization of the four-chamber view. Subsequent activation of the slice function (iSlice) allows simultaneous visualization of different scanning planes. It is also possible to select the most useful slices to visualize the most interesting scanning planes, at the same time allowing an easier evaluation of the cardiac structures.

Distance between slices can be modified and must adapted to different gestational ages. It’s suggested to use a “9 slices view”: the four-chamber view is placed in the fifth slice and the distance is set to obtain visualization of the stomach in the ninth slice.

Figures 7 and 8 show simultaneous visualization of transverse views from the abdomen (situs) to the outflow tracts.

The spin technique can be applied to images displayed within the iSlice view, because spatial relations between the planes are present in all slices.

Figure 7. iSlice representation of a volume data set acquired in gray-scale

Figure 8. iSlice representation of a volume data set acquired with Color Doppler
Fetal heart volume analysis: rendering modes and the “surgical view”

Rendering is an algorithm that, by simulation of lights and shadows, allows the representation of a three-dimensional object through a two-dimensional image (Figure 9).

Surface rendering

Using a low level of transparency, a surface rendering mode can be applied to the fetal heart using the interface between the cavities and the cardiac walls. It allows the operator to obtain standard cardiac views (e.g., four-chamber view, long left axis, short right axis), or new views not otherwise available with two-dimensional ultrasound. These new views are defined as “surgical views” (e.g., “en face” view of the cardiac views) (Figure 10a).

Minimum mode rendering

Increasing transparency to a high level enables the heart and blood vessels to be seen in a projection. By choosing this mode, structures with high transparency (anechoic) can be demonstrated as a 3D projection of black appearing structures in a surrounding of more echogenic tissue. Images obtained with this rendering mode are similar to X-ray or MRI images (Figure 10b).

Inversion mode

Inversion mode is a new rendering algorithm that transforms echogenic structures into echogenic voxels. Therefore, anechoic structures such as the heart chambers, vessel lumen, stomach and bladder appear echogenic in the rendered image, whereas structures that are normally echogenic before gray scale inversion appear anechoic.

The quality of the inversion mode rendered image depends on the quality of the acquired volume data set. Nevertheless, regulation of threshold, contrast and transparency can improve image quality.

One of the advantages of this technique is that the image is similar to that acquired by power Doppler, but without the difficulties encountered in adjusting the image. The volume can be acquired in gray scale as a 3D static volume, or as a STIC volume at high frame rate and resolution, whereas volumes with power Doppler information have a low frame rate and are subject to movement artifacts (Figure 10c).
**Glass body model**

When the volume is acquired with color or power Doppler, the 3D volume includes the Doppler information. The acquisition can be a static 3D volume or a STIC volume, and it can be displayed in three modalities: either in gray scale alone, in color scale alone, or in a combination of both (glass body mode). This rendering algorithm is based on the simultaneous representation of gray and color Doppler scale, and it allows demonstration, at the same time, of the ventricular filling and the crossing of the great arteries, without changing the scanning plane (Figure 10d).

Depending on the desired mode of 3D visualization, the rendering algorithm can be modulated through a series of parameters characterizing the rendering of single voxels (Figure 11).

- **Threshold**: the gray (or color) intensity value below which the voxel is not represented in the rendered image
- **Transparency**: represents the possibility of making the reference voxel more or less transparent
- **Brightness**: represents the gray value corresponding to the white point
- **Opacity**: a combination of transparency and threshold values
- **Smoothing**: regulates the smoothness of the voxel’s shape, making images softer or harder

*Figure 11. Different modalities of surface rendering of the four-chamber view*
Figure 12. Construction of the rendering of the four-chamber view is obtained by positioning the rendering line of the view (blue line) at the level of the aorta in the short axis view.

Figure 13. Example of two frames from a STIC loop with surface rendering during systole, with closed atrioventricular valves (first frame) and during diastole, with open atrioventricular valves.

Figure 14. The “en face” view of the atrioventricular and semilunar valves from the atria.

Figure 15. The interventricular septum view from the left ventricle.
Three-dimensional ultrasound has become popular because of fetal face surface rendering. A similar principle is applicable to fetal heart, and it allows visualizing the region of interest as a three-dimensional image. In order to obtain this, the examiner sets the volume rendering box on the fetal heart, selecting the region of interest. It’s necessary to choose the direction line through which the rendering is done, in order to properly set the trim line.

In Figure 12, for example, the line is positioned below the aortic root, in order to obtain the four-chamber view.

Therefore it is possible to demonstrate the surface volume rendering of the four-chamber view and to evaluate the kinesis in the cardiac cycle (Figure 13), or, by a rotation of planes, it is possible to obtain the long axis view and the short axis view.

By proper placement of the trim line it is possible to obtain some “surgical views” of the valves and septa. By applying the rendering mode to the different phases of the cardiac cycle, the dynamic movements of opening and closing of the valves is displayed (Figures 14,15).

From the volume data set a rendered 3D image of the heart can be created. Compared to the 2D image, in which a thin slice of anatomy is displayed, the rendered 3D image contains depth. The depth of the image can be controlled: with decreased depth, a slice through the heart can be isolated (Figure 16a); with increased depth, the back wall of the chambers of the heart can be viewed while simultaneously viewing the atrioventricular valves (Figure 16b). The rendered view can be examined as a cine loop or a still image.
Discussion
In the context of a fetal cardiology unit the application of 3D and 4D technologies for the fetal heart evaluation offers the following benefits, compared to the conventional 2D examination:

1. **Shortening of examination time:** When a complex congenital heart defect (CHD) is detected, an accurate diagnosis is essential for appropriate prenatal counseling. The acquisition of all the views that are needed for a detailed diagnosis could require several hours, taking a long time for the operator and for the patient too. The sequential segmental analysis of the cardiovascular structures and their connections is very time consuming. Using the STIC-technology, the operator can systematically examine the fetal cardiovascular structures off-line with several approaches and rendering modes. 3D and 4D technology can shorten the examination time for the patient.

2. **Ease of obtaining standard views:** The ability to slice and rotate the volume in an unlimited number of sections may allow the examiner to easily and quickly obtain the standard fetal cardiac views, even if he or she has limited ultrasound experience.

3. **Ability of obtaining non-conventional views:** Volume dataset post-processing offers an unlimited number of 2D and 3D views that cannot be obtained in any way with the 2D echocardiography. Moreover, the immense capability of 3D rendering represents a significant help in complex or rare congenital heart defects.

4. **Remote diagnosis:** The volume data set can be transmitted over networks for consultation in tertiary care centers or by different operators, achieving clinical and diagnostic complementary details. It has been shown that a telemedicine link via the Internet is technically feasible, and STIC volume analysis was useful in order to diagnose or to rule out some intracardiac abnormalities.

5. **Advice with pediatric cardiologist and cardiac surgeon:** Rendered and reconstructed images can be shown to pediatric cardiologists and cardiac surgeons in order to obtain more information that can optimize counseling with parents, and perinatal management of cardiac defects. 3D rendering and tomographic imaging make the comprehension of type and entity of cardiac defects easier. In fact, they provide images very similar to the surgical or the postnatal radiological images.

6. **Patient communication:** 3D and 4D rendered images can be used to explain, in a clearer and more intelligible way, the fetal cardiac anatomy and, especially when a cardiac malformation is detected, may allow the patient to better understand the findings of the examination.

7. **Teaching and training in fetal cardiology:** Fetal heart 3D and 4D visualization offers new approaches to teaching and training in fetal cardiology.

In the context of ultrasound, the application of 3D and 4D technology could play a significant role. The ability to acquire a volume data set and to examine it off-line, providing standard image planes, may contribute to improving prenatal detection rate of congenital heart defects.
References


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Printed in The Netherlands
4522 962 28231/795 * NOV 2007