THE JOURNAL OF
Obstetrics and Gynaecology Research

The official Journal of Asia and Oceania Federation of Obstetrics and Gynaecology
Japan Society of Obstetrics and Gynecology

doi:10.1111/j.1447-0756.2010.01224.x

J. Obstet. Gynaecol. Res. Vol. 36, No. 3: 513–518, June 2010

Four-dimensional volume-rendered imaging of the fetal ventricular outflow tracts and great arteries using inversion mode for detection of congenital heart disease

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Abstract

Aim: Using four-dimensional (4D) sonography with an inversion mode, we evaluated fetal ventricular outflow tracts and great vessels for the detection of congenital heart disease.

Methods: Volume datasets of the fetal heart were acquired with spatiotemporal image correlation (STIC), which uses automated transverse and longitudinal sweeps of the anterior chest wall. A total of 12 normal fetuses and seven fetuses with congenital heart disease (one case of double-outlet right ventricle, one case of tetralogy of Fallot, one case of transposition of the great arteries, one case of hypoplastic pulmonary artery with a large ventricular septal defect, and three cases of hypoplastic left heart syndrome) at 16–37 weeks of gestation were studied using transabdominal 4D sonography with an inversion mode. 4D inversion mode images of great arteries were evaluated.

Results: 4D ultrasound with an inversion mode demonstrated real-time 3D angiographic features of fetal cardiac outflow tracts in both normal and abnormal fetal hearts. This modality facilitated visualization of the relationships, size, and course of the outflow tracts, thus helping the examiner to more effectively understand the spatial relationships between the vessels. In normal fetal hearts, it was clearly shown that the pulmonary artery crosses in front of the aorta. In the three cases of hypoplastic left heart syndrome, an extremely small ascending aorta was evident. In the one case of tetralogy of Fallot, a relatively small pulmonary artery was noted. In the one case of hypoplastic pulmonary artery with a large ventricular septal defect, a markedly small main pulmonary artery was depicted. In the case of transposition of the great arteries, the vessels left the ventricles parallel to each other. In the case of double-outlet right ventricle, great arteries leaving the right ventricle in parallel were shown.

Conclusion: 4D ultrasound in the inversion mode provides a means of evaluating fetal cardiac outflow tracts in 3D in real time. This technique may assist in the evaluation of spatial relationships between the great vessels and both ventricles, and the difference in the size of great vessels. Moreover, the inversion mode images should be more readily discernible than those obtained by conventional ultrasonography. 4D ultrasound in the inversion mode may be an important modality in future fetal cardiac research and in the evaluation of fetal congenital heart disease.

Key words: 4D ultrasound, congenital heart disease, fetal great arteries, fetal ventricular outflow tracts, inversion mode, STIC.

Received: April 23 2009.
Accepted: July 17 2009.

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Introduction

An examination offering a four-chamber view is an excellent screening test for the antenatal detection of major congenital heart disease because it is not only simple but also reliable.[1–3] However, there are some limitations in the detection of abnormalities of the ventricular outflow tracts and great arteries.[4,5] The clear visualization of the crossing of the aorta and pulmonary artery is difficult to achieve with conventional color Doppler.[6] Moreover, the method to examine the left and right ventricular outflow tracts and great arteries is not easy to teach and learn, and is often time-consuming.[3,7]

Spatiotemporal image correlation (STIC) is a recent advance that allows dynamic multiplanar slicing and surface rendering of the heart anatomy, and offers a new approach for the sonographic assessment of the fetal heart.[8,9] This feature offers an easy-to-use technique to acquire data from the fetal heart and its visualization in a four-dimensional (4D) cine sequence. Fetal heart volumes are acquired with a single automated sweep of the transducer, and spatial and temporal information is combined to display real-time images that can be extracted from volume datasets.[8] This cine sequence presents the fetal heart beating in real time in multiplanar and rendered displays. The examiner can navigate within the heart, re-slice, and produce all of the standard and unique planes necessary for a comprehensive diagnosis.[10]

The inversion mode is a volume analysis approach to three-dimensional (3D) and 4D ultrasonography for the visualization of fluid-filled fetal structures.[11–13] Similar to the postmortem pathologic casts, this modality has been proposed as a technique capable of providing ‘digital casts’ of the fetal cardiac chambers, great vessels, and abnormal systemic venous connections.[14–20] The feasibility of the inversion mode in the antenatal detection of congenital heart disease has been reported in several investigations, but in only three of these were these abnormalities of the ventricular outflow tracts and great arteries.[14,17,18] Using this novel technique, we evaluated fetal ventricular outflow tracts and great vessels for the detection of congenital heart disease in normal fetal heart and congenital heart disease.

Methods

A total of 12 normal fetuses and seven fetuses with congenital heart disease (one case of double-outlet right ventricle, one case of tetralogy of Fallot, one case of transposition of the great arteries, one case of hypoplastic pulmonary artery with a large ventricular septal defect, and three cases of hypoplastic left heart syndrome) at 16–37 weeks of gestation were studied using transabdominal 4D sonography with an inversion mode and STIC capabilities (VOLUSON 730 Expert or VOLUSON E8; General Electric Medical Systems, Kretztechnik, Zipf, Austria). Volume datasets of the fetal heart were acquired with STIC, which employs automated transverse and longitudinal sweeps of the anterior chest wall. Using a curved array transducer (2–5 or 4–8.5 MHz), volume acquisition lasted from 10 to 12.5 sec. Acquisition angles ranged from 25 to 40 degrees. One to three recordings were obtained using a transabdominal 4D probe. Fetal movement necessitated a repeat volume acquisition to obtain satisfactory data. 4D reconstruction was carried out using the ‘inversion’-rendering algorithm. Low threshold and transparency levels were adjusted until the structures of interest were visualized. The volume data were analyzed with 4Dview 2000 version 2.1 computer software (General Electric Medical Systems, Kretztechnik, Zipf, Austria). By transforming echolucent structures into solid voxels, both ventricles and great arteries were converted into hyperechogenic 4D structures. The surface was displayed in a mixture of gradient light and a smooth-surface mode. All volumes were treated by the MagicCut function to show both ventricles and great arteries. These techniques encompassing both ventricles and great arteries were used to visualize 4D cardiac blood flows. The endless cineloop showing the beating heart could be played in slow motion and stopped at any time for detailed analysis. Because 4D data are used to generate each frame scan, planes could be moved and rotated. Therefore, these volumes could be seen from any direction. The fetal heart was monitored using conventional two-dimensional (2D) echocardiography before 4D ultrasound with inversion mode examination in each subject. The dataset was stored on a 700 Mbyte CD-R, and could be retrieved for further analysis. All sonographic examinations were performed by one examiner (T. H.) for the data reported here. The time needed to produce rendered images by 4D reconstruction of the outflow tracts in the inversion mode was within 30 min.

All patients were nonsmokers with no history of illegal drug use. Fetal age determination was based on the first day of the last menstrual period and was confirmed by first- and early second-trimester sonographic measurements. As fetal echocardiography is routinely used at our institution for the evaluation of fetal cardiac anatomy and abnormality in the second and third trimesters of pregnancy, no institutional review board permission was needed. However, all patients gave verbal informed consent after the nature of the study was fully explained. Patients also gave their informed consent after confirmation that they would not undergo any additional ultrasound scans as a result of the study. Neonatal echocardiographic examinations after birth were consistent with the prenatal findings.

After the completion of 2D evaluation of the fetal heart, 4D ultrasound with inversion mode examinations of the fetal heart were conducted. After the entire fetal heart was scanned in a single volume, the processing of volume data was performed after the patients had left the room. This began with adjustments of various settings to optimize the images, including gamma curve correction to optimize tissue contrast resolution and the gray scale threshold and transparency to improve image quality. All volume data for each patient were examined, and optimal images were selected for further analysis. Static 3D inversion image and rotation video clip use in the one case of double-outlet right ventricle has been reported previously by our group.[18] This case of double-outlet right ventricle and one of the cases of hypoplastic left heart syndrome have also been reported previously by our group, using different rendering techniques for 3D and 4D examination of the fetal heart.[21–23]

Results

The conventional 2D echocardiographic visualization of both ventricles and great arteries of the fetal heart was performed in all fetuses studied in this investigation.

Rendered images employing 4D reconstruction of the outflow tracts in the inversion mode in cases with congenital heart disease were compared with a normal fetal heart. 4D ultrasound in the inversion mode demonstrated real-time 3D angiographic features of fetal ventricular outflow tracts and great arteries in both normal and abnormal fetal hearts. This modality facilitated visualization of the relationships, size, and course of the ventricular outflow tracts and great arteries, thus helping the examiner to better understand the spatial relationships between the vessels.

In normal fetal hearts, it was clearly shown that the pulmonary artery crosses in front of the aorta (Fig. 1). In the three cases of hypoplastic left heart syndrome, an extremely small ascending aorta and large main pulmonary artery were evident (Fig. 2). In the case of tetralogy of Fallot, a relatively small pulmonary artery was noted (Fig. 3). In the case of hypoplastic pulmonary artery with a large ventricular septal defect, a

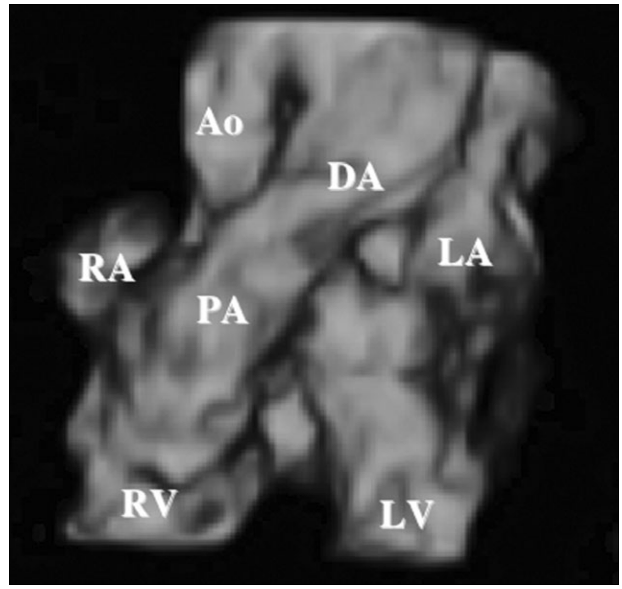

Figure 1 Four-dimensional reconstruction of the fetal heart using the inversion mode in a normal fetus at 30 weeks and 6 days of gestation. The aorta (Ao) arises from the left ventricle (LV) and the pulmonary artery (PA) leaves from the right ventricle (RV). It is clearly shown that the PA crosses in front of the Ao. DA, ductus arteriosus; LA, left atrium; RA, right atrium.

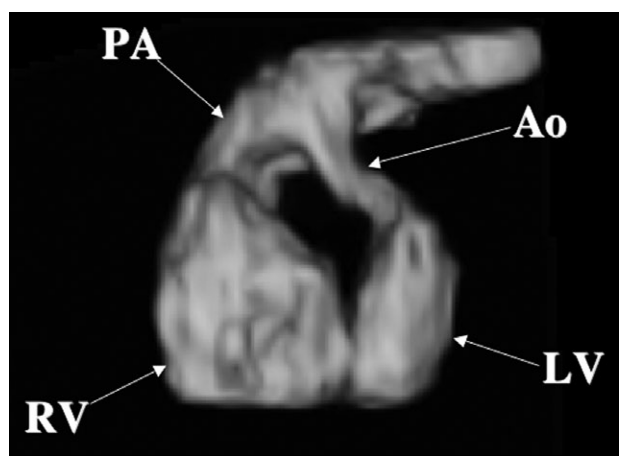

Figure 2 Four-dimensional reconstruction of the fetal heart using the inversion mode in a fetus with hypoplastic left heart syndrome at 37 weeks of gestation. An extremely small ascending aorta (Ao) and large main pulmonary artery (PA) are evident. LV, left ventricle; RV, right ventricle.

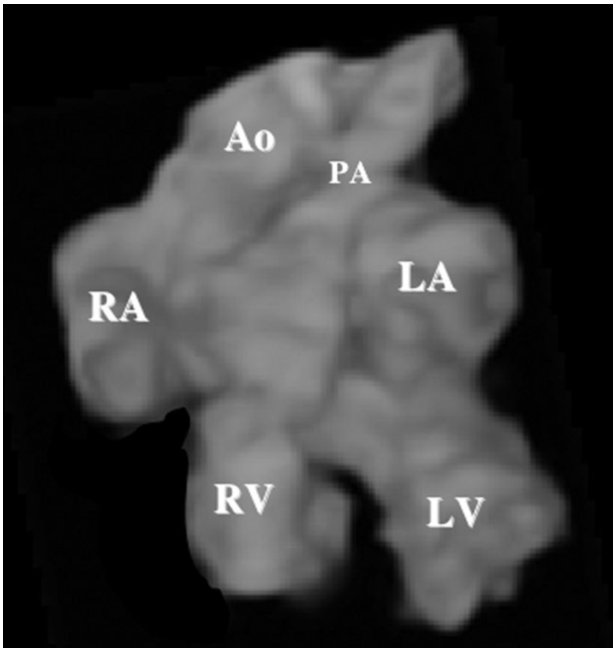

Figure 3 Four-dimensional reconstruction of the fetal heart using the inversion mode in a fetus with tetralogy of Fallot at 29 weeks of gestation. A relatively small pulmonary artery (PA) was noted. Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

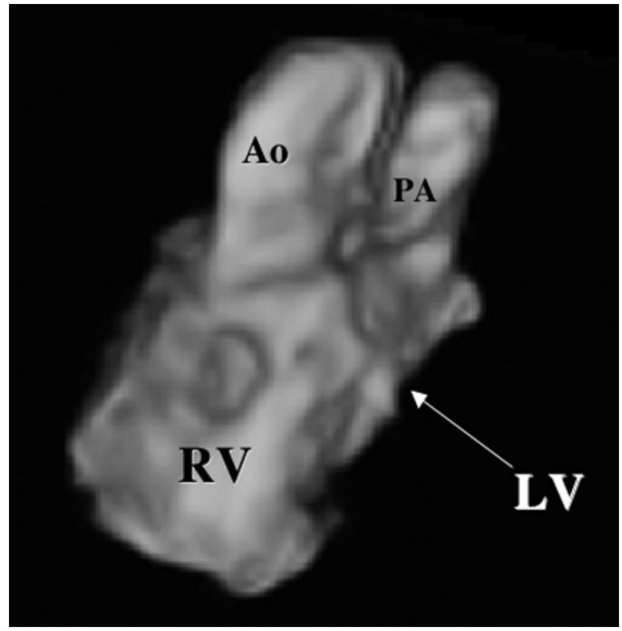

Figure 4 Four-dimensional reconstruction of the fetal heart using the inversion mode in a fetus with transposition of the great arteries at 28 weeks and 3 days of gestation. Both arteries left the ventricles parallel to each other. Ao, aorta; LV, left ventricle; PA, pulmonary artery; RV, right ventricle.

markedly small main pulmonary artery and large ascending aorta were depicted. In the case of transposition of the great arteries, the pulmonary artery connected to the left ventricle, and the aorta connected to the right ventricle. Both arteries left the ventricles parallel to each other (Fig. 4). In the case of double-outlet right ventricle, both the pulmonary artery and aorta were shown to arise in parallel from the right ventricle.

Discussion

Many new developments in fetal echocardiography have led to a greater understanding of the complex cardiac morphology and to a more accurate prenatal diagnosis.[6,21–25] The inversion mode is a post-processing tool that inverts the gray scale of the volume voxels.[11–14] Therefore, anechoic structures, such as the heart chambers, vessel lumen, stomach, gallbladder, renal pelvis, and bladder appear echogenic in the rendered images, whereas structures that are normally echogenic before gray scale inversion (e.g. bones) appear anechoic.[17] Recent reports have described the role of this technique in visualizing cardiac chambers, great vessels, and systemic venous connections in the normal fetal heart and congenital heart anomalies.[14–20] The main advantage of this technique is that the image is similar to that acquired by power Doppler but without the difficulties encountered in adjusting the image.[24] The volume can be acquired in a grey scale as an STIC volume at a high frame rate and resolution. Application of the inversion mode with STIC generates information about the anatomy and pathologic characteristics of the fetal heart (digital casts) that cannot be obtained with 2D fetal echocardiography.[17] With this rendering algorithm, structures can be inspected from all directions. As shown in the present study, the spatial relationships between the outflow tracts as well as the connection between the arteries and ventricular chambers and the size of great vessels visualized in the inversion mode image were readily discernible. Moreover, the inversion mode with STIC led to clearly rendered images of the beating fetal heart with complex pathologies in one complete heart cycle. However, mastering this technique does involve a learning curve, and not all fetal sonographers may be familiar with it. Moreover, inversion mode application with STIC involves a time-consuming and highly operator-dependent 4D reconstruction of both ventricles and great arteries. In addition to technical familiarity, a detailed knowledge of the cardiovascular anatomy is essential for the application of this technique. Therefore, this approach may not be considered as a screening method for the prenatal diagnosis of congenital heart disease.

Another important advantage of the 4D inversion mode is the offline analysis of the acquired volume. With our scanner, the entire volume of the fetal heart was acquired rapidly during 25 to 40 degrees over a period of 10–12.5 sec. We could then navigate through the volume data on the heart to identify the region of interest.[22]

Compared to other 3D and 4D techniques, the inversion mode has been shown to be superior to power Doppler in terms of image quality, but it provides less information about neighboring tissue than the glass body mode.[24] It can be used to display any fluid-containing structure, but it lacks information on the velocity or direction of blood flow.[18] Another limitation was that we did not have sufficient examples of cardiovascular anomalies with a confirmed postnatal outcome to compare 3D reconstructions produced using inversion mode.[17] Based on our search of the literature, we identified three investigations that described the use of inversion mode imaging for the visualization of ventricular outflow tracts and great vessels in congenital heart diseases such as the transposition of the great arteries, coarctation of the aorta, pulmonary stenosis, pulmonary atresia, and double-outlet right ventricle.[14,17,18] In this study, 4D sonography in the inversion mode also clearly showed an extremely small ascending aorta in the case of hypoplastic left heart syndrome, and a relatively small pulmonary artery in the case of tetralogy of Fallot. Further studies are needed to confirm this diagnostic potential.

With respect to the limitations associated with inversion mode use with STIC, fetal movement and acoustic shadows required a repeat examination to acquire satisfactory data. Moreover, limitations in achieving optimal data acquisition were experienced in fetal arrhythmias. These problems with STIC may be resolved as further technical advances are made.

In previous investigations[14,17,18] and in our cases, inversion mode use with STIC provided useful information not generated by conventional 2D echocardiography for an accurate prenatal diagnosis. Conventional 2D echocardiography can facilitate a correct prenatal diagnosis of congenital heart disease in most cases, but it requires much experience, and is time-consuming for novice echosonographers. Inversion mode use with STIC may be easier for less experienced sonographers to learn and make a diagnosis. We also expect that this technique will be useful in explaining abnormalities to physicians and sonographers in training at a time when the patient is not in the room.

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