Published in final edited form as:
J Ultrasound Med. 2006 June ; 25(6): 745–755.

Applications of 2D Matrix Array for 3D and 4D Examination of the Fetus: A Pictorial Essay

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Abstract

Objectives—Two-dimensional matrix array is a new technology for the performance of three-dimensional (3D) and four-dimensional (4D) ultrasonography. Thus far, this technology has been used in obstetrics only for the evaluation of the fetal heart. In this study, we report the use of a 2D matrix array transducer for the examination of fetal anatomical structures, including the fetal heart.

Material and methods—Thirty-four fetuses and 19 with one or more congenital anomalies diagnosed by two-dimensional (2D) ultrasonography were examined with a 2400-element 2D matrix array transducer (x3-1, IE-33, Philips Medical Systems, Bothell, WA). Median gestational age at examination was 25 6/7 weeks (range: 13 0/7 – 40 1/7 weeks). Real-time direct 4D, full volume acquisitions and live xPlane imaging were used to evaluate fetal anatomical structures.

Results—1) 360 degree rotation and examination of selected structures were possible in second trimester fetuses; 2) Structures were examined by maintaining the transducer in a fixed position and rotating the volume dataset with the system trackball; 3) Dorsal and ventral parts of the hands and feet were visualized in a single volume dataset in real-time, with no need to move the transducer; 4) real-time *en face* visualization of atrioventricular valves was achieved from the ventricular or atrial chambers; 5) 3D images of bones were obtained during the early second trimester by decreasing gain settings only, with no need for cropping the surrounding structures; 6) 4D reconstruction of vascular structures was possible by using full volume acquisitions. Two limitations were identified: 1) lower resolution when compared to commercially available mechanical volumetric transducers, and 2) narrow volume display, which led to incomplete visualization of fetal structures in the third trimester.

Conclusion—Real-time direct 4D imaging with 360 degree rotation for examination of fetal anatomical structures is possible. An important feature, when compared to currently available mechanical volumetric transducers, includes the possibility of examining fetal structures from multiple perspectives, in real-time, without the need to move the transducer in the maternal abdomen. Further technological developments may overcome the limitations identified in this study.

Keywords

2D matrix array; 3D; 4D; ultrasound; fetus; prenatal diagnosis; anomalies; fetal echocardiography

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Introduction

Among several methods available for three-dimensional (3D) ultrasonography, the majority (free-hand acquisition using a conventional two-dimensional [2D] ultrasound transducer without position sensing, free-hand acquisition using a conventional 2D ultrasound transducer with position sensing, automated acquisition using dedicated mechanical volume probes) rely on the acquisition of a series of 2D frames that are then reassembled by the ultrasound equipment and displayed as a 3D volume dataset[1,2]. In order to produce "real-time" four-dimensional (4D) ultrasonographic images (i.e., three spatial dimensions plus motion), volume datasets need to be acquired and displayed faster than the capacity of the human eye to retain a visual impression, which is estimated as one tenth to one thirtieth of a second[3]. Currently available mechanical probes are capable of volume acquisition rates of up to 40 volumes per second by rapidly oscillation of a convex array mounted on a mechanical wobble located inside the transducer housing (rapidly oscillating transducer technology)[4]. While this technology is widely available and currently offers the best spatial resolution for volume ultrasonography, it is not capable of direct volume scanning. Direct volume scanning is a term proposed by Deng,[3] in 2003, to describe 3D/4D systems capable of scanning a volume of interest (1) in its totality, (2) within a time in which movement is negligible (in an instant), and (3) with sufficient spatial resolution. Since in the case of mechanical transducers the totality of the volume of interest is not scanned in an instant, the term "indirect volume scanning" applies to 3D/4D ultrasound systems that employ this technology.[3] This has considerable implications for the examination of the moving fetus and, specially, the fetal heart, since motion artifacts can easily interfere with the quality of the images obtained if the structure of interest moves faster than the speed at which the volume dataset is being acquired.

In contrast, 2D matrix array transducers allow direct volume scanning by electronically interrogation of a region of interest and acquisition of a pyramidal volume of ultrasonographic data,[5–9] currently at rates of 24 volumes per second. This technology has the potential to minimize motion artifacts associated with 3D/4D ultrasonography and, provided that spatial resolution is satisfactory, may become an attractive alternative to examine fetuses. Although several studies have described potential applications of this technology for the examination of adult[10–19] and fetal hearts,[20–26] real-time volumetric scanning of fetal anatomical structures other than the fetal heart by 2D matrix array transducers has not been previously reported. The objective of this study is to describe our initial experience with 3D and 4D ultrasonography of the human fetus using 2D matrix array technology.

Material and Methods

Fifty-three fetuses between 13 and 41 completed menstrual weeks (median 26 weeks, interquartile range 20 to 28 weeks) were examined by 3D and 4D ultrasound using 2D matrix array technology (x3-1 transducer, 3-1 MHz, IE-33, Philips Medical Systems, Bothel, Washington, USA) between April and July 2005. Patients were enrolled in research protocols approved by the Institutional Review Board of the National Institute of Child Health and Human Development (NIH), Bethesda, Maryland, and the Human Investigation Committee of Wayne State University, Detroit, Michigan. All patients gave written informed consent before participating in the study.

Volume datasets were acquired using the following techniques: 1) real-time direct 4D ultrasound; 2) Full volume 3D ultrasound; 3) full volume 4D ultrasound with gray-scale only; 4) full volume 4D ultrasound with gray-scale and color Doppler; and 5) live xPlane imaging. A brief description of each acquisition method is provided below:

1. **Real-time direct 4D ultrasound.** In this modality: a) volume acquisitions are performed with a negligible delay between volume acquisition and display (i.e., the images are updated as quickly as the observer's visual persistence); b) volume datasets are acquired in totality with sufficient spatial resolution; and c) the spatial and temporal dimensions are simultaneously and synchronously acquired.[3] With currently available 2D matrix array technology, this is the only acquisition mode that allows real-time volumetric imaging. A current limitation of this acquisition mode is a narrow field of view in the azimuth plane, since only one-third of the matrix array's aperture is active during acquisition.
2. **Full volume 3D ultrasound.** In this mode, all elements of the array are activated during acquisition. Since temporal information is not acquired, the volume datasets are static. The acquisition process is fast (1 to 2 seconds), minimizing the likelihood of motion artifacts.
3. **Full volume 4D ultrasound.** In full-volume 4D ultrasound, all elements of the transducer are fired in sequence and the full aperture of the array is utilized. In children and adults, the temporal information to trigger acquisition is provided by the patient's electrocardiogram (ECG) signal. In this study, the temporal information was artificially provided by an external ECG simulator device (Model 430B, 12 lead ECG simulator, Med Cal Instruments, Inc., Lewis Center, Ohio), which transmitted ECG signals to the equipment with a frequency of 120 beats per minute. Volume acquisitions in this mode are indirect and not in real-time.
4. **Full volume 4D ultrasound with color Doppler.** This acquisition mode is similar to the full-volume 4D ultrasound mode described above. However, color Doppler information is added to the volume dataset.
5. **Live xPlane imaging.** In live xPlane imaging, two planes of section with identical resolution are simultaneously imaged by the 2D matrix array. Images are displayed using a split-screen format. The original imaging plane is displayed on the left side of the screen, whereas the right side shows one of several possible planes of section that can be selected by the operator through electronically steering the ultrasound beam in lateral, rotation or elevation planes. The disadvantage of this mode is that a volume dataset is not acquired and, therefore, only the last two screens imaged by the examiner are stored, either as static images or video clips.

All volume datasets were evaluated off-line with the Q-LAB software (version 4.1, Philips Medical Systems, Bothel, WA).

Results

Fifty-three fetuses were examined and 699 volume datasets were acquired during the study period. Thirty-four fetuses were considered normal and 19 had one or more anomalies diagnosed by 2D ultrasonography. The median number of volume datasets acquired per patient was 10, ranging from 1 to 34 (interquartile range: 5 to 14).

Examination of the fetal extremities

Two hundred and twenty-eight volume datasets of the fetal extremities were acquired during the study period. Ten fetuses had the following anomalies: polydactyly (n=3); clubfeet (n=2); rocker bottom feet (n=2); short and bowed femur, tibia, and fibula (n=1); radial ray aplasia/hypoplasia (n=1); and fused fingers (n=1). The examinations were conducted using either real-time direct 4D or full-volume 3D ultrasound. Real-time 360 degree visualization of legs, arms, and feet was possible by rotating the volume dataset in any direction with the equipment trackball, while the transducer was held in a stand still position on the maternal abdomen

(Figure 1,Video Clip 1). In addition, 360 degree visualization of the fetal bones was possible by decreasing the ultrasound gain during the early second trimester or, alternatively, by displaying the volume datasets with the maximum intensity projection mode during the late second and early third trimesters. For volume datasets acquired with real-time direct 4D, this could be done in real-time with no need to move the transducer on the maternal abdomen **(Figure 2, Video clip 2)**.

An important limitation of real-time direct 4D ultrasonography for the examination of fetal extremities was the narrow aperture of the volume dataset on the azimuth or "z" plane. The narrow aperture of the 2D matrix array in real-time made it difficult to fit an entire extremity within the region of interest in some cases, especially during the late second and third trimesters of pregnancy (Figure 3, Video Clip 3). Although acquisitions performed using the full-volume 3D modality could overcome this limitation, the temporal component of the examination was lost. Figure 4 shows rendered images of abnormal fetal extremities in cases of radial aplasia/ hypoplasia, syndactyly, and polydactyly. **Video clip 4** shows a case of postaxial polydactyly visualized from the palmar and dorsal faces of the hand in a volume acquired by real-time direct 4D.

Examination of the fetal face

Fifty-six volumes of the fetal face were acquired with full-volume 3D, full-volume 4D, real-time direct 4D and live xPlane imaging. In general, antero-posterior surface rendered images of the fetal face (Figures 5A and 5B) were best visualized in full-volume 3D ultrasound datasets, whereas profile rendered images could be obtained with either full-volume 3D ultrasound or real-time direct 4D (Figure 5C). Facial expressions, such as eye-blinking **(Video Clip 5)** or yawning (Figure 5D) could be observed in those datasets acquired with real-time direct 4D. Antero-posterior rendered views of the fetal face were difficult to obtain with real-time direct 4D because of the narrow aperture of the 2D matrix array, as discussed above. During the early second trimester, however, the whole fetal head could be fitted within the volume dataset, and the skull bones were visualized by decreasing the ultrasound gain to suppress the muscles and soft tissue from the images being displayed **(** Figures 5E and 5F).

Examination of the fetal heart and other maternal and fetal vascular structures

One hundred and sixty-four volume datasets of the fetal heart, as well as 24 volume datasets of other maternal (uterine arteries, n=3) and fetal vascular structures (umbilical cord vessels, n=19; middle cerebral artery n=1; and ductus venosus, n=1) were acquired by real-time direct 4D, full volume 3D ultrasound, full volume 4D ultrasound (both with gray scale and color Doppler) and live X-plane imaging.

Figure 6 and Video Clip 6 show examples of normal and abnormal fetal hearts evaluated with real-time direct 4D ultrasonography. Besides visualization of the depth of the structures, a feature not possible with real-time 2D ultrasound (see **Figures 6A,** normal left ventricular outflow tract; **6B**, echogenic focus in the left ventricle; **6C**, atrioventricular septal defect), ventricular septal defects could be imaged from both sides of the interventricular septum without moving the transducer simply by electronically rotating the volume dataset **(Figures 6D, 6E, and 6F)**.

Figure 7 illustrates visualization of the atrioventricular valves en face after cropping and rotating the volume dataset in real-time during the examination. Normal atrioventricular valves are visualized in Figures 7A and 7B (Video Clip 7A). A ventricular septal defect is shown for comparison in Figures 7C and 7D (Video Clip 7B).

Color Doppler imaging could only be incorporated into the volume datasets if they were acquired using full volume 4D ultrasonography (Figure 8, Video clips 8A and 8B). An interesting feature of this type of acquisition was the possibility of digitally suppressing the gray scale and, therefore, visualizing digital casts of cardiac (atrioventricular chambers and outflow tracts) (Figures 8A through 8D, Video Clip 8A) and other vascular structures (umbilical cord vessels, middle cerebral artery, ductus venosus, and uterine arteries) (Figures 8E and 8F, Video Clip 8B).

Figure 9 and Video Clip 9 illustrate the various planes of section of the fetal heart obtained by live X-plane imaging. By imaging the four-chamber view on the left screen and changing the elevation angle on the right screen, the transverse section of the abdomen (Figure 9A), 5-chamber view (Figure 9B), and three-vessel view (Figure 9C) could be visualized. Visualization of the ductal arch (Figure 9D), short-axis view of the pulmonary artery (Figure 9E), and the aortic arch (Figure 9F) were obtained by electronically tilting the ultrasound beam in the lateral direction.

Discussion

This study shows the feasibility of examining fetal structures, including the fetal heart, by 2D matrix array technology. Real-time 360 degree rotation of volume datasets while maintaining the transducer in a fixed position on the maternal abdomen is possible, and this feature was particularly useful to image the fetal bones during the second trimester of pregnancy. Other features reported in this study included: (1) real-time rendering of cardiovascular structures, including *en face* views of the atrioventricular valves; (2) real-time 4D visualization of facial expressions; (3) 4D visualization of vascular structures after digital suppression of the gray scale in volume datasets acquired by full-volume 4D ultrasound; and (5) the possibility of simultaneously examining two planes of section with live xPlane imaging.

Two-dimensional matrix arrays have been extensively used in clinical practice for the examination of adult hearts[10–19] and, more recently, for fetal echocardiography.[20–26] In 1999, Sklansky et al.[20] reported preliminary observations on real-time examination of the fetal heart in 10 fetuses between 21 and 36 weeks of gestation, four of which had congenital heart disease diagnosed by 2D ultrasonography. Fair to good image quality was achieved in 11 of 12 examinations and, in 70% of the cases basic cardiac views could be adequately visualized. In 2000, Scharf et al.[21] obtained images of at least satisfactory quality in 13 fetuses examined with a 2D matrix array transducer between 20 and 24 weeks of gestation. Deng et al.[22] described optimal imaging windows to examine the fetal heart using this technology. Maulik et al.[23] reported that a comprehensive assessment of cardiac valves, atrial and ventricular chambers, and outflow tracts was possible in a group of 12 fetuses examined between 16 and 37 weeks of gestation by either real-time direct 4D ultrasonography or full volume 4D ultrasonography acquisitions triggered by an external ECG simulator device. Sklansky et al.[24] used full volume 3D acquisitions to image fetal cardiac structures, and were able to successfully visualize a wide range of cardiac anomalies (hypoplastic left heart syndrome, atrioventricular canal, double inlet single ventricle, double outlet right ventricle and transposition of the great arteries) but not small ventricular septal defects. More recently, Acar et al.[25] reported successful visualization of fetal cardiac structures in 56 of 60 fetuses examined with either real-time direct 4D ultrasonography or live xPlane imaging.

The strength of the 2D matrix array approach for examination of fetal structures lies on the possibility of directly acquiring a pyramidal volume of ultrasonographic data,[5] currently at rates of 24 volumes per second. When compared to reconstructive 3D/4D ultrasonography, this technique minimizes artifacts related to maternal and fetal motion, as well as those related to cardiac gating when examining the fetal heart. The system also allows beam steering and focusing in the 3D volume dataset,[6,8] making it possible to simultaneously examine two different planes of section of the same structure, in real-time, without resolution loss. Current limitations for fetal volumetric imaging include lower image resolution due to lower transducer frequencies in the 2D matrix array probe (1 to 3 MHz in the current study) when compared to commercially available mechanical volumetric transducers (2 to 8 MHz), and the narrow aperture of the volume dataset in the z-plane, which impairs the examination large fetal structures (e.g. fetal face, limbs and spine) during the late second and third trimesters of pregnancy. Lower image resolution may result in distortion of fetal anatomy when compared to images obtained by the latest generation of mechanical volumetric transducers. However, in a few cases in which fetuses were scanned with both mechanical volumetric and 2D matrix array transducers, rendered images were of acceptable quality (Figure 10). In order to overcome the limitations related to the narrow aperture of the transducer, some investigators[26,27] have proposed a "sweep volume" acquisition technique, in which the transducer is manually and steadily swept during volume acquisition to incorporate the portion of the structure not initially contained within the volume dataset.

Although today's mechanical 3D volume acquisition transducers have provided an interim approach for "real-time" imaging, they are currently unable to achieve acquisition speeds that are potentially achievable using 2D matrix array transducers. However, substantial obstacles still remain 2D matrix array transducers are widely accepted in clinical practice. Practical clinical applications will depend on several technical factors, including the development of satisfactory image resolution and reliable maintenance of fast volume data acquisition rates. These developments will need to simultaneously occur against a backdrop of rapidly emerging improvements in computer processing speed, novel display methods, nanotechnology, and probe manufacturing technology. The recently announced development of convex 2D matrix array transducer composed of 8,000 piezoelectric elements[28] (as opposed to the currently commercially available transducers with up to 3,000 elements), may help to address some of the limitations observed in this study. Nonetheless, a similar historical analogy would compare the diagnostic benefit of static ultrasound images with the introduction of real-time obstetrical ultrasonography. Evidence-based studies will certainly need to identify key obstetrical problems that are most likely to benefit from this new modality. Clinicians will require clear guidelines about why they would consider using 2D matrix array transducers over more conventional three- and four-dimensional imaging methods.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This research was supported by the Intramural Research Program of the National Institute of Child Health and Human Development, NIH, DHHS

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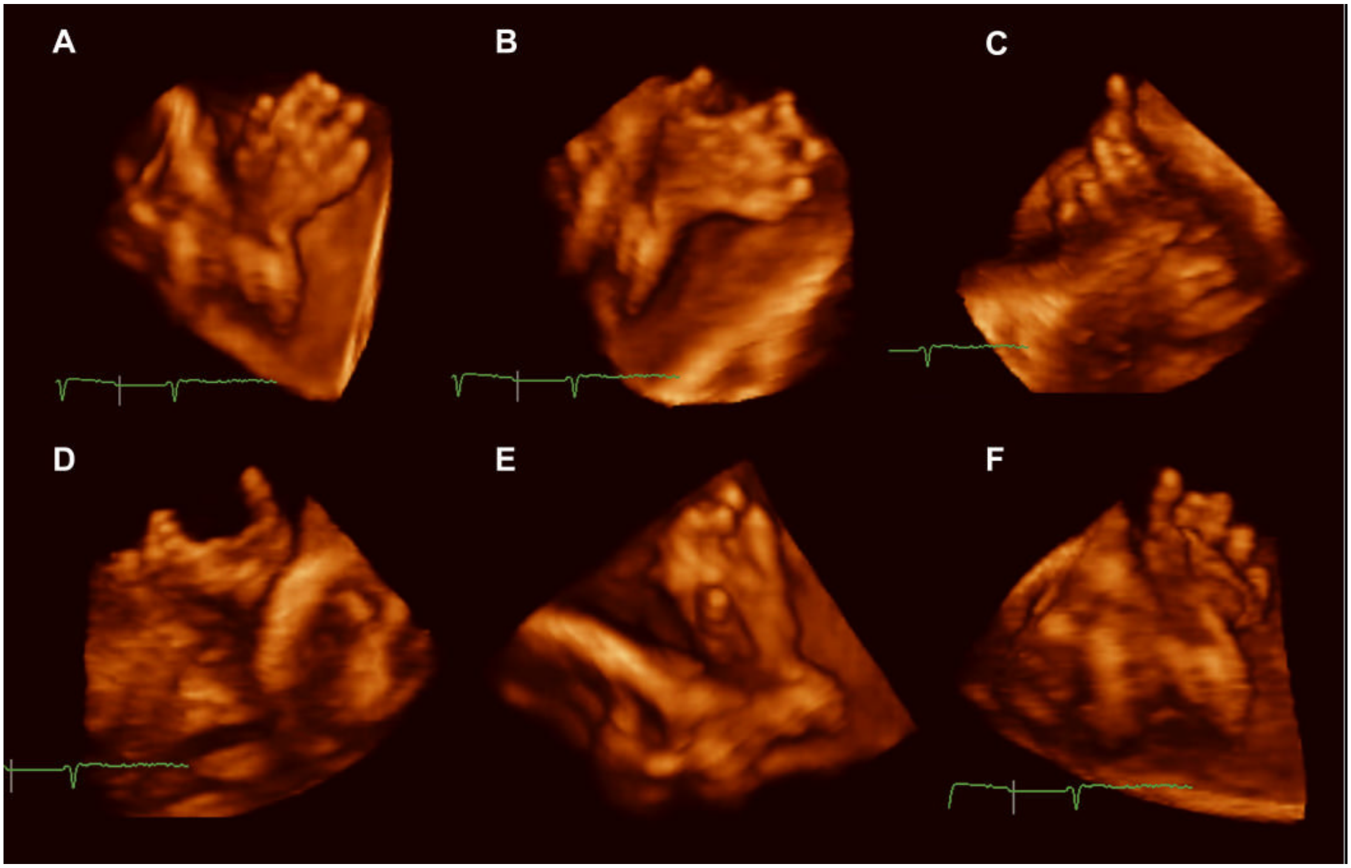

Figure 01.

From A to F, the figure shows images of the fetal hand from multiple angles. The images were acquired using real time-direct 4D ultrasonography of a normal fetus at 26 weeks and 4 days of menstrual age. Video Clip 01 shows finger movements during opening and closing of the fetal hand while rotating the volume dataset.

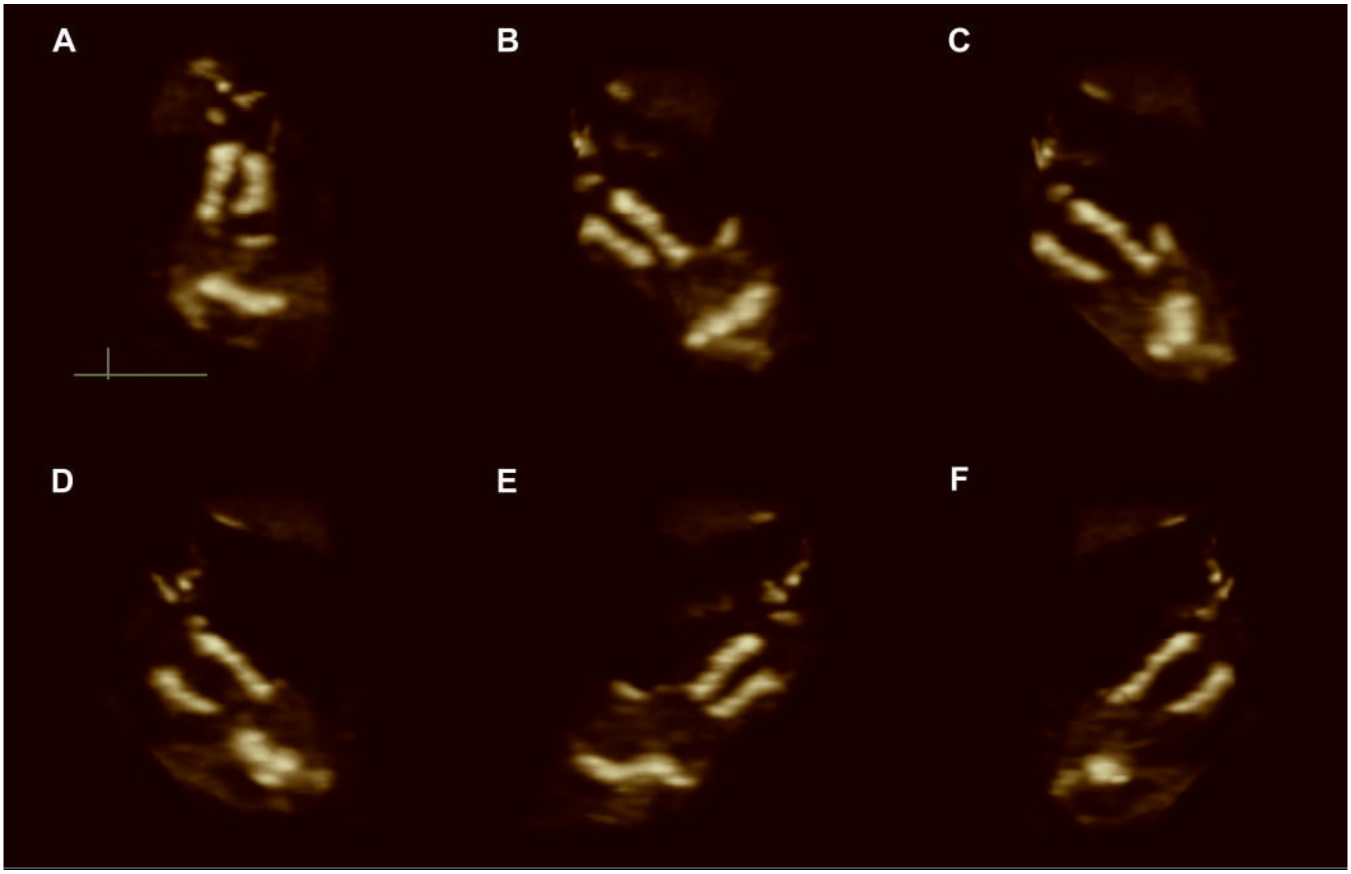

Figure 02.
From A to F, the figure shows rendered images of the femur, tibia, and fibula in a 20 week fetus with thanatophoric dysplasia from multiple angles. The images were acquired by real-time direct 4D ultrasonography (see also Video Clip 02).

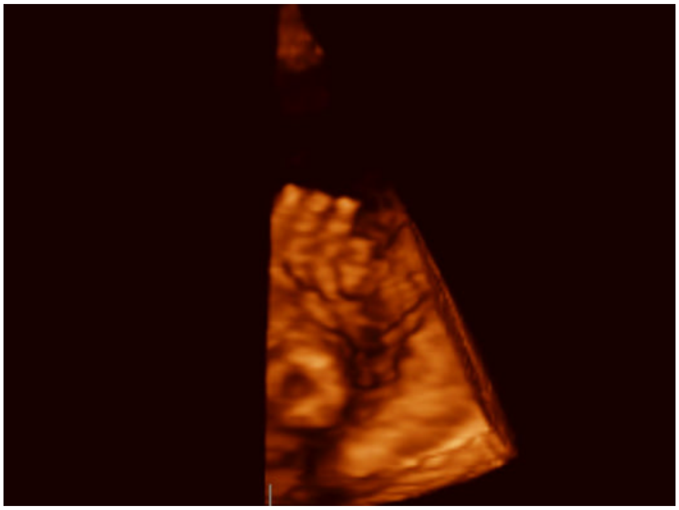

Figure 3.
This rendered image of a normal hand at 29 weeks of gestation illustrates one of the limitations of real-time 4D ultrasonography using the currently available 2D matrix array technology: narrow aperture on the azimuth or “z” plane. In this case, only three of the fingers were completely visualized, the second finger was partially visualized and the thumb was excluded from the volume dataset.

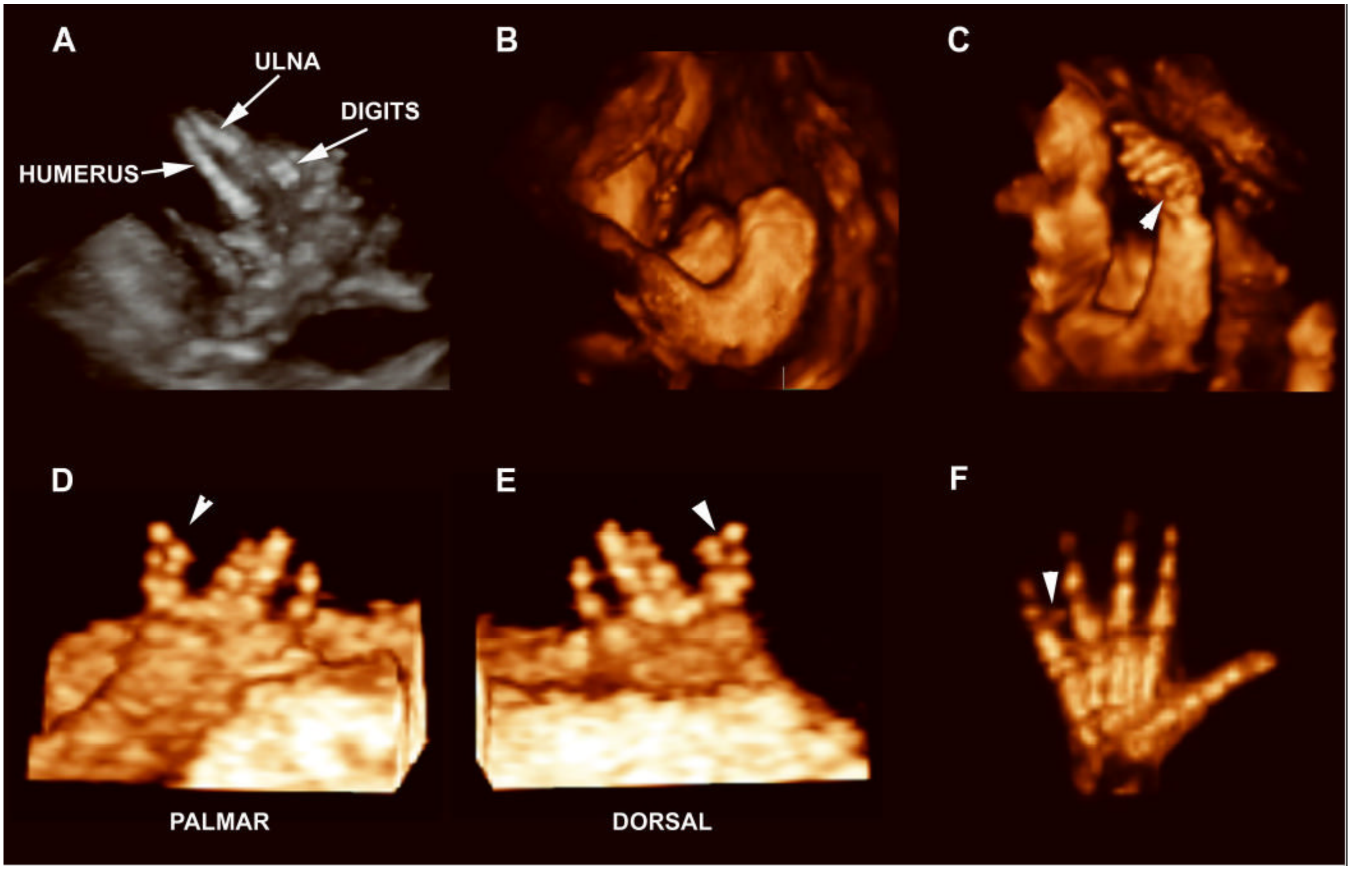

Figure 4.
Rendered images of abnormal hands and feet. A) Real-time direct 4D rendered image of radial aplasia and only two digits. B) Full volume 3D image of syndactyly of all five toes. C) Full-volume 3D image of Isolated postaxial polydactyly (arrowhead). D and E) Real-time direct 4D images of postaxial polydactyly (arrowheads) in a case of trisomy 18; the palmar and dorsal aspects of the hand are visualized. E) F) Isolated postaxial polydactyly (skin tag - arrowhead).

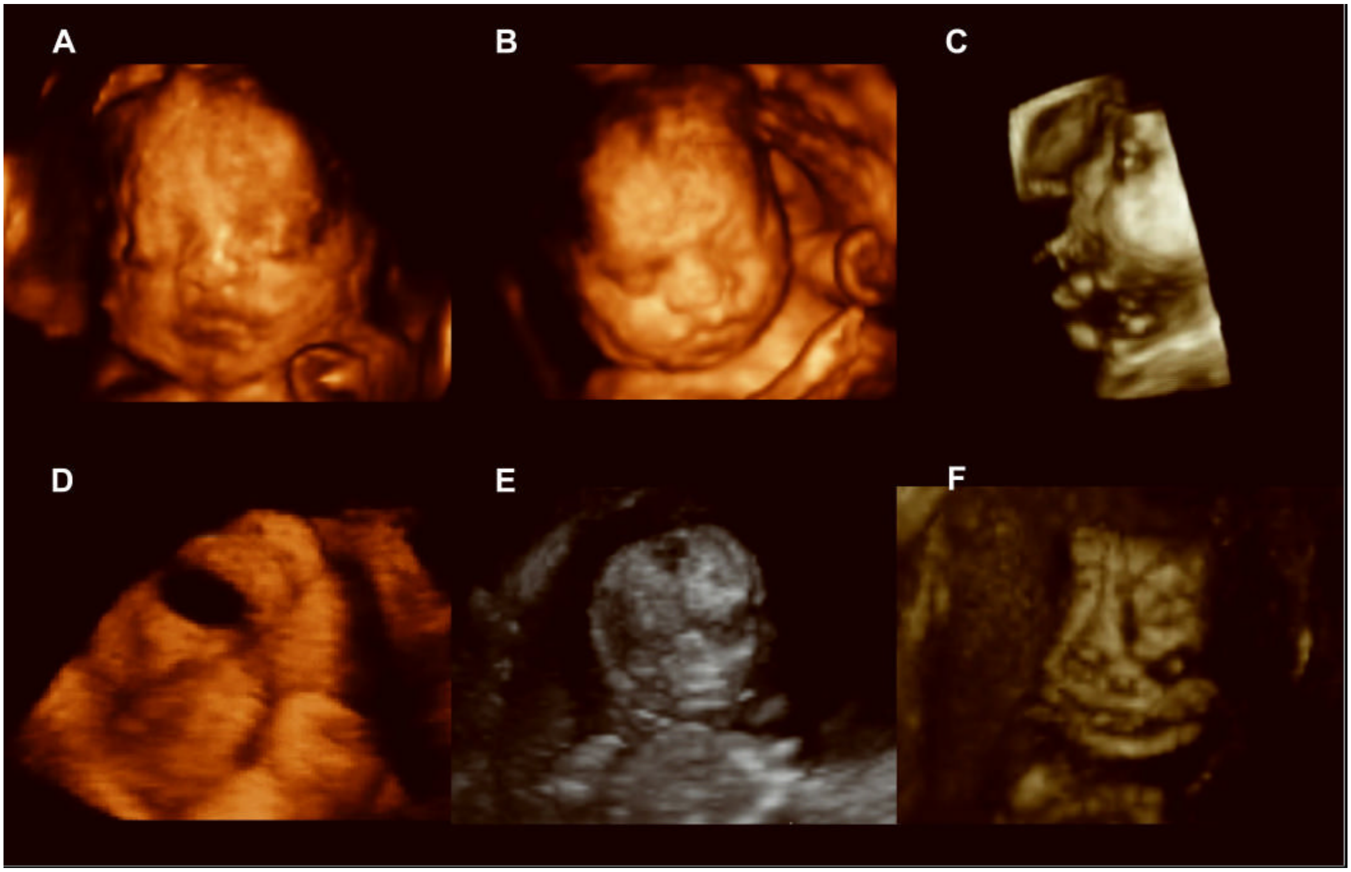

Figure 5.
A) Full volume 3D rendered view of the fetal face in the antero-posterior projection at 28 weeks of gestation. B) Full volume 3D rendered view of a different fetus at 28 weeks of gestation. C) Profile rendered image of the fetal face at 26 weeks of gestation; the volume dataset was acquired with real-time direct 4D and eye blinking could be easily observed (Video Clip 05). D) Fetal yawning captured with real-time direct 4D. E and F) Visualization of the fetal skull bones in the early second trimester achieved by decreasing the ultrasound gain during volume acquisition (E: 15 weeks of gestation; F: 16 weeks of gestation).

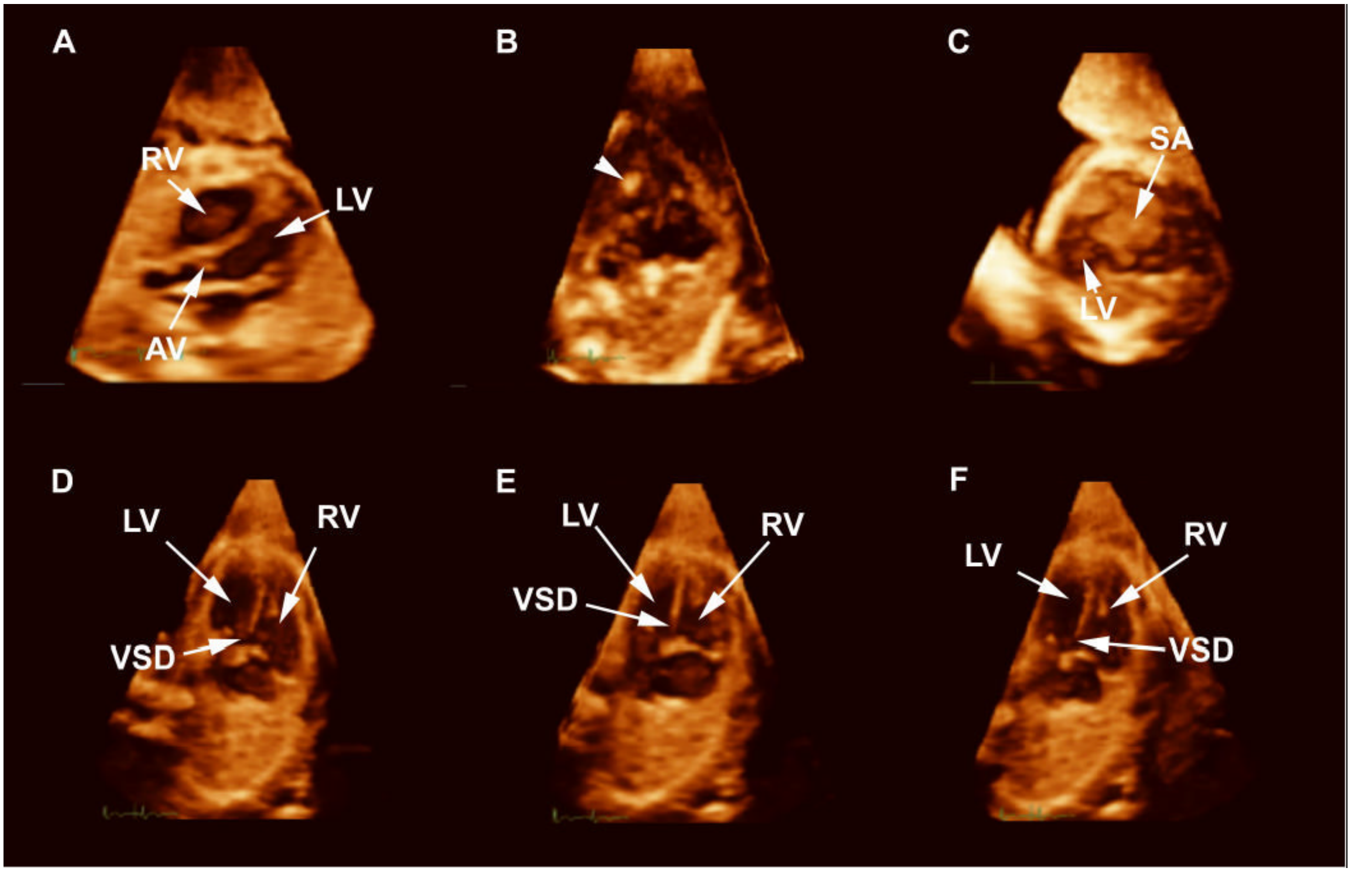

Figure 06.

Real-time direct 4D ultrasonography of the fetal heart. A) Left ventricular outflow tract. B) Echogenic foci in the left ventricle. C) Unbalanced AV canal with hypoplastic right ventricle. D, E and F) Perimembranous ventricular septal defect visualized from the left ventricle (D), in the antero-posterior projection (E), and from the right ventricle (F). Legends: RV = right ventricle; LV = left ventricle; AV = aortic valve; SA = single atrium; VSD = ventricular septal defect.

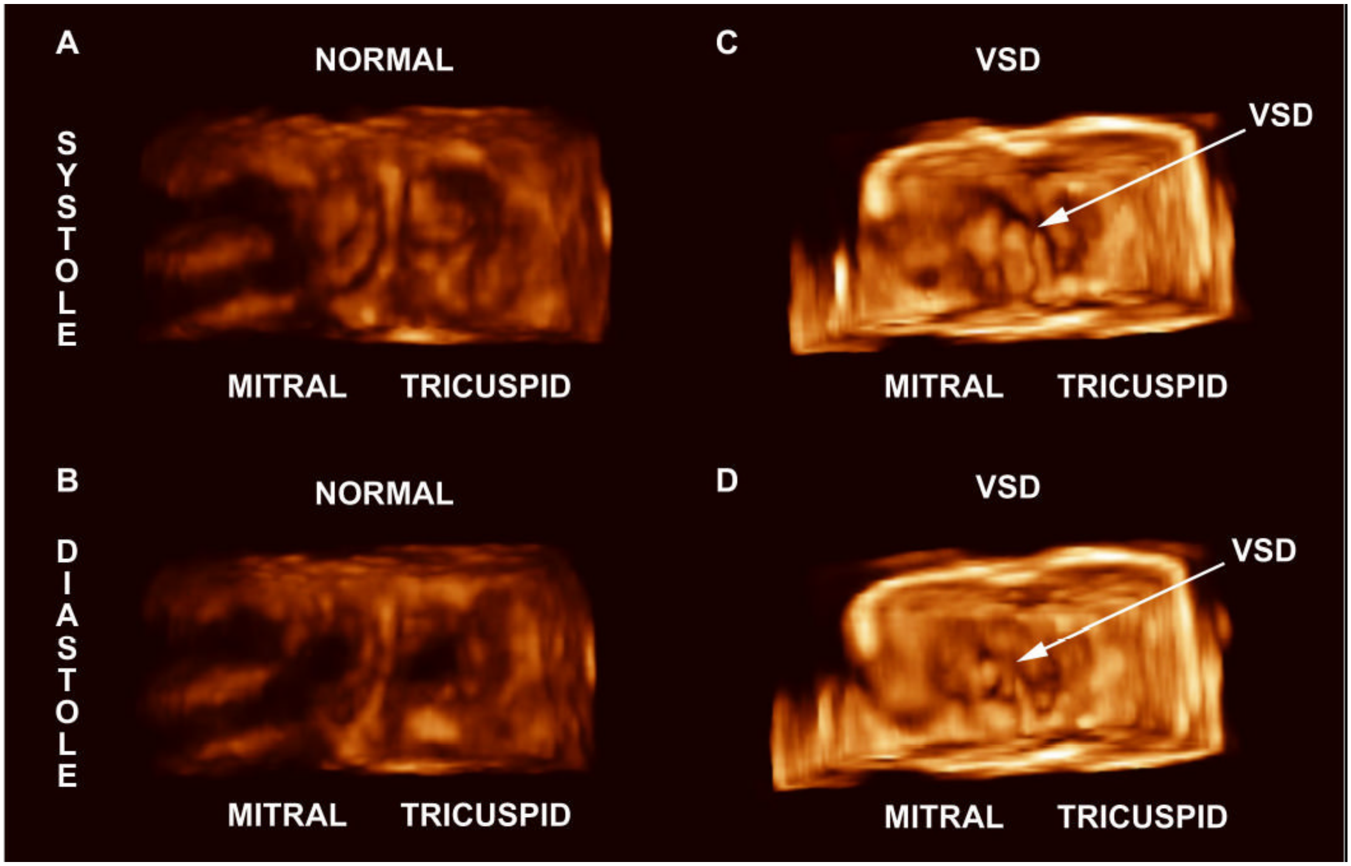

Figure 7.

Real-time direct 4D rendering of the atrioventricular valves “en face”. A and B) normal “*en face*” views of a normal mitral valve in systole and diastole. C and D) Ventricular septal defect (VSD) demonstrated in systole (C) and diastole (B).

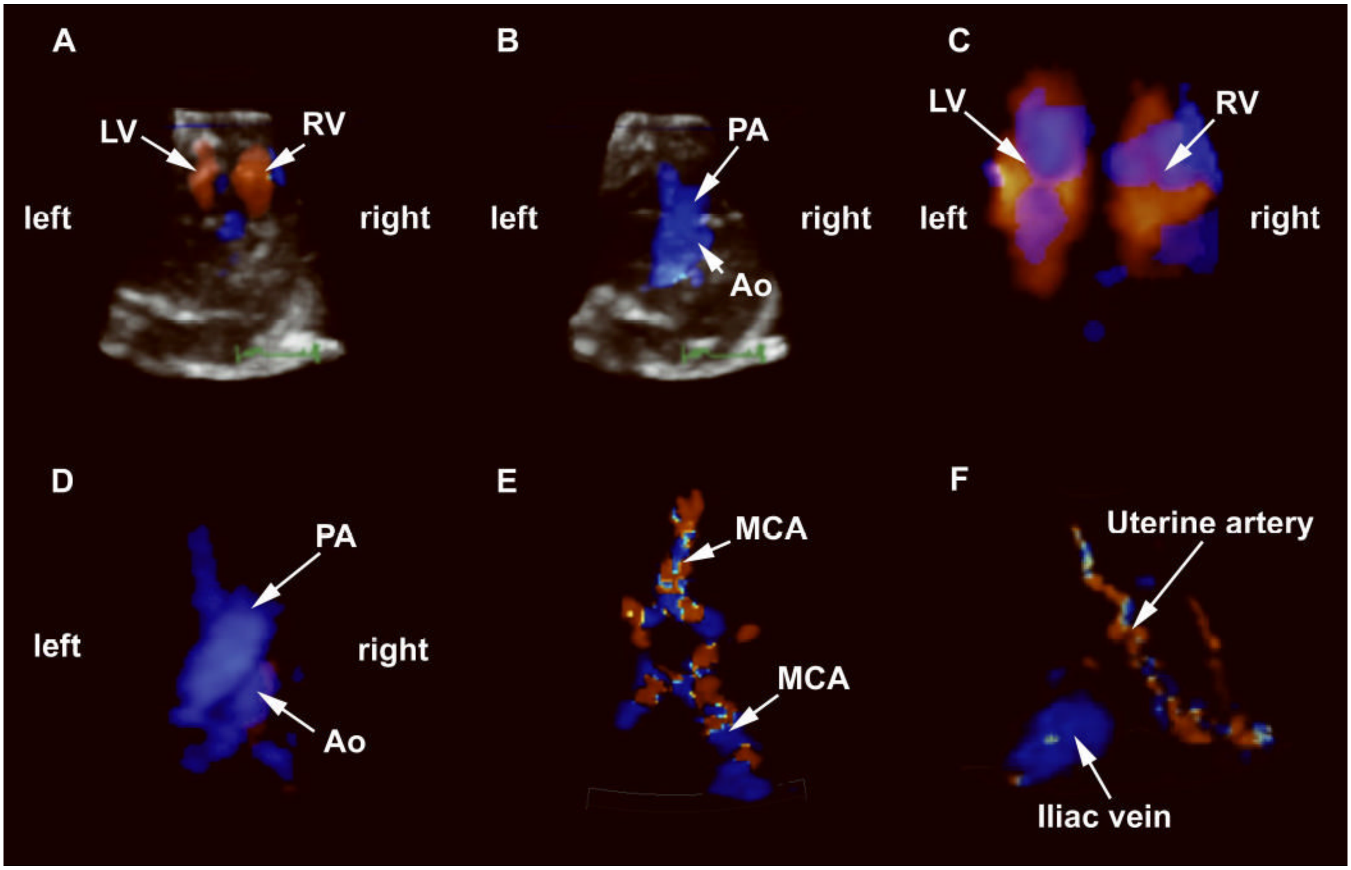

Figure 8.
A) Full volume 4D color volume dataset of a normal fetal heart; the gray scale was partially suppressed; the left (LV) and right (RV) ventricles are visualized in red during diastole. B) Full volume 4D color volume dataset of a normal fetal heart in systole; the pulmonary artery (PA) crosses in front of the aorta (Ao). C and D) Same volume datasets as A and B, with complete gray scale suppression. E) Full volume 4D volume dataset of the circle of Willis; both middle cerebral arteries (MCA) are visualized. F) Full volume 4D color dataset of a maternal uterine artery.

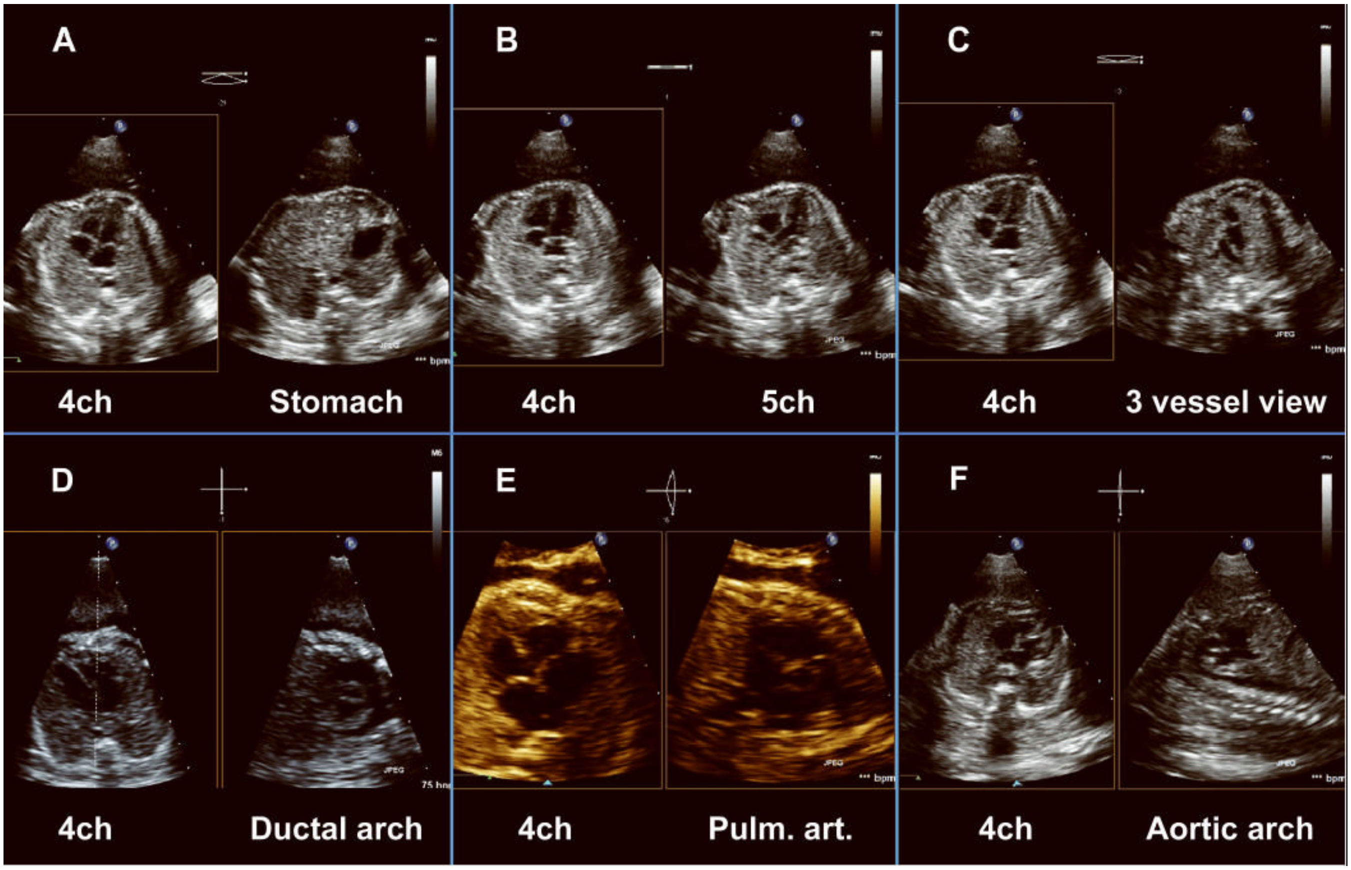

Figure 9.

Live xPlane imaging of the fetal heart. The left side of the screen shows the original plane of acquisition (in this case the four-chamber view – 4ch). The right side of the screen displays planes of section that are obtained by electronically steering a secondary ultrasound beam using elevation or lateral tilts. The transducer does not move while the beam is electronically steered. Figures 8A through 8C show images that were obtained with elevation tilts of the transducer while imaging the 4ch: abdominal circumference, 5-chamber view (5ch), and three-vessel view. Figures 8D through 8F show images that were obtained with lateral tilts of the transducer while imaging the 4ch: ductal arch, short axis view of the right ventricular outflow tract, and aortic arch.

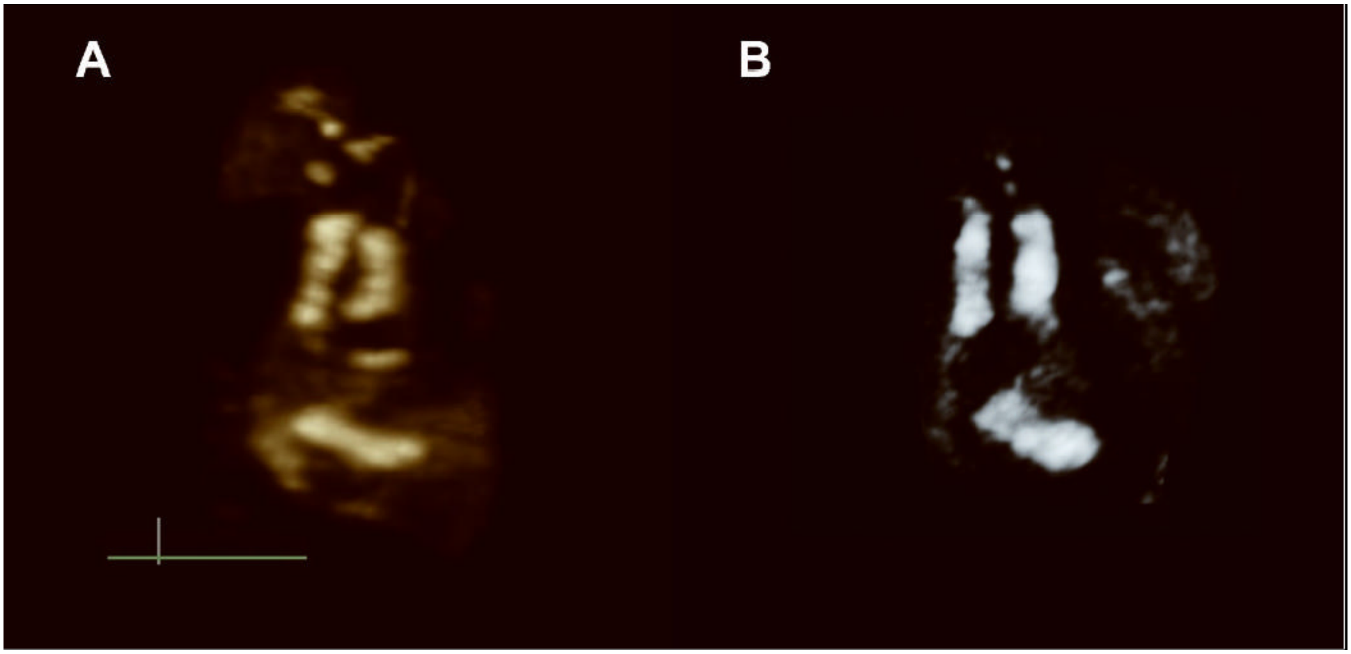

Figure 10.
Femur, tibia, and fibula in a 20 week fetus with thanatophoric dysplasia. A) Rendered view of the bones obtained with the 2D matrix array transducer in real-time. B) Rendered view of the bones obtained by reconstruction of the volume dataset acquired using a mechanical probe.