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173 Three-Dimensional Ultrasound: Techniques and Clinical Applications

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Introduction

Fetal anatomy is three-dimensional (3D). Cross-sections obtained during real-time ultrasound (US) examination are an artificial reduction of anatomy to produce one still image, created to capture a standard view or the essence of a particular pathology. Acquisition of a good US volume is not trivial, but a comprehensive volume may enable examination at a greater level of detail than is possible from a single cross-section; this is similar to a video in that multiple different neighboring sections are displayed.

Volume Displays

Three-dimensional US volumes can be analyzed visually in two principal ways: by viewing cross-sections or surface-rendered views. Cross-sections (planes placed anywhere in the volume) are viewed in either one single plane or two/three (typically orthogonal) planes. The latter is usually called *multiplanar display* (Fig. 173.1). Before examining the anatomy, the multiplanar display should be used to align the volume according to standard planes (Fig. 173.2 [face acquire, align]). A curved section can also be placed to follow anatomic structures that do not lie in a straight plane, such as the fetal palate (Fig. 173.3). A display of a number of parallel cross-sections is usually called *tomographic display* (Fig. 173.4). Surface-rendered views are formatted to display tissue interfaces, either of soft tissue (e.g., the facial skin surface, seen from the amniotic fluid cavity) or bone (e.g., the skull bones, seen from the outside or inside), or a mixture of both (Fig. 173.5).

Technique

It is a misunderstanding and oversimplification to assume that any volume containing the structures of interest will enable extraction of diagnostic images. Three main aspects, each of which requires physical knowledge and careful execution, determine the diagnostic quality of successful 3D US: volume

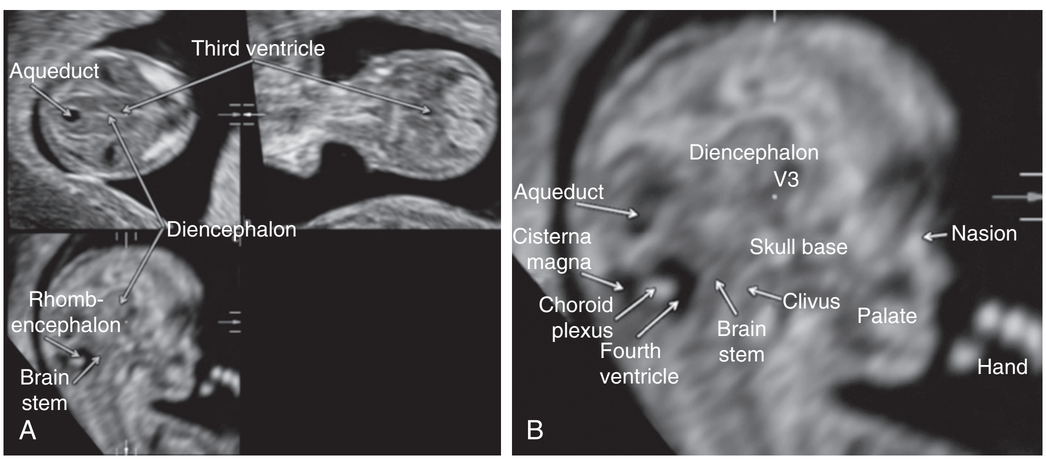
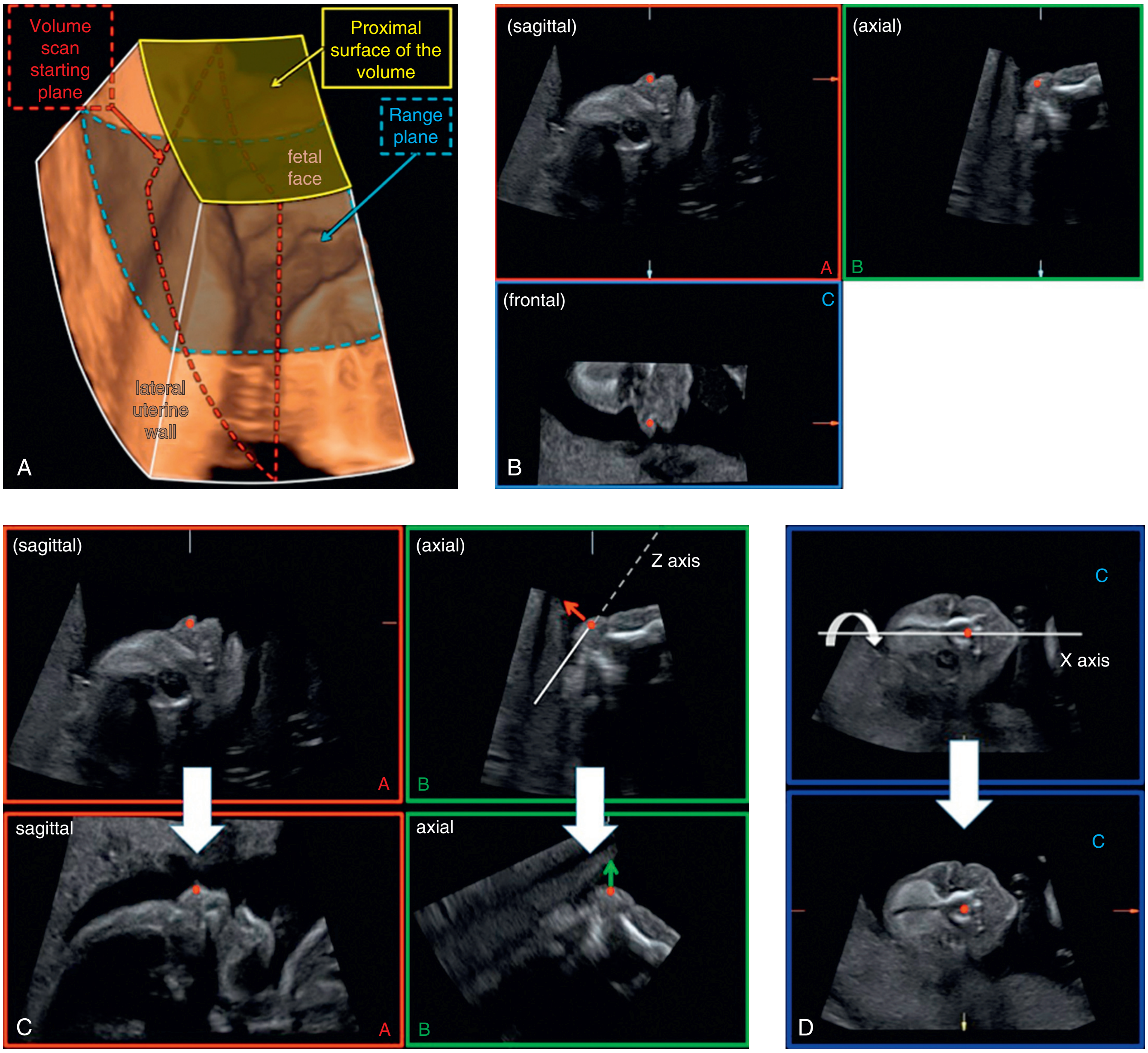


Fig. 173.1 Multiplanar display of the head of a normal fetus at 44 mm crown-rump length (corresponding to 11 postmenstrual weeks). The volume was acquired transvaginally with a median section and aligned anatomically. The reference dot is positioned in the third ventricle, and volume contrast enhancement (1 mm slice thickness) was used. (A) Multiplanar display of axial, coronal, and sagittal sections. (B) Sagittal section, reformatted from the same volume (selected anatomic structures labeled).



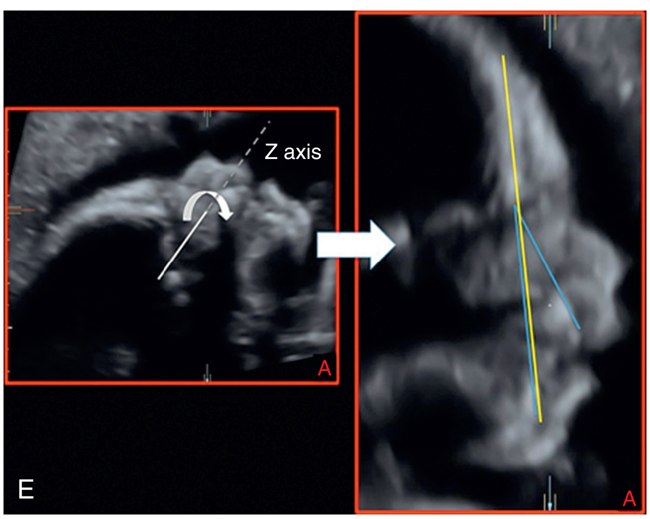


Fig. 173.2 Systematic approach to volume acquisition and stepwise alignment and rotation to extract the exact median section of a normal fetal face at 21 weeks' gestation (3). This volume was obtained from a fetus whose profile could not be obtained using real-time scanning because the fetus was facing to the side. First, the closest possible section to the profile was selected as the starting scan. Panels B to E show the stepwise extraction and eventually, analysis of the profile. (A) After volume acquisition a data block is stored, but usually not displayed. To understand the alignment better the entire volume block is shown, and the volume scan starting plane *(red)* and the range plane *(blue)* are indicated. (B) The reference dot is the intersection of the three orthogonal planes (highlighted as a *red dot* in near-sagittal, axial, and frontal sections in panels A, B, and C). In the multiplanar display the reference dot is placed on an easily recognizable structure, e.g., the tip of the nose. (C) Using the volume rotation in panel B, the direction of the nose is turned upright *(red and green arrows)*, using rotation around the Z-axis (so-called *in-plane rotation)*. (D) Then, the apparent nonalignment in panel C is adjusted to show the frontal view, using rotation around the X-axis in plane C. (E) Finally, the perfectly aligned, exactly median profile is rotated upright and studied, using the maxilla-nasion-mandible angle *(blue lines)* and the facial profile line *(yellow line)*.

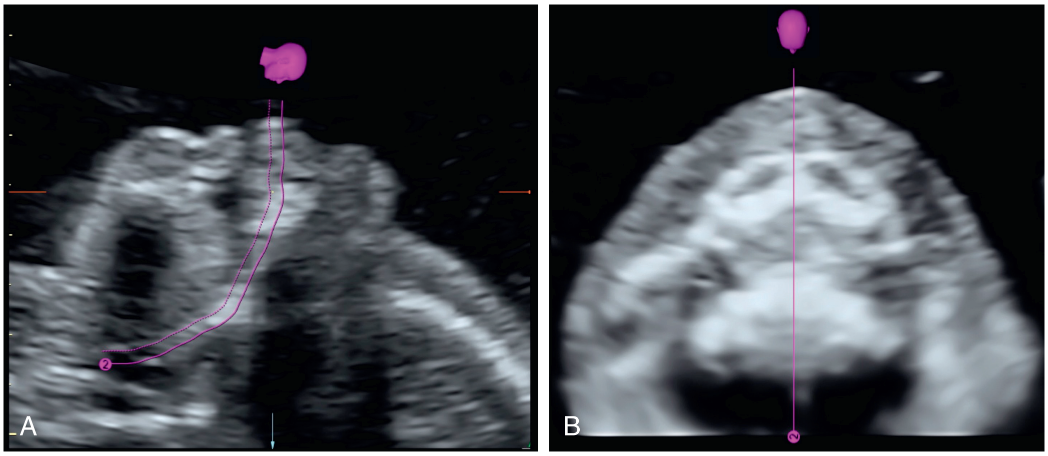


Fig. 173.3 Reconstruction of the normal fetal palate, using a curved plane. A frontal insonation of the fetal profile with transducer parallel to the frontal edges of the maxilla and the mandible was used to acquire the volume. The curved reconstruction plane (placement shown by the purple line in the sagittal section [A]) displays the entire hard and the soft palate down to the uvula in (B). *(From Tutschek B, Blaas HG, Abramowicz J, Baba K, Deng J, Lee W, et al. Three-dimensional ultrasound imaging of the fetal skull and face.* Ultrasound Obstet Gynecol *[Epub ahead of print], 2017.)*

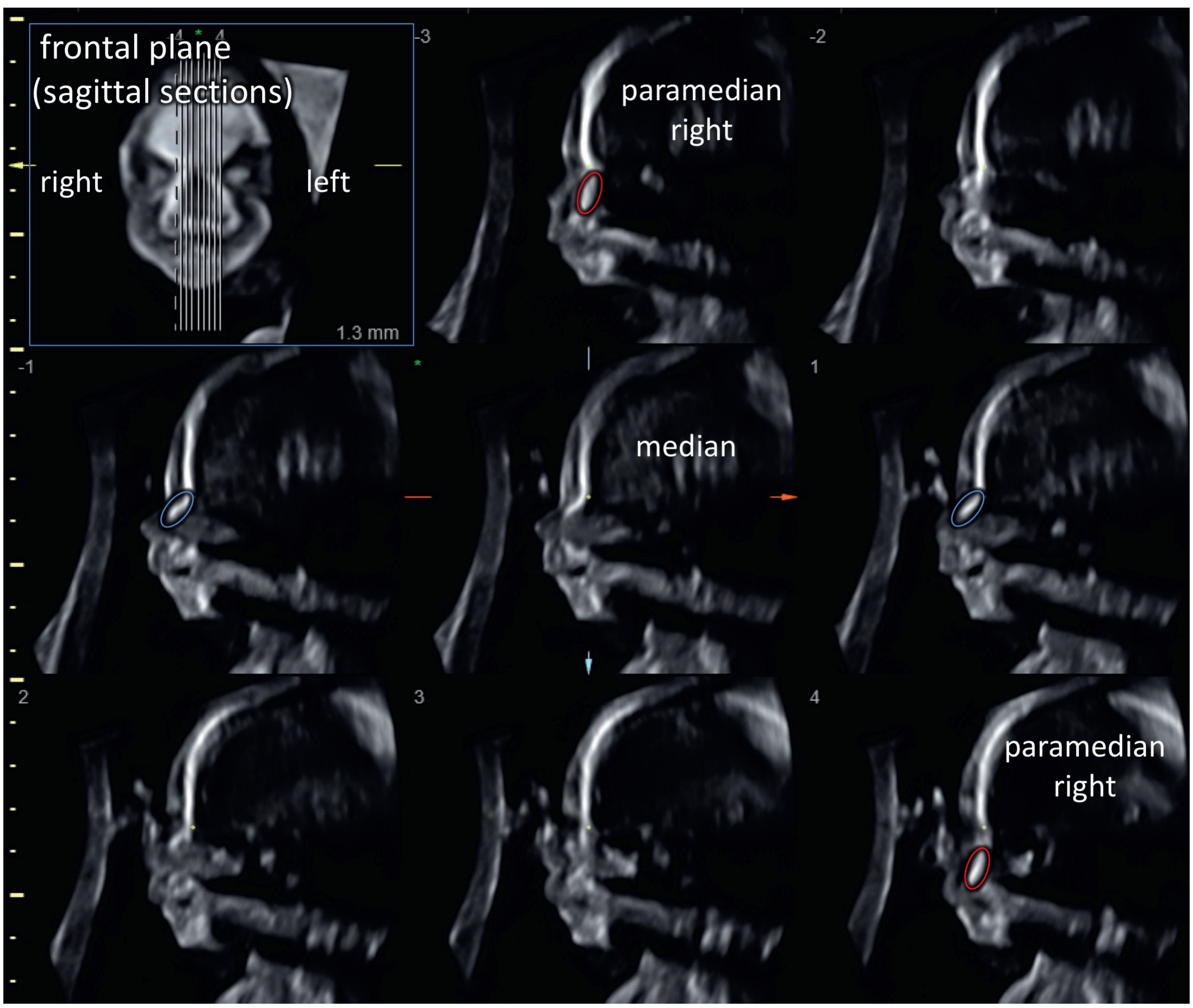


Fig.173.4 Tomographic imaging of a normal fetal profile. Narrow spacing of the adjacent sections permits differentiation between the nasal bones *(blue circles*, images −1 and 1) and the maxillary processes *(red circles*, images −3 and 4) on both sides. *(From Tutschek B, Blaas HG, Abramowicz J, Baba K, Deng J, Lee W, et al. Three-dimensional ultrasound imaging of the fetal skull and face.* Ultrasound Obstet Gynecol *[Epub ahead of print], 2017.)*

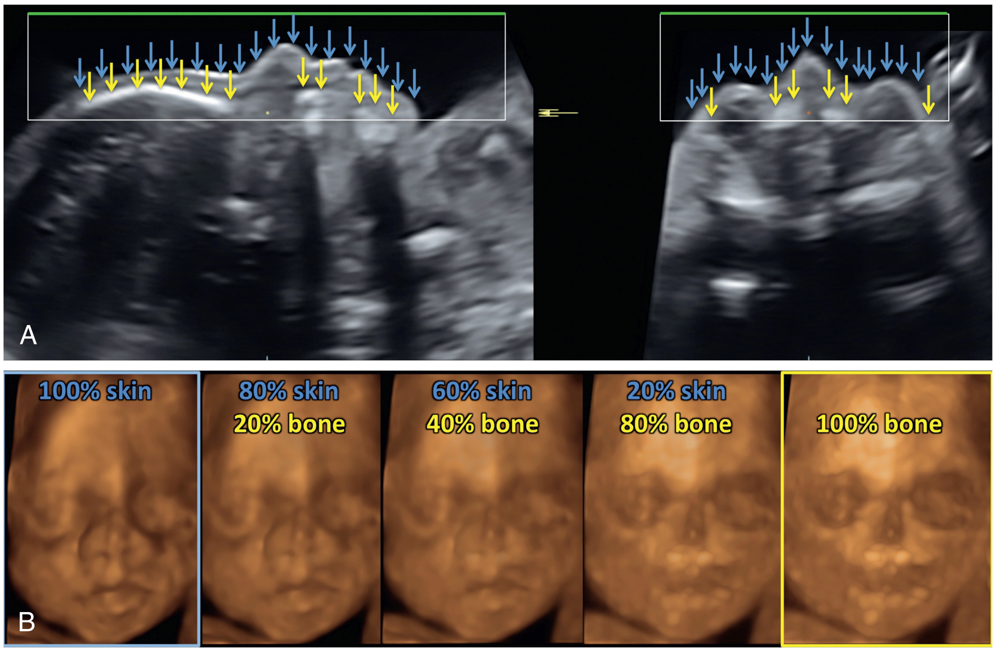


Fig. 173.5 Three-dimensional US surface rendering of the fetal face. All images in this figure were reformatted from the same volume that had been acquired using frontal insonation. For such a volume, ideally at least a small amount of amniotic fluid should be present between the face and other echogenic structures beneath the transducer. (A) Sagittal and axial sections: the adjustable render box *(white lines)* determines what the algorithm will display in 3D. The *green line* defines the direction of rendering (not necessarily, but in this example also the direction from which the object is viewed), in this example from the front. The *blue arrows* define the soft tissues seen in the display in (B), the *yellow arrows* define the bones. (B) The same volume can be "rendered" (surface-reconstructed) for either the skin surface ("100% skin," far left) or the bone surface ("100% bone," far right), or a mix of both. Note the absent ossification of both nasal bones apparent in the far-right image of (B) in this fetus with trisomy 21. *(From Tutschek B, Blaas HG, Abramowicz J, Baba K, Deng J, Lee W, et al. Three-dimensional ultrasound imaging of the fetal skull and face.* Ultrasound Obstet Gynecol *[Epub ahead of print], 2017.)*

acquisition and alignment; volume contrast enhancement; and possibly, surface rendering.

ACQUIRING AND ALIGNING A VOLUME

Successful 3D US first requires optimization of the two-dimensional (2D) image. The correct starting insonation angle with regard to the structure(s) of interest is of paramount importance. Not all sections that can be reformatted (extracted) from a 3D volume have the same resolution. In diagnostic US, the axial resolution (in the axis directed perpendicular away from the transducer) is better than the lateral resolution. Therefore the resolution in the acquisition plane (also called *azimuth plane)* is best; this plane is typically displayed in panel A directly after volume acquisition. The so-called *range plane* (blue plane in Fig. 173.2A), which cannot be obtained in real-time scanning by simply rotating the transducer, offers the lowest resolution, yet it often contains valuable information that cannot be obtained by maneuvering the transducer on the maternal abdomen, or in case of transvaginal scanning, in the vagina.

The starting plane for a volume acquisition should be placed to show the structures of interest as well as possible. Then the volume is acquired and initially displayed in the multiplanar mode (showing three orthogonal planes: A, B, and C; Fig. 173.6). Each of these planes can be aligned, using rotation around the X, Y, and Z axes, respectively, to achieve the intended orientation, typically in standard anatomic sectional planes. A clinical example of this workflow for the fetal face is shown in Fig. 173.2.

VOLUME CONTRAST ENHANCEMENT

US volume contrast enhancement is an excellent tool to differentiate tissues better than simple real-time 2D imaging. Its principle is to compare information for closely adjacent parallel sections ("slices") in the volume to identify true signals and "noise." Then only signals present in several sections are displayed, resulting in a markedly improved contrast. The "slice thickness" for volume contrast enhancement can be adjusted according to the age of the embryo or fetus (usually 1 mm during early gestation; see Fig. 173.1) or 2–5 mm or more (from the second trimester onward) and that of the targeted anatomic region, e.g., brain, trunk (Fig. 173.7), or extremities (Fig. 173.8).

Volume contrast enhancement works on static volumes as well as during live scanning. Static volumes analyzed with contrast enhancements are particularly useful for examination of early pregnancies (with transabdominal and transvaginal scanning) and for the fetal brain. Dynamic volume contrast enhancement is useful for regions with relevant anatomic structures in adjacent but different planes, such as the small bones in the hands and feet or the vessel near the fetal heart (Video 173.1).

SURFACE RENDERING

Rendered views display outer or inner surfaces using 3D US data. A *render box* defines the exclusive volume in which structures will be considered for spatial reconstruction (see Fig. 173.5). It also determines the direction of view toward the reconstructed

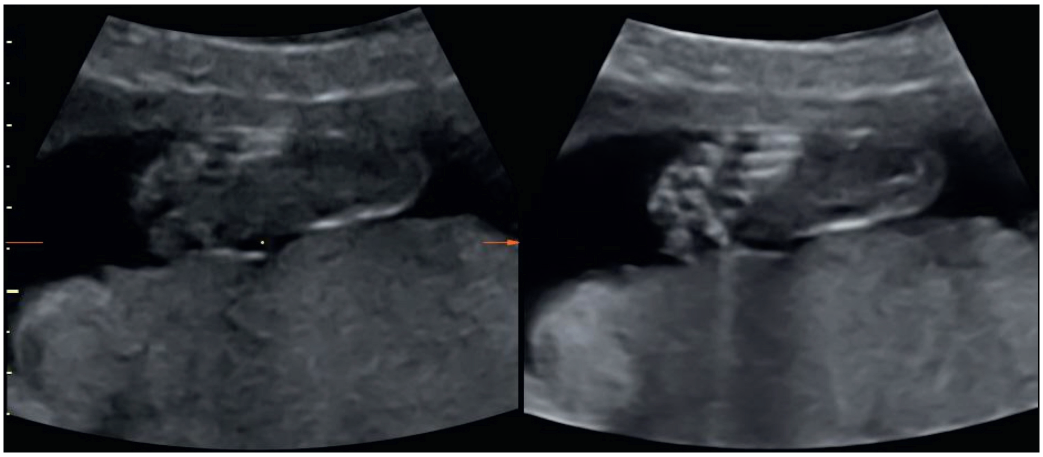


Fig. 173.6 Still image from a real-time scan to examine the foot of a normal 20-week fetus using volume contract enhancement. The regular cross-sectional image is shown on the left, and the three-dimensional ultrasound image with volume contrast enhancement on the right. In the left panel, the foot can be seen, and a few of the small bones are apparent. Real-time volume contrast enhancement (right panel) visualizes both the soft tissue as well as all mineralized bones from all toes and the middle foot that lie in different, but neighboring, sections. The slice thickness used for this example was 5 mm.

Fig. 173.7 Median section of a normal fetal trunk, 3D display using volume contrast enhancement. This still image was extracted from Video 173.1 acquired as a live sequence with a slice thickness of 5 mm. *Desc. Ao*, Descending aorta; *DV*, ductus venosus; *IVC*, inferior vena cava; *RV*, right ventricle; *UV*, umbilical vein.

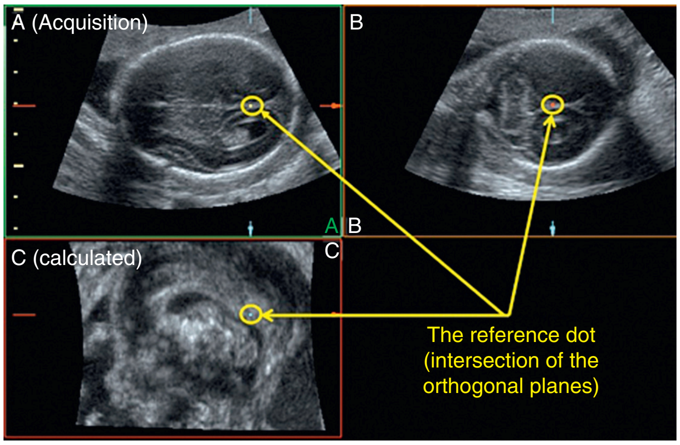


Fig.173.8 Multiplanar display of a normal fetal head, reformatted from the volume acquired using lateral insonation with the ear facing the transducer. Panel (A) initially represents the section corresponding to the starting section of the volume sweep, in this case an axial view of the transventricular plane. Panel (B) could also be obtained in real-time cross-sectional scanning by rotating the transducer around its cable axis. (C) is the most heavily "calculated" plane, in this case a sagittal section of the head that in this fetal lie could not be obtained using transabdominal scanning.

structure. The render box can be adapted to encompass the entire anatomic structure of interest. The "skeletal mode" is used to display skeletal structures such as the fetal skull or other segments of the fetal skeleton.[1,2] Changing the postprocessing allows display of surface views for the skin and/or the bones from the same volume (see Fig. 173.5).

Fetal Anatomic Evaluation

BRAIN

Even in the first trimester, embryonic and fetal brain structures can be resolved using transvaginal and transabdominal probes, often with amazing detail (see Fig. 173.1).

Beyond the first trimester, a typical starting insonation for standard axial section is a lateral view with the ear facing the transducer (see Fig. 173.6). The resulting multiplanar display is then used to align the volume anatomically in three planes, analogous to the description for the fetal face (see Fig. 173.2) using the reference dot (the intersection of the three orthogonal planes) to navigate, and by rotating and scrolling each plane.

The posterior fossa and its contents benefit from a slightly more dorsal starting view, exploiting the mastoid fontanel and the lambdoid suture (Fig. 173.9). This insonation, possibly combined with volume contrast enhancement, permits detailed analysis of the cerebellar vermis. The ideal starting insonation to obtain a volume optimized for the cerebellar vermis is a median section. Although a median section is often more difficult to obtain, the fontanels can be used as acoustic windows (Fig. 173.10). The midline structures and the posterior fossa are better resolved in median sections, both in 2D and 3D.[3] If the fetus is not in cephalic lie, a median section can usually be acquired by exploiting the sagittal suture and the anterior and posterior fontanels (see Fig. 173.10), or using the transvaginal approach, if the fetus is in cephalic lie.[4]

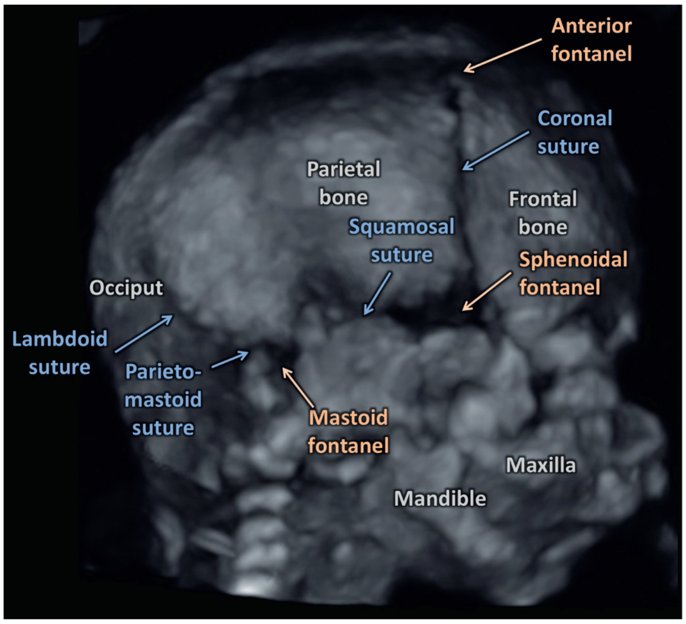


Fig. 173.9 A normal skull of a 19-week fetus, analyzed using three-dimensional ultrasound. This volume had been acquired transabdominally, with a starting scan in axial orientation and the fetal ear facing the transducer, and rendered for bone surfaces. *(From Tutschek B, Blaas HG, Abramowicz J, Baba K, Deng J, Lee W, et al. Three-dimensional ultrasound imaging of the fetal skull and face.* Ultrasound Obstet Gynecol *[Epub ahead of print], 2017.)*

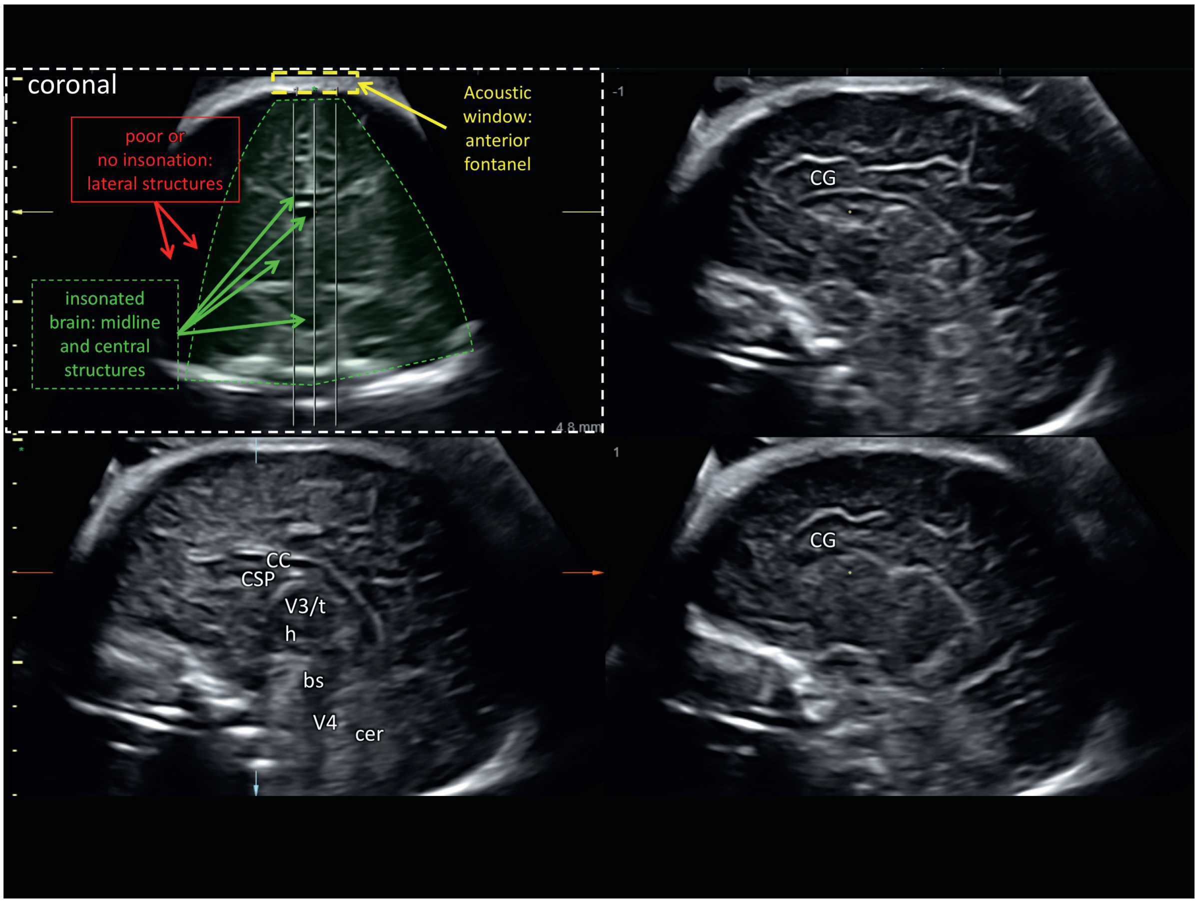


Fig. 173.10 Detailed brain analysis in a 33-week fetus, using transabdominal three-dimensional ultrasound and transfontanel insonation. This image shows a volume contrast-enhanced multiplanar view of a fetal brain, acquired through the large fontanel and sagittal suture with the 3D transducer placed above the vertex. Three-dimensional US provided excellent resolution of the fissures and gyri on the medial brain surface. *bs*, Brain stem; *CC*, corpus callosum; *cer*, cerebellar vermis; *CG*, cingulate gyrus; *CSP*, cavum of the septum pellucidum; *V3/th*, third ventricle and thalamus; *V4*, fourth ventricle.

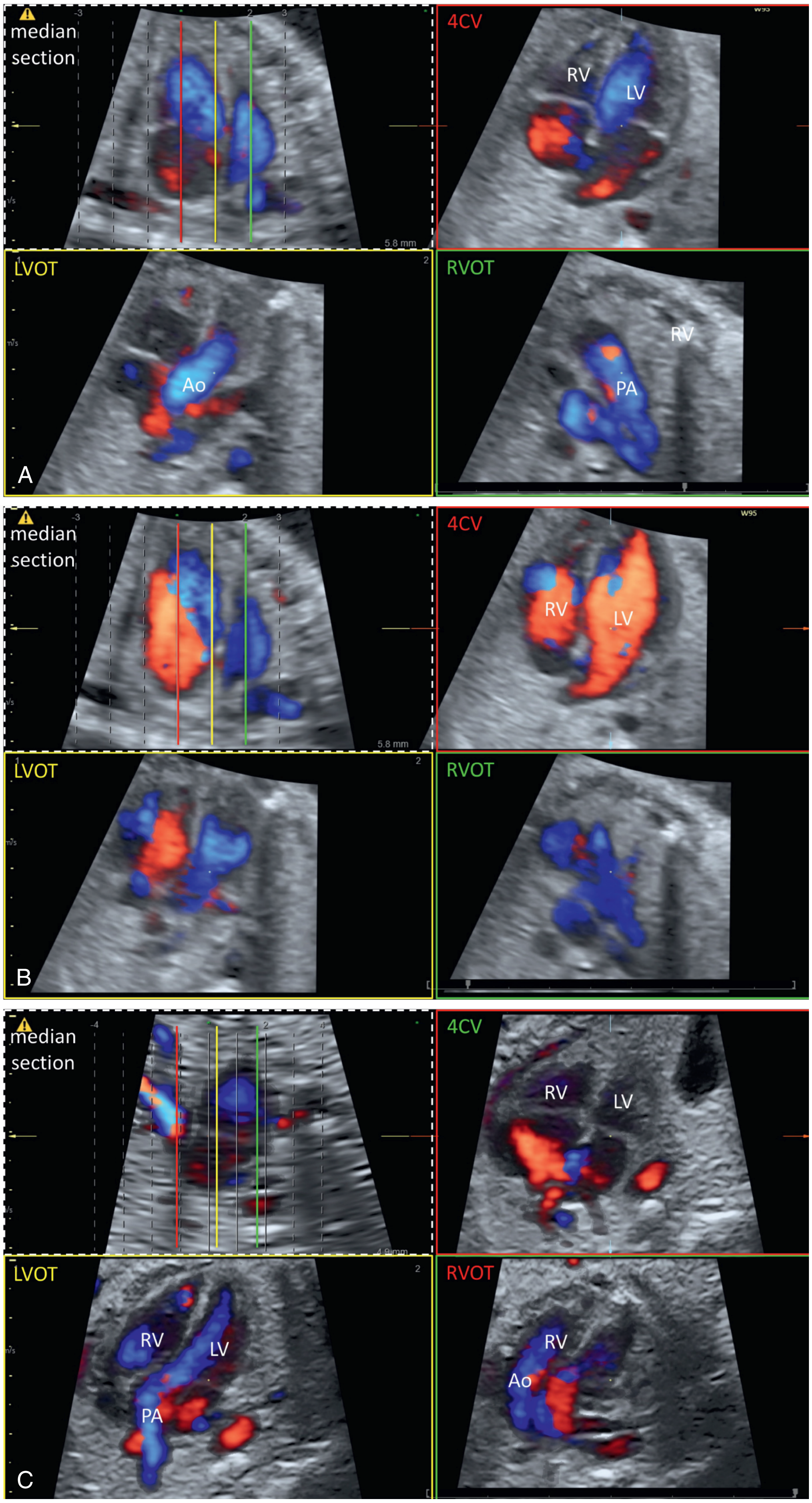


Fig. 173.11 Normal and abnormal midtrimester fetal hearts, displayed using color Doppler and tomographic imaging. (A) A fetal heart at 23 weeks in systole, showing tomographic imaging of the four-chamber view *(4CV)* and the left and right outflow tracts *(LVOT/Ao, RVOT/PA)* in systole. Note that at 23 weeks in a normal heart the *4CV, LVOT,* and outflow tracts are almost in parallel planes and that these planes are at an equal distance of about 5 mm apart from each other. (B) The same heart in diastole. For a video of this display, see Video 173.2. (C) The same display used for a fetal heart with d-transposition of the great arteries *(d-TGA)* at 23 weeks. The vessel arising from the left ventricle branches after a short course; it is the transposed pulmonary artery. The second vessel, arising from the right ventricle, is the aorta, which travels parallel to the pulmonary artery and does not cross the pulmonary artery. For a video of this display, see Video 173.3. *Ao,* Aorta; *LV,* left ventricle; *LVOT,* left ventricular outflow tract; *PA,* pulmonary artery; *RV,* right ventricle; *RVOT,* right outflow tract.

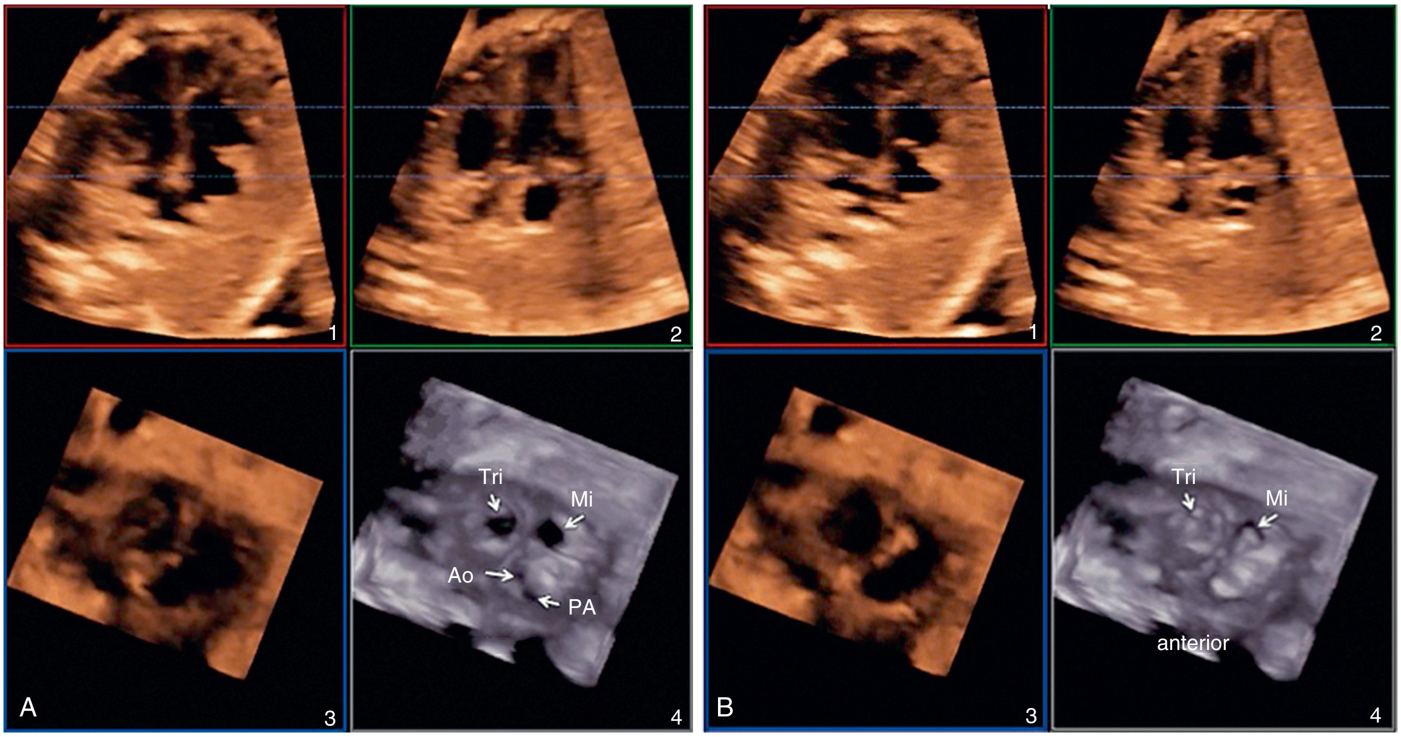


Fig. 173.12 Multiplanar display plus surface rendering of a normal midtrimester heart. The sepia-colored panels show three orthogonal planes with the four-chamber view in the top left. The gray image is a rendered *en-face* view of the atrioventricular *(AV)* valve plane. (A) shows the AV-valves open, (B) closed (Video 173.4). *Ao,* Aortic valve; *Mi,* mitral valve; *PA,* pulmonary artery; *Tri,* tricuspid valve.

In the third trimester, there is increasing shadowing because of progressive ossification of the skull. Using the sutures and fontanels as acoustic windows into the brain (see Figs. 173.9 and 173.10) can help to partially overcome this limitation. Fig. 173.10 shows a volume contrast-enhanced multiplanar view of a fetal brain, acquired from a normal 33-week fetus in transverse position through the large fontanel and sagittal suture. In this fetal lie, positioning of the 3D transducer above the vertex is possible. Appropriate use of 3D US provides excellent resolution, superior to 2D US, to study the fissures and gyri on the medial brain surface.

Detailed descriptions of the 3D US analysis of the fetal brain have been proposed.[4-7] Operators with specific technical expertise have demonstrated that remote review of 3D US volumes of the fetal brain can provide accurate and reliable diagnoses of fetal brain anomalies.[8]

3D US is also ideally suited for teaching, self-study, and to provide reference material or atlases of normal and abnormal anatomy. Normal brain section in anatomic standard orientations and an interactive atlas of fetal brain pathologies can be seen at http://pb.fetal.ch.[9]

HEART

Capturing images of the fetal heart adds another level of complexity, a "fourth" dimension: motion. Today's diagnostic systems cannot yet acquire volume sequences at a rate that would allow detailed assessment of the fetal heart with sufficient temporal resolution during a cardiac cycle. Reconstructed echocardiography is the current standard: during an automated sweep of the probe across the fetal heart over a few seconds, a series of adjacent cross-sectional images is acquired. Then reconstruction into one virtual heartbeat as a volume sequence is achieved by automatic spatial and temporal rearrangement of several hundred sections (spatial-temporal image correlation [STIC]).[10] Clinical systems commercially available today mostly use STIC for grayscale and color Doppler[11-13] (for review, see Tutschek et al.[14]).

Cardiac volumes or volume sequences can be used to extract a single diagnostic plane, to produce multiplanar or tomographic displays, or to reconstruct (inner) surfaces including the space occupied by blood flow, detectable with color Doppler. Fig. 173.11 shows a normal and abnormal fetal midtrimester heart, analyzed identically using tomographic imaging. Reconstructions of inner surfaces are useful to assess atrioventricular valve anatomy or relationship of valve orifices—for example, from a reconstructed plane resembling the view of the cardiac surgeon from the atria onto the atrioventricular valve plane (Fig. 173.12).

Blood flow can be visualized together with the surrounding tissues, which can be useful to characterize small vessels or shunts (Fig. 173.13). The blood pool during individual segments of the cardiac cycle can be rendered as an "internal surface," which is possible also with added blood flow information from color Doppler (Fig. 173.14).

WHAT THE REFERRING PHYSICIAN NEEDS TO KNOW

Diagnosticians should of course understand anatomy in its three dimensions. Currently, 2D US is the standard for the fetal screening exam, but there should be a low threshold for using 3D US because of its potential for enhanced visualization of fetal structures.

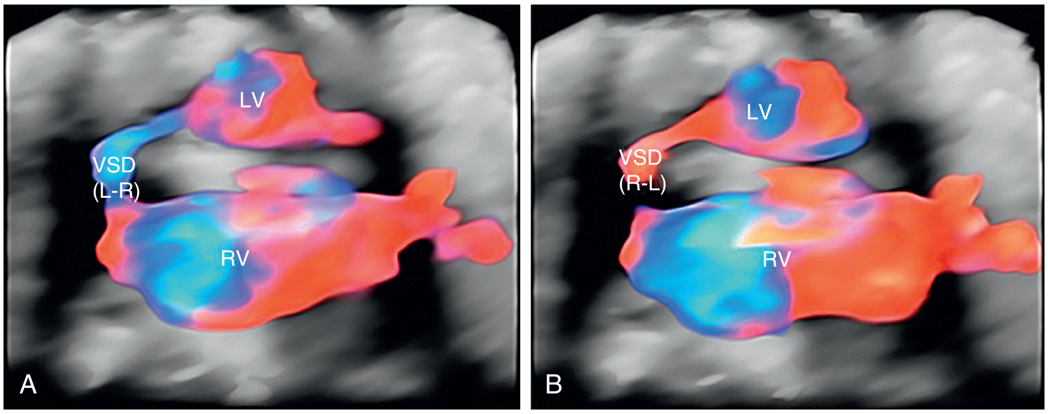


Fig. 173.13 Fetal muscular ventricular septal defect *(VSD)* at 27 weeks, shown in three-dimensional imaging with color Doppler, rendered to display only the ventricles and the VSD. This VSD was not apparent on the central four-chamber view because it crossed the septum close to the diaphragmatic surface. Note the bidirectional flow; (A) left to right, *shown in blue;* (B) right to left, *shown in red,* apparent in different segments of the cardiac cycle. See Videos 173.5 and 173.6. *LV,* Left ventricle; *RV,* right ventricle; *VSD (L-R),* ventricular septal defect, left-to-right shunt; *VSD (R-L),* ventricular septal defect, right-to-left shunt.

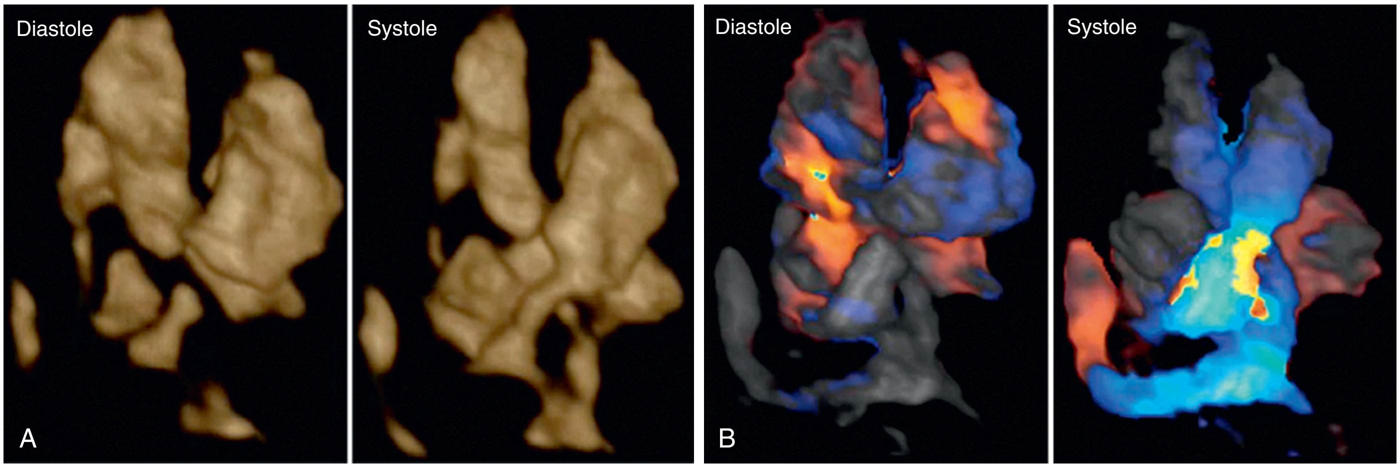


Fig. 173.14 Reconstruction of blood flow and blood pool as "internal surface" of a normal fetal heart at 29 weeks' gestation, full volume rendering seen from cranially. (A) Blood pool, surface rendered. (B) Blood pool plus color Doppler signal from moving blood, surface-rendered. *(From Tutschek B, Sahn DJ. Three-dimensional echocardiography for studies of the fetal heart: present status and future perspectives.* Cardiol Clin *25(2):341–55, 2007.)*

KEY POINTS

- Obtaining 3D volumes, while not trivial, is certainly possible and easily learned.
- 3D US can add significant value to the fetal anatomic examination, especially for certain structures such as central nervous system, face, and heart.
- 3D US should be considered an integral part of the general obstetric US.

***All references available online at* www.expertconsult.com**