REVIEW ARTICLE

Development of 3D Ultrasound

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Abstract

Significant advances have been made in recent years in clinical application of 3D sonography in both obstetrics and gynecology. Since the author pioneered the use of 3D sonography many new clinical useful techniques have been used for better visualization of early human development and for the diagnostics of many gynecological problems as well as the use of 3D in management of female infertility. In this review we are describing further development in 3D ultrasound, which should be of general interest of readers of this journal.

Keywords: 3D sonography, Clinical application, Gynecological tumors, Early human development.

Szilard developed a mechanical three-dimensional (3D) display system to see a fetus three-dimensionally in 1974.[1] Brinkley and colleagues developed a 3D position sensor for a probe. They acquired many tomographic images of a stillbirth-baby under water, traced its outline manually and showed its wire-framed 3D image in 1982.[2]

A modern 3D ultrasound system was first developed by Baba and colleagues in 1986 and a live fetus *in utero* was depicted three-dimensionally.[3,4] The system was comprised of an ultrasound scanner, position sensor and computer. An imaging technology named surface rendering was used for 3D image construction. This system was also applied to placental blood flows (by combining 3D ultrasound with color Doppler) and breast ducts and tumors (by so-called inversion mode).[5]

A 3D probe and an ultrasound scanner, that displayed three orthogonal planes on a screen, were developed and became commercially available in 1989. In the early 1990s, clinical applications of the three-orthogonal plane display in obstetrics were reported.[6,7] Sohn reported translucent display by using volume rendering in 1991.[8] Since 1994, the number of reports on a 3D image of the fetus has been increasing rapidly because a 3D ultrasound scanner, that could construct and display a 3D image as well as three orthogonal planes, became commercially available.

Two unique 3D ultrasound technologies were also developed. One was defocusing lens method,[9,10] and the other was real time ultrasonic beam tracing.[11] Only a probe with a defocusing lens was used in the former method and a fetal volume image was obtained. In the latter, construction of a 3D image and 3D scanning were performed simultaneously and a complete 3D image could be obtained just when the 3D scanning was completed without any delay.

The first world congress of 3D ultrasound in obstetrics and gynecology was held in Mainz, Germany, in 1997 and the first English book on 3D ultrasound in obstetrics and gynecology was published in the same year.[12] Development of 3D ultrasound has been accelerated afterwards and all major manufacturers of ultrasound scanners provide 3D ultrasound scanners now.

What can 3D Ultrasound Do?

Three-dimensional ultrasound handles 3D data, whereas conventional 2D ultrasound can handle only 2D data (Fig. 1). These are some functions that 3D ultrasound can do but 2D ultrasound cannot:

1. Display of a 3D image
2. Display of an arbitrary section
3. Measurement in 3D space (including volume measurement)
4 Display of a 3D blood flow image

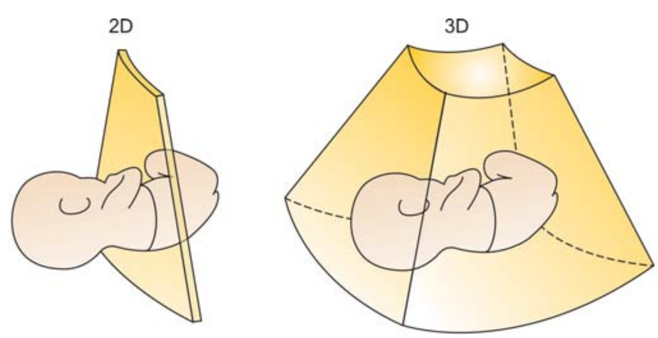


Fig. 1: Two-dimensional data for conventional 2D ultrasound (left) and 3D data for 3D ultrasound (right)[13]

5 Saving, copying and transmission of all information in 3D space
6. Reexamination with a saved 3D data set, without the patient.

TECHNICAL ASPECTS OF 3D ULTRASOUND

Various images are obtained through the following processes in 3D ultrasound:
1. Acquisition of 3D data (3D scanning)
2. Construction of a 3D data set
3. Volume visualization.

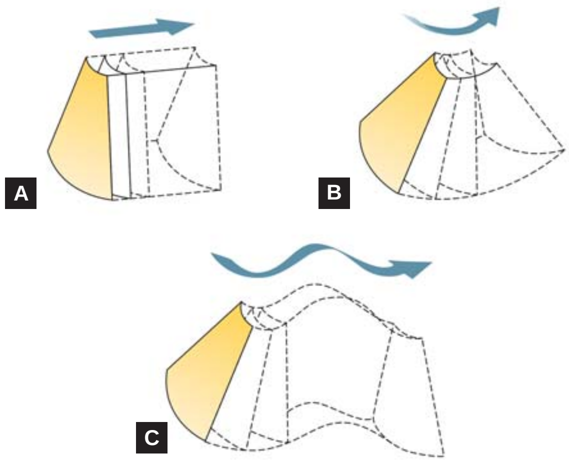
Acquisition of 3D Data

Three-dimensional data are usually acquired as a large number of consecutive tomographic images through movements of an ultrasound transducer array (conventional 2D ultrasound probe). There are some 3D scanning methods (Figs 2A to C). Each tomographic image should be acquired with its positional information for the following process, construction of a 3D data set. Accurate positional information can be obtained through an electromagnetic position sensor or an electric gyro attached to the probe (Fig. 3). However, the most popular way for 3D data acquisition now is to use a 3D probe because of its easiness for scanning. A 3D probe has a built-in transducer array (2D ultrasound probe) which tilts in the 3D probe and 3D data are obtained automatically (Fig. 4).

Ultrasound travels in a soft tissue at an average speed of 1540 m/s. This speed limits 3D scanning speed. Parallel receiving technique (Figs 5A and B) is a method to overcome the limitation. In this technique, one broad ultrasonic beam is transmitted and its echoes are received as plural ultrasonic beams. In a 2D array probe (Fig. 6), a high degree of parallel receiving (at least 1:16) is used and high speed 3D scanning is possible.[16,17]

Construction of a 3D Data Set

A number of tomographic images obtained through 3D scanning must be constructed three-dimensionally into a 3D data set for further computer processing (Fig. 7). This



Figs 2A to C: 3D scanning methods (A) parallel scanning; (B) fan-like scanning; (C) free surface scanning[14]

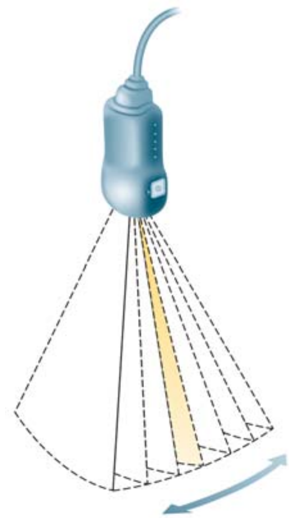


Fig. 4: 3D scanning by a 3D probe[15]

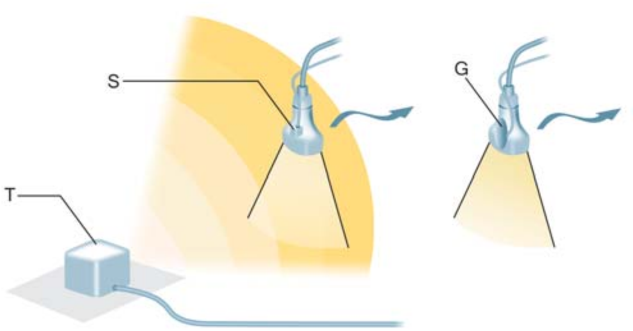
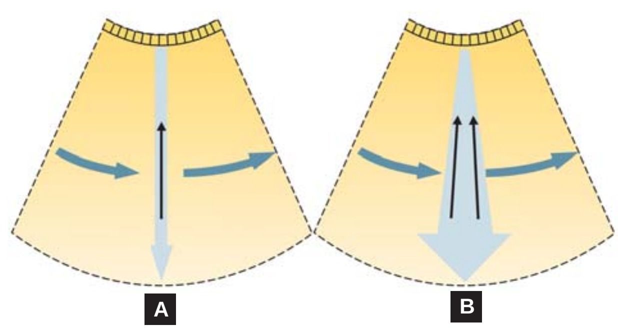


Fig. 3: A position sensor or an electric gyro attached to a probe detects a relative position of the probe. T—transmitter; S—electromagnetic sensor; G—electric gyro[15]



Figs 5A and B: Electrical scanning (A) conventional 1:1 (transmission and reception) scanning; (B) Scanning time can be reduced by 1:2 parallel receiving[15]

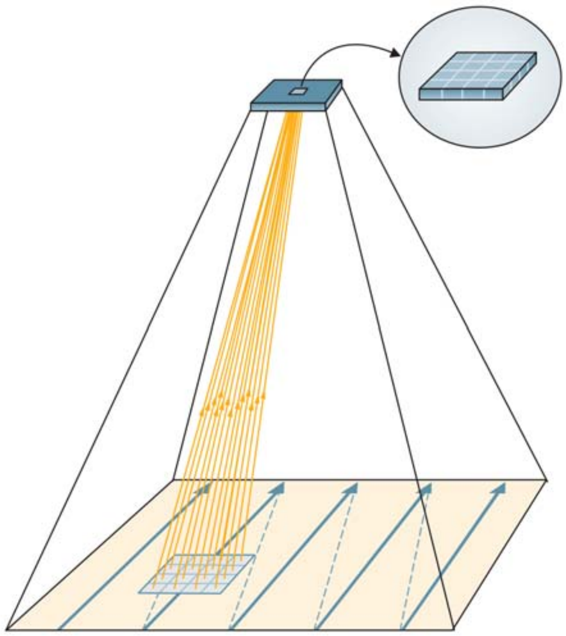


Fig. 6: 3D scanning by a 2D array probe. Transducers are arranged two-dimensionally and 3D scanning is performed electrically. High speed 3D scanning is possible by 1:16 parallel receiving[13]

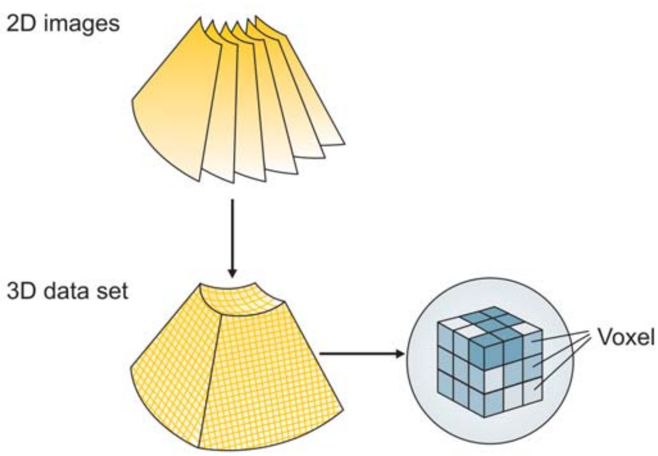


Fig. 7: Construction of a 3D data set[15]

construction process involves interpolation and improvement of data quality by filtering.[14] A 3D data set is composed of a set of voxels (volume elements). Each voxel has a gray value.

For scanning of the heart, a gated technique is applied[18,19] to avoid distortion of a 3D data set due to movement. Tomographic images are rearranged according to the phase of the cardiac cycle and a 3D data set is constructed with only tomographic images at the same phase of the cardiac cycle (Fig. 8). The heart can be seen beating three-dimensionally by constructing many 3D data sets in a single cardiac cycle.

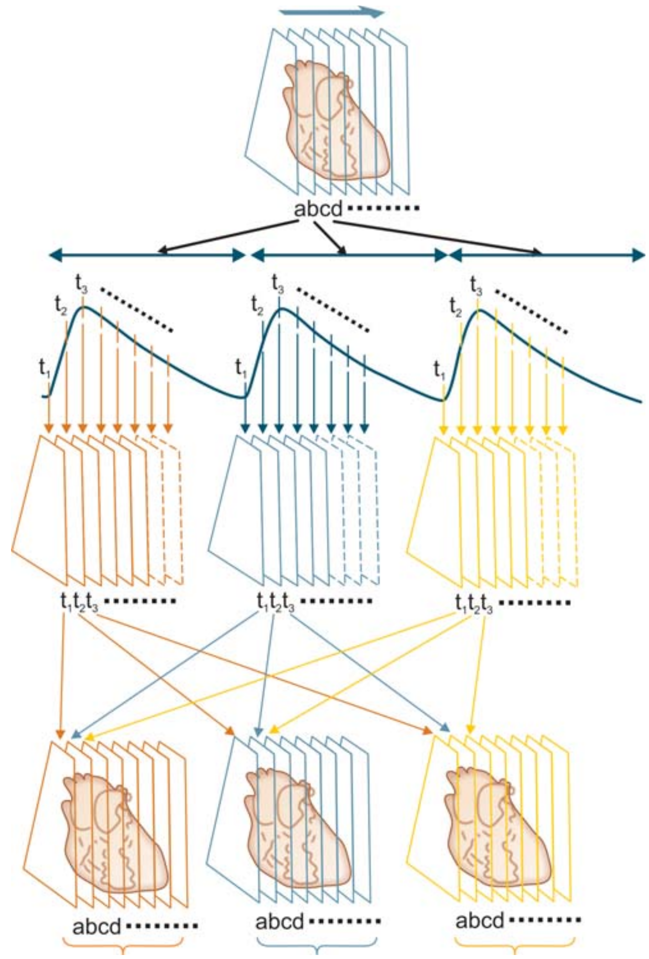


Fig. 8: A gated technique for 3D scanning of the fetal heart[13]

Volume Visualization

A 3D data set should be processed by a computer to be displayed on a 2D screen. This process is called volume visualization. These three methods are usually used for volume visualization in 3D ultrasound:

1. Section reconstruction
2. Surface rendering
3. Volume rendering.

Section Reconstruction

A sectional image can be obtained by cutting a 3D data set. An arbitrary section can be selected and displayed through translation and rotation of the 3D data set (Fig. 9). Usually three orthogonal sections (Fig. 10) or parallel sections (Fig. 11) are displayed on a screen simultaneously for better understanding of the position and orientation of each section in 3D space. These reconstructed sections, some of which cannot be obtained by conventional 2D ultrasound, are very useful for diagnosis in some cases. Three orthogonal sections may also be allocated three-dimensionally (Fig. 12).

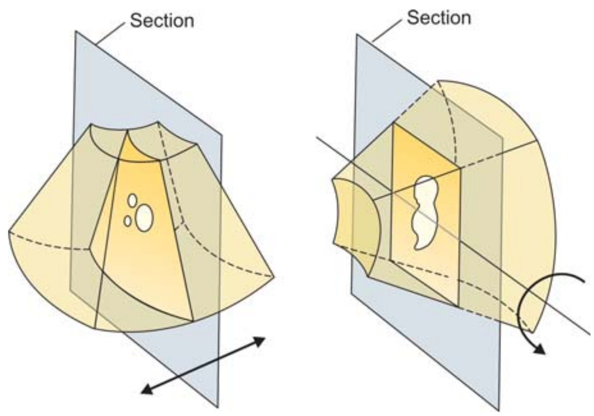


Fig. 9: Arbitrary section display by translating (left) and rotating (right) the 3D data set[15]

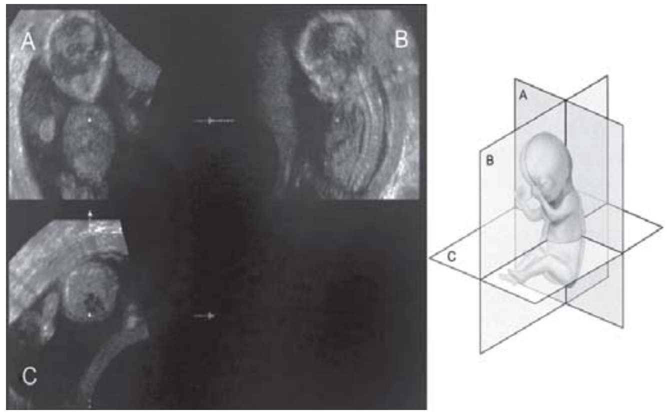


Fig. 10: Three-orthogonal-plane display of a fetus. Orthogonal triple sections of a fetus are displayed simultaneously[15]

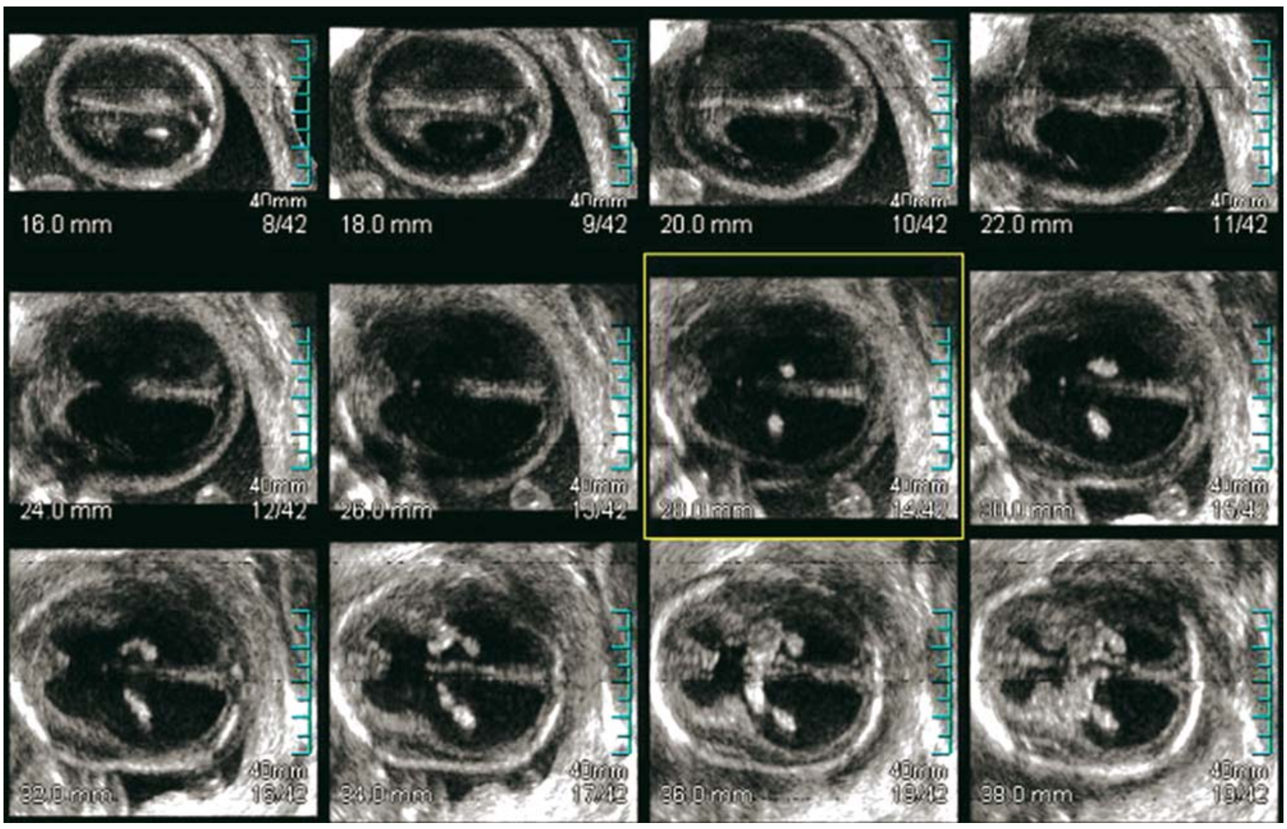


Fig. 11: Parallel sections of a fetal head with hydrocephalus at 22 weeks of gestation

Surface Rendering

A 3D surface image of the object is obtained in surface rendering. A smaller 3D data set for rendering (3D image generation) is extracted from the original 3D data set to eliminate unnecessary parts around the object as much as possible (Fig. 13). Figure 14 illustrates the principle of surface rendering. The object is extracted from the 3D data set, transformed to a set of intermediate geometrical data and projected on a 2D plane.

Extraction of the object is performed either by setting a appropriate threshold (Fig. 15) or by manual tracing. Intermediate geometrical data are composed of small cubes or small polygons (Fig. 16). Shading is necessary to model the projected image (Figs 17A and B).[14]

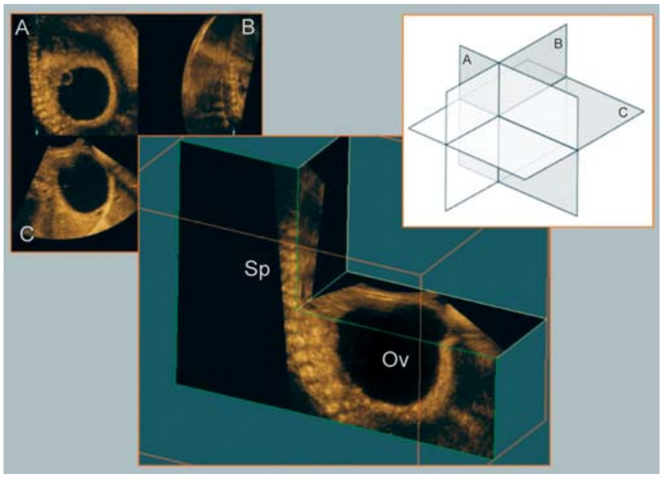


Fig. 12: A fetal ovarian cyst at 36 weeks of gestation. Three-orthogonal-plane display (left) and a display in which 3-orthogonal planes are allocated three-dimensionally (middle) as shown in the schema (right). Sp—spine; Ov—ovarian cyst

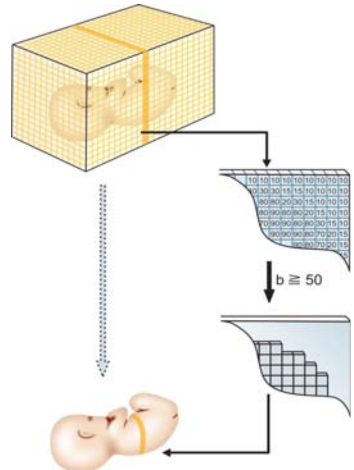


Fig. 15: Extraction of the object (segmentation) can be performed by setting a threshold properly[15]

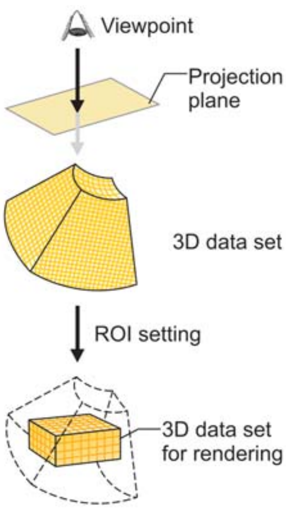


Fig. 13: Settings of a viewpoint and ROI (region of interest) for a 3D data set for rendering[15]

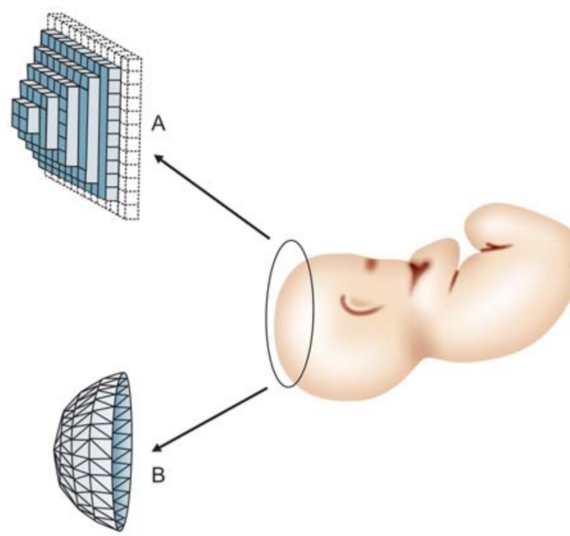


Fig. 16: Intermediate geometrical data set composed of small cubes (A) or small polygons (B)[15]

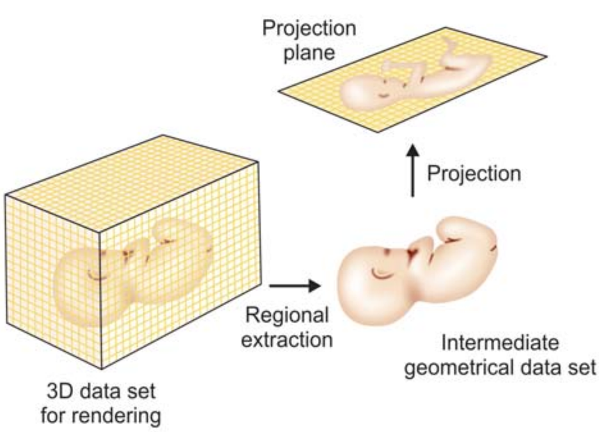
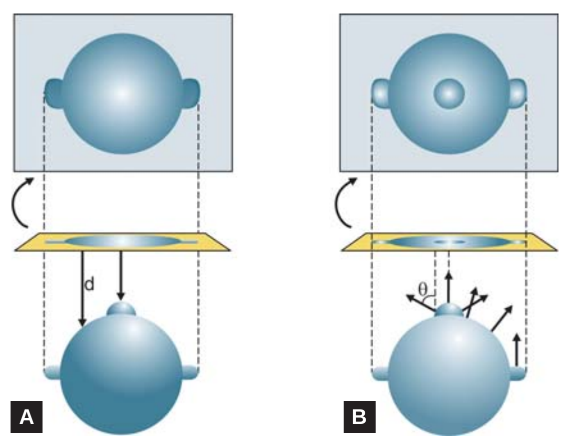


Fig. 14: Surface rendering[15]



Figs 17A and B: Shading makes a 3D image more realistic. (A) depth-only shading; (B) shading with the orientation of the object surface[15]

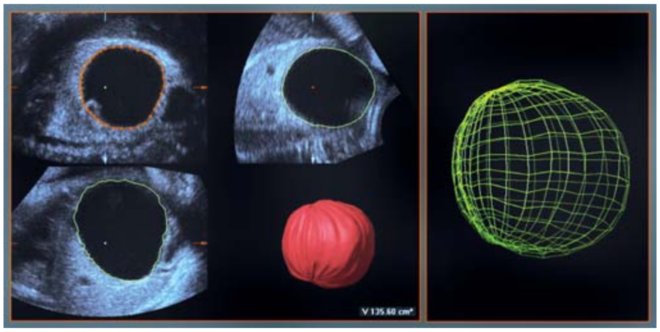


Fig. 18: Surface rendering and measurement of the volume of a fetal ovarian cyst at 36 weeks of gestation. The outlines of the cyst were traced on three-orthogonal planes and its 3D image by surface rendering is displayed (left). The 3D image is based on polygon data (right) and the volume is calculated automatically with the data

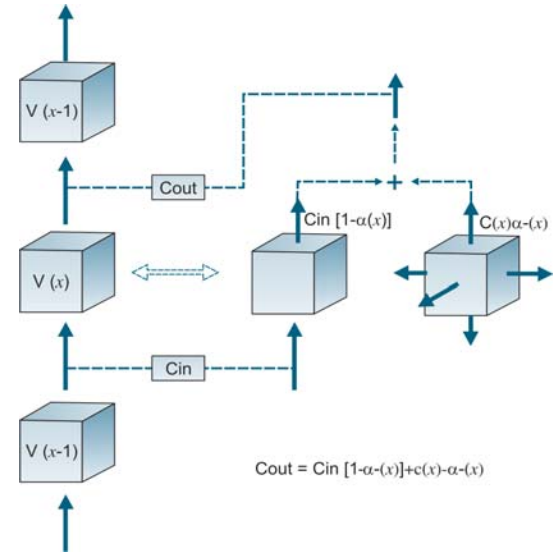


Fig. 20: The original method of calculation in volume rendering[15]

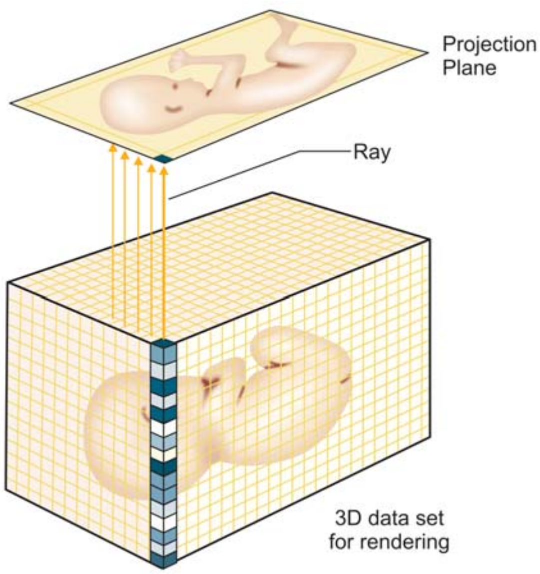


Fig. 19: Volume rendering[15]

Fig. 21: A surface-rendered image of a fetus at 33 weeks of gestation by volume rendering

Intermediate geometrical data can be easily used for the calculation of the object's volume (Fig. 18).

Volume Rendering

A 3D data set for rendering (Fig. 13) is projected directly on a projection plane (Fig. 19) in volume rendering, not through intermediate geometrical data set as in surface rendering. Rays are assumed from each pixel on the projection plane into the 3D data set. Brightness of each pixel is determined based on gray values of voxels on each corresponding ray. Figure 20 illustrates how gray values of voxels are calculated in the original volume rendering.[20]

A fetal surface image (Fig. 21) is obtained through volume rendering. An inside view of the heart can be depicted three-dimensionally by using a 3D data set constructed with a gated technique (Fig. 22). In surface rendering, boundaries of the object should be outlined strictly, because even low level noises around the object affect a 3D image much. But in volume rendering, boundaries of the object does not need to be outlined strictly, because low level noises around the object become transparent and do not affect the final 3D image much.

Some other kinds of images can be obtained by volume rendering. A fetal skeletal image is obtained when only the maximal gray values on each ray are displayed on the projection plane (Fig. 23). A 3D image of cystic parts and blood vessels is obtained when only the minimal gray values on each ray are displayed on the projection plane (Fig. 24). However, a 3D image shows only silhouettes in this way. A surface rendered 3D image of cystic parts is obtained by

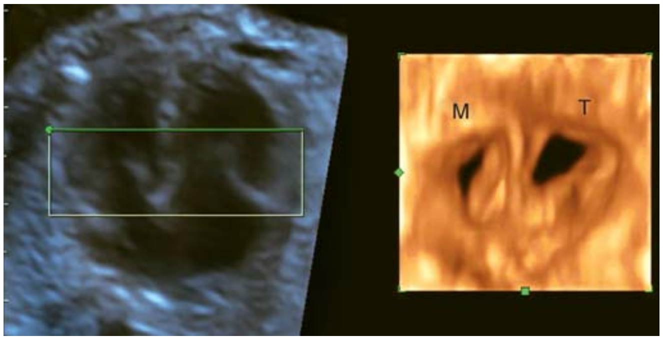


Fig. 22: A tomographic image for ROI setting (left) and a 3D image of openings of mitral (M) and tricuspid (T) valves (right). A normal fetus at 28 weeks of gestation

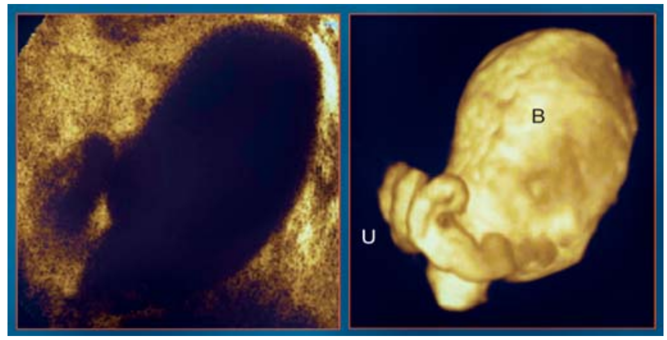


Fig. 25: A 3D image of the megalocystis and megaureters by minimum intensity projection (left). A 3D surface image of the megalocystis (B) and megaureters (U) by inversion mode (right)

Fig. 23: A 3D image of the fetal skeleton by maximum intensity projection

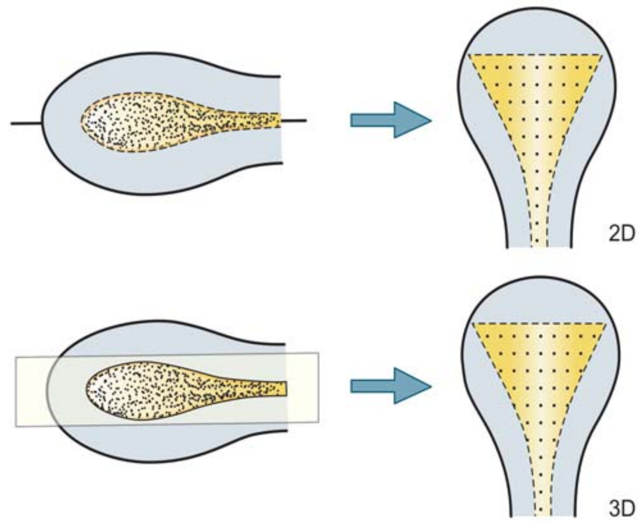


Fig. 26: A plane image of a coronal section of the uterus (upper right) and a 3D image (lower right). A higher contrast image can be obtained by volume rendering

Fig. 24: A 3D image of a fetus with bilateral hydronephrosis by minimum intensity projection. The stomach and blood vessels are also depicted

inverting black and white and processing cystic parts as solid parts.[5] Figure 25 shows the difference between images by so called minimum mode and by inversion mode.

Speckle noises are accumulated in volume rendering and a higher contrasted and clearer image than a sectional image can be obtained in some cases (Fig. 26). A 3D image of blood flows (blood vessels) is obtained by using color Doppler or power Doppler images instead of B-mode images (Fig. 27). Volume rendering is a good rendering method for observation but not for volume measurement.

Real Time Ultrasonic Beam Tracing

In this method, each ultrasonic beam is regarded as a ray in volume rendering. Calculation for each ultrasonic beam is performed immediately after the beam is received (Fig. 28). This means that 3D scanning and volume rendering are performed simultaneously. This method does not require construction of a 3D data set, but a 3D image is always displayed as seen from the probe.

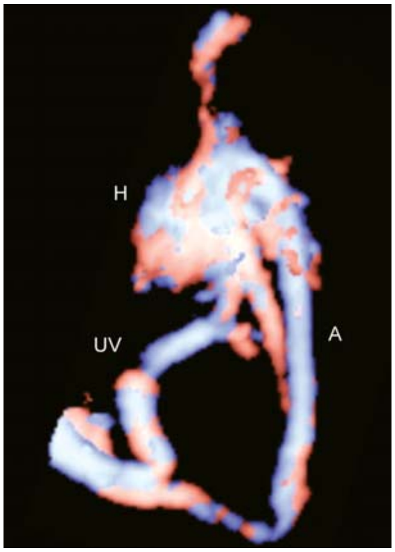


Fig. 27: A 3D image of fetal circulation. The heart (H), the aorta (A) and the umbilical vein (UV). A normal fetus at 19 weeks of gestation

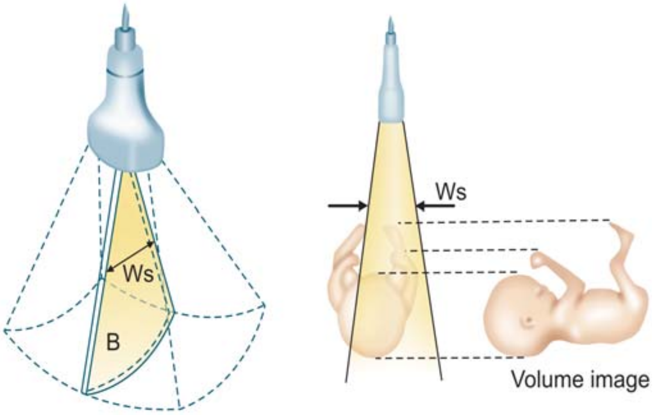


Fig. 29: Volume imaging. Slice width (Ws) is widened by a defocusing lens attached to the surface of a conventional probe[15]

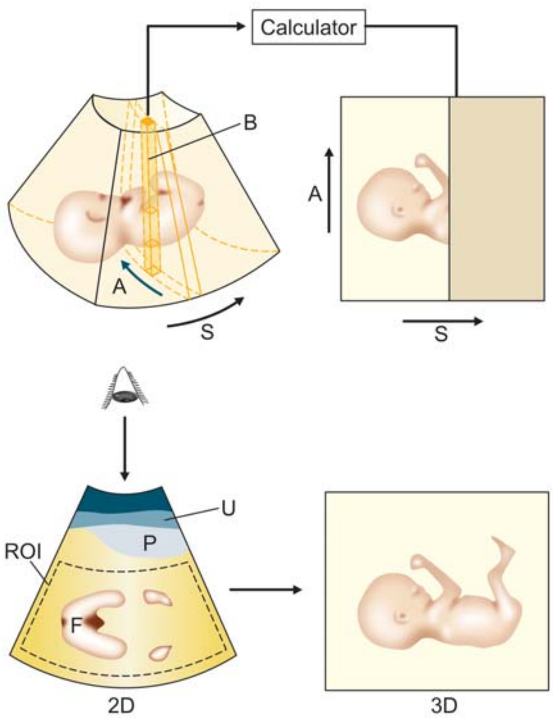


Fig. 28: 3D image generation by real time ultrasonic beam tracing[15]

Defocusing Method

This method is referred to as volume imaging or thick slice 3D imaging. A thick slice by defocusing lens attached to the surface of a conventional probe captures an object three-dimensionally (Fig. 29). Real time observation is possible, but the clinical application of this method is very limited.

PRACTICAL TIPS

3D Scanning

Figure 30 illustrates the relation between a 3D probe and initial three-orthogonal planes. The first point is to find a proper probe position and orientation for 3D scanning before 3D scanning. For a fetal surface image, a position and orientation where a sufficient amount of amniotic fluid is seen over the fetus should be selected.

The second point is to consider the direction of 3D scanning. An ultrasonic beam is converged electrically in the direction of transducer array. In the direction perpendicular to the tomogram (the direction of slice width), only an acoustic lens is used for converging the beam (Fig. 31). But convergence by an acoustic lens is not good enough and the object in the 3D data set tends to be expanded in the direction of slice width or in the direction of 3D scanning (Fig. 32). Consequently, the width of the object on a 3D image varies on the direction of 3D scanning (Fig. 33) and resolution of a 3D image varies on the direction.

Region of Interest

Figure 34 illustrates the relation between three-orthogonal planes and a 3D image. A 3D data set for rendering is extracted by setting a ROI (region of interest) on the three-orthogonal planes. The point is to fit the ROI to the object as much as possible, by translating and rotating the original 3D data set and by selecting ROI size (Fig. 35).

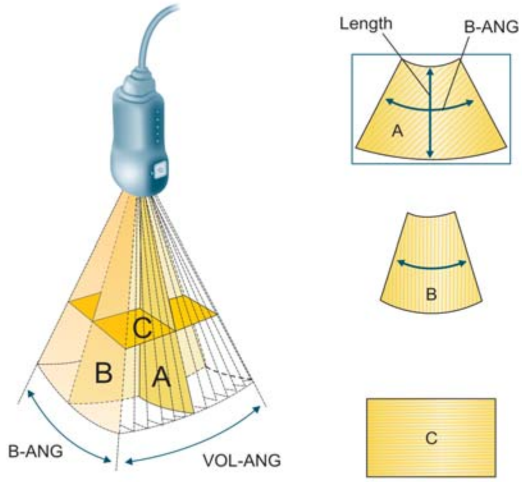


Fig. 30: Relation between a 3D probe and initial three-orthogonal planes on the screen[21]

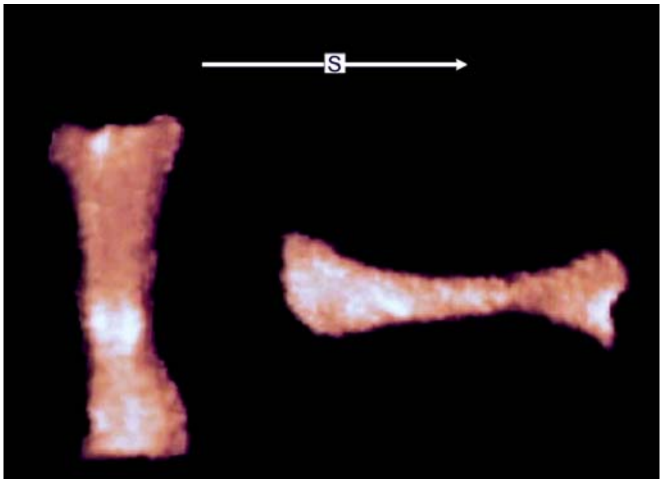


Fig. 33: An example of influence of slice width on a 3D image. The same fetal femur was scanned in different directions. Its thickness is displayed differently. S direction of 3D scanning

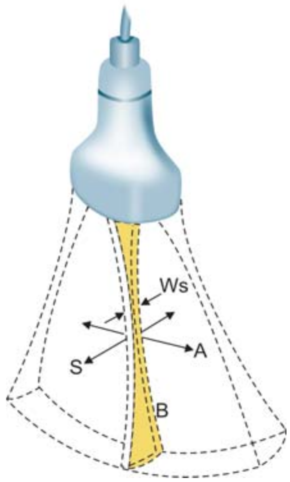


Fig. 31: Widths of an ultrasonic beam (B). The width (Ws) in the direction of slice width (S) is much wider than the width in the direction of transducer array (A)[15]

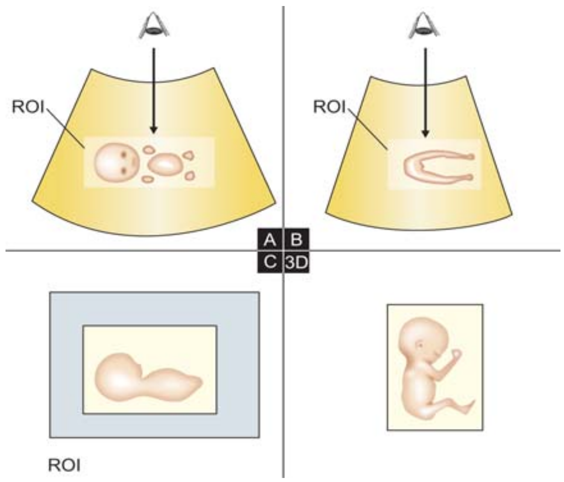


Fig. 34: Relation between three-orthogonal planes and a 3D image (lower right)[21]

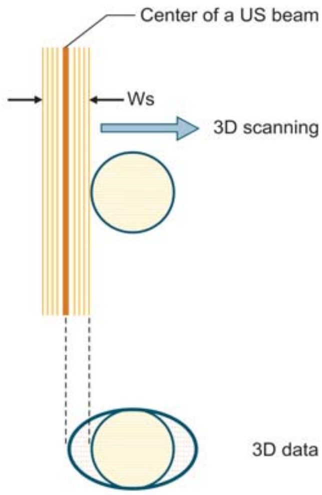


Fig. 32: Influence of slice width (Ws) on 3D data. The 3D data of the object is expanded in the direction of 3D scanning

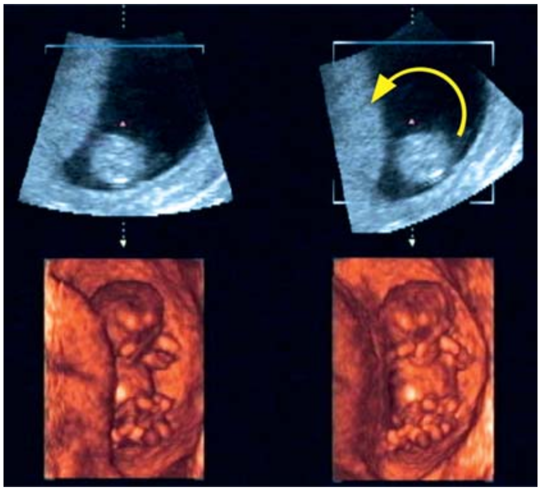


Fig. 35: The uterine wall hides a part of a fetus at 10 weeks of gestation (left). The whole body of the fetus can be seen by rotation of the 3D data set (right)

Threshold

Setting the threshold properly is also very important to obtain a good 3D image. By setting the threshold properly, unnecessary weak noises around the object can be removed and a clear 3D image can be obtained. When the threshold is too low, weak noises around the object hide the object. When the threshold is too high, parts of the object are also eliminated (Fig. 36).

Electrical Scalpel

Even when unfavorable images remain around a 3D image of the object after proper settings of ROI and threshold,

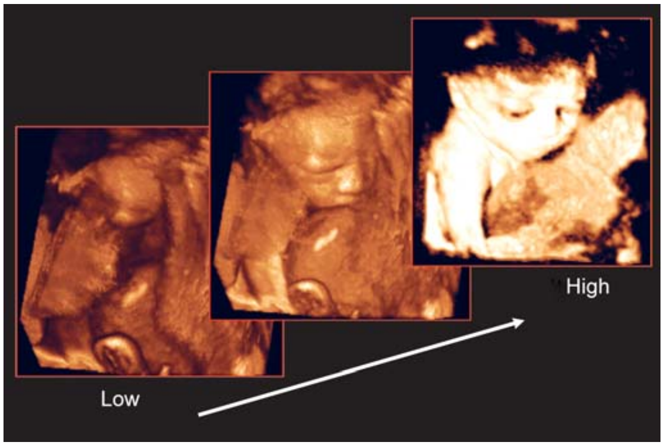
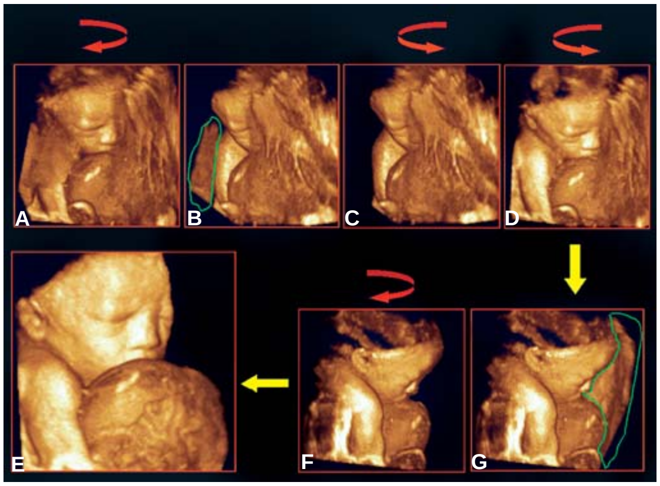


Fig. 36: Three-dimensional images of a fetus with omphalocele at 35 weeks of gestation. The fetus cannot be seen with a low threshold (left). The fetal face can be seen with increasing the threshold, but parts of the face are also eliminated when the threshold is set too high (right)



Figs 37A to G: Removal of unfavorable parts around a fetus with omphalocele at 35 weeks of gestation. (A) The fetus is partially covered by the uterine wall. (B and C) The uterine wall over the right shoulder is eliminated after rotating the 3D image and surrounding the uterine wall (green line). (D to F) The uterine wall covering left side of the fetus is also eliminated in the same manner. (G) A 3D image after removal of all unfavorable parts around the fetus

unnecessary parts in the 3D data set can be removed in the computer and unfavorable images can be eliminated (Figs 37A to G). This function is called electrical scalpel or 3D cutting. Even a separated fetal bone can be displayed by this function (Fig. 33).

CONCLUSION

Three-dimensional ultrasound has many functions and possibilities that are not involved in conventional 2D ultrasound. Both surface rendering and volume rendering give a 3D image. In the former, the intermediate geometrical 3D data set can be easily used for volume measurement of the object as well as 3D image generation. Volume rendering provides various kinds of 3D images as well as a surface-rendered image. Some considerations are required in 3D scanning, ROI setting, threshold setting and electrical scalpel to obtain a clearer 3D image.

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