REVIEW ARTICLE

# Three-dimensional and Four-dimensional Ultrasound: Techniques and Abdominal Applications

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Three-dimensional (3D) or four-dimensional (4D) ultrasound (US) has been developed and researched in two major ways. One is to overcome the limitations of 2D US by providing an imaging technique that reduces the variability of the 2D technique and allows the clinician to view the anatomy in 3D, the other is to provide better spatial guidance for various interventional procedures, such as biopsy, focal ablative therapy or image-guided surgery. In the field of diagnostic radiology, various 3D US techniques, such as US cholangiography using minimum intensity projection and volume contrast imaging, have shown excellent performance in achieving better spatial resolution and have reduced inherent noise in comparison with conventional 2D US. As a guidance for interventional procedures, 3D US was proved to be useful in improving the depiction and understanding of the geometric relationships of needles and probes to tumors and other nearby structures, so as to optimize delivery of the needle or ablative agent. Furthermore, 4D US, which is a dynamic 3D US, provides real-time feature of volume datasets instead of "static" 3D US images, and so enables more intuitive recognition of the 3D spatial relationship between the needle and the target lesion and allows easy alteration in the orientation of the needle under real-time monitoring. The advantages of 3D US are primarily derived from the fundamental properties of 2D US. US has many advantages over computed tomography and magnetic resonance imaging, including real-time imaging with vessel visualization, decreased procedure time and cost, portability, and lack of ionizing radiation. With continuing technological improvements including computer technology and visualization techniques, 3D US imaging is beginning to migrate from the research laboratory to the examination room. Therefore, radiologists or sonographers should be ready to accept the paradigm shift of viewing 3D images on a computer monitor rather than viewing 2D US images on the ultrasound machine, and they must be familiar with 3D US user interfaces.

**KEY WORDS** — abdomen, diagnostic techniques, three-dimensional image, ultrasonography

■ *J Med Ultrasound* 2007;15(4):228–242 ■

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## Introduction

Although 3D US imaging has been possible for nearly 25 years, the quality, affordability, and speed has only recently been improved enough to allow its incorporation into clinical practice. The goal of 3D US imaging is to overcome the limitations of 2D US by providing an imaging technique that reduces the subjectivity of the 2D technique and allows the clinician to view the anatomy in 3D. Two-dimensional US examinations are limited primarily by the subjectivity of the examiner. In addition, the examiner must interpret multiple 2D images and must mentally integrate this information to develop a 3D impression of anatomic and pathologic structures [1]. In a 3D US system, however, transducer motion is taken out of the examiner's hands and replaced by mechanical means, and 3D integration is performed by a computer [2–4]. This computer-generated image acquisition decreases subjectivity after an initial period of learning to operate the system and interpret the 3D images. Furthermore, the ability to view findings in multiple planes, for an unlimited number of times, increases the certainty of the findings and diagnosis.

In this review, we will describe how to perform 3D US imaging. Specifically, data acquisition, reconstruction, and rendering methods of 3D images are described with specific examples. Since 3D US has been used for imaging various abdominal organs and pathologies, we will discuss its abdominal applications and illustrate representative cases, including methods to measure the volume of organs or lesions from the 3D images. Finally, real-time 3D, namely 4D US, which can overcome a number of the drawbacks of 2D US for various US-guided techniques, will be illustrated by recent research.

## How to Perform 3D US Imaging

3D US imaging can be described simply using three steps: image acquisition, reconstruction, and display. All of these steps are discussed in the following sections.

### *Acquisition*

Compared with computed tomography or magnetic resonance imaging, US has an advantage in the flexibility of image acquisition. The series of tomographic images necessary for 3D US imaging can be acquired in arbitrary orientations. However, because image acquisition characteristics of a 3D US system are crucial to determine the quality of the final 3D image, radiologists should bear in mind that the image acquisition must be performed rapidly or gated appropriately to avoid artifacts and distortions due to respiratory, cardiac and involuntary motion. Currently, there are three methods of image acquisition: free-hand acquisitions, acquisitions with a motor-driven 3D transducer, and acquisitions with a 2D matrix array transducer [5] (Fig. 1). The free-hand acquisition technique is highly dependent on the operator's ability [5,6]. It requires the operator to manually hold an assembly composed of the probe attachment in the position and angulation of choice over the anatomy in question. This allows the operator to select the optimal view and orientation and has the added benefit of being able to deal with complex patient surfaces. Unfortunately, to reconstruct the 3D geometry properly, the exact relative angulation and position of the ultrasound probe must be known for each acquired image. Furthermore, when scanning the anatomy in question, the operator must ensure no significant gaps are left [5]. Thus, although the free-hand acquisition technique offers greater flexibility, the uncertainty of 3D geometry in terms of the probe's position and possible gaps during scanning may reduce the image quality, as well as induce inaccurate quantification (Fig. 1). The mechanical, motor-driven, 3D transducer is an alternative method, which reduces the limitations of free-hand acquisition. With this method, the 3D volumetric data are obtained by mechanical movement of the transducer, which acquires 2D US images at predefined spatial intervals sampling the volume in question properly, without missing any regions (Fig. 1). However, the main disadvantage of this technique is the bulkiness and weight of the 3D transducers in use today, compared with conventional 2D transducers. The 3D transducers house

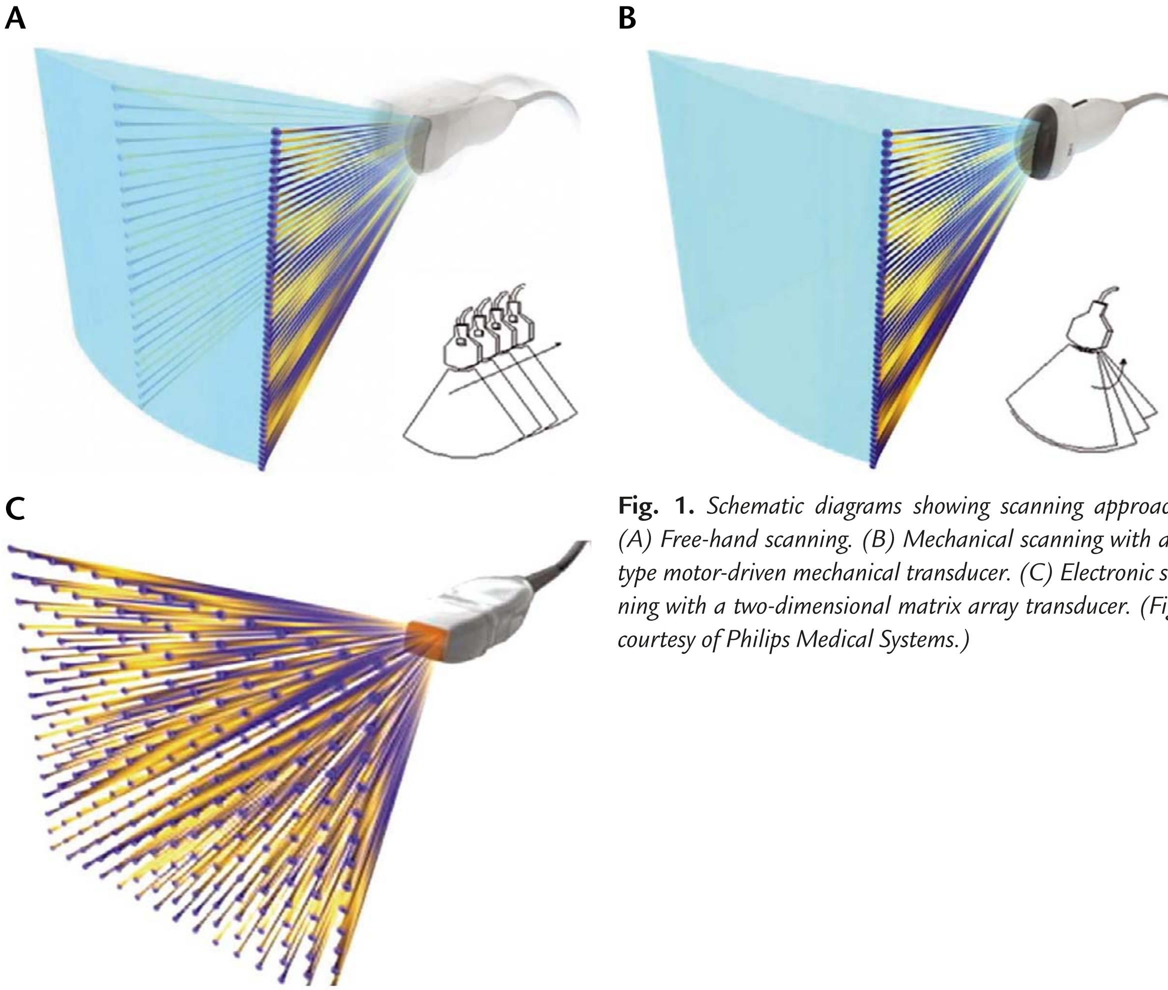


**Fig. 1.** *Schematic diagrams showing scanning approaches. (A) Free-hand scanning. (B) Mechanical scanning with a fan type motor-driven mechanical transducer. (C) Electronic scanning with a two-dimensional matrix array transducer. (Figure courtesy of Philips Medical Systems.)*

both the motor and transducer, making it more difficult to handle the transducer [7]. Recently, 2D matrix array transducers have been introduced, which generate a pulse of US diverging away from the array in a pyramidal shape (Fig. 1). The echoes are then processed generating real-time 3D information. With this technique, information about the third dimension is achieved through electronic scanning and may solve the limitations of mechanical 2D scanning. This approach may be the ultimate approach for most 3D US image acquisitions and is reminiscent of the transition from mechanical transducers to electronic phased arrays in 2D imaging.

### *Reconstruction*

3D image reconstruction is the process in which a set of 2D images are translated into a 3D representation of the structures in question. There are two ways to perform this reconstruction: feature-based and voxel-based [5,8]. In feature-based reconstruction, the 2D images of the anatomic structures of interest are outlined, and only the resulting boundary surfaces are presented to the viewer in 3D. This reduces the amount of information needed to be processed, thus allowing more efficient 3D rendering, while providing increased contrast between segmented structures [5]. Unfortunately, important image information may be lost during this reduction of the information. In voxel-based reconstruction, 2D images of the anatomic structures in question are placed in a 3D Cartesian volume in its correct location. The grayscale values not sampled by the 2D images are created through interpolation of the presented 2D images. If the volume is not sampled properly and the distance between acquired images is too large, then image information will be lost.

This voxel-based reconstruction approach removes the limitations of feature-based reconstruction; however, it results in a larger dataset that requires a high performance computer, because it must be manipulated in real-time for viewing and quantitative measurements of 3D geometry [8].

### 3D rendering

In addition to proper image acquisition, the rendering technique chosen also plays an important and, at times, dominant role in determining the information transmitted to the operator by the 3D US image display. There are many techniques for displaying 3D images, and they are divided into three classes: surface rendering, multiplanar viewing, and volume rendering [5,8]. The optimal choice of rendering technique is generally determined by the clinical application.

1. Surface-based rendering: The most common 3D display technique is based on visualization of surfaces of structures or organs. In this approach, a segmentation or classification step precedes rendering. Segmentation procedures are used to isolate voxels of similar characteristics for the demonstration of specific anatomic structures [9]. Algorithms can be selected according to the statistical and geometric properties of the image and may range from simple thresholding to something more complicated [5]. This technique can also be performed manually with the operator determining the boundaries of the structures or by automated techniques [10,11]. After the tissues or structures have been classified, a surface-rendering algorithm shades and illuminates the surface representation, at times adding depth cues so that topography and 3D geometry are more easily understood. An example of 3D surface-rendering is shown in Fig. 2, which demonstrates a large polyp in the distended gallbladder. Fig. 3 shows another example of 3D surface-rendering in a cirrhotic liver with a large amount of ascites. The operator may view the anatomy from different perspectives using either automatic rotation or user-controlled motion.

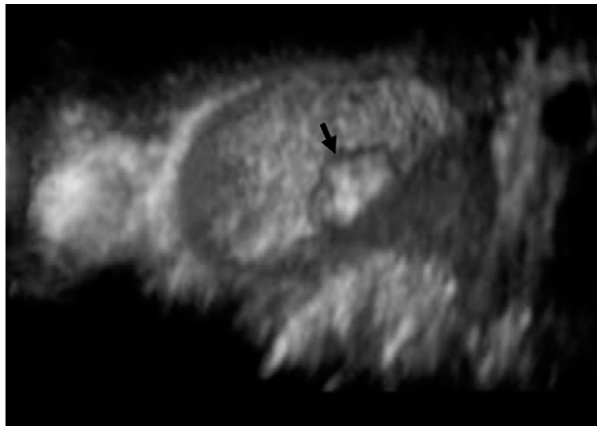

**Fig. 2.** *Three-dimensional surface-rendering image of a gallbladder (GB) polyp in a 30-year-old man. On pathologic examination after cholecystectomy, this lesion was confirmed as GB metastasis from malignant melanoma.*

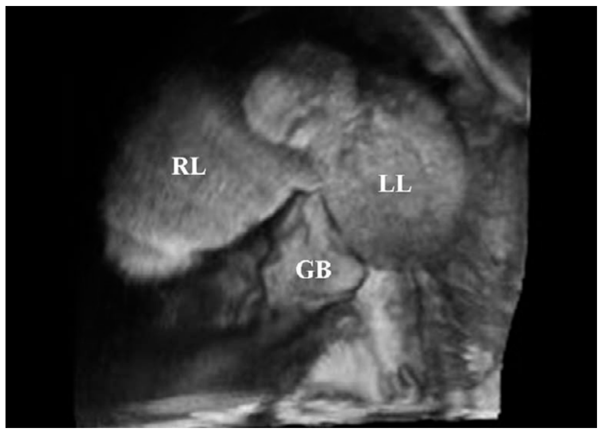


**Fig. 3.** *Three-dimensional surface-rendering image of a cirrhotic liver in a 48-year-old man. Liver is severely contracted, resulting in fissural widening between right (RL) and left lobes (LL) of the liver. The gallbladder (GB) is also seen. Note the mild surface undulation of the liver due to macronodular liver cirrhosis.*

2. Multiplanar viewing: In multiplanar viewing, a 3D voxel-based image must first be reconstructed and be easily accessible by the display algorithm. Computer user interface tools allow a selection of planes from the volume, including the oblique, to be viewed as reformatted 2D images. Not only do these planes appear similar to that obtained by conventional 2D US imaging with proper interpolation, they provide a display of an arbitrary plane that was not possible using the conventional 2D US technique [5]. Three perpendicular planes are displayed

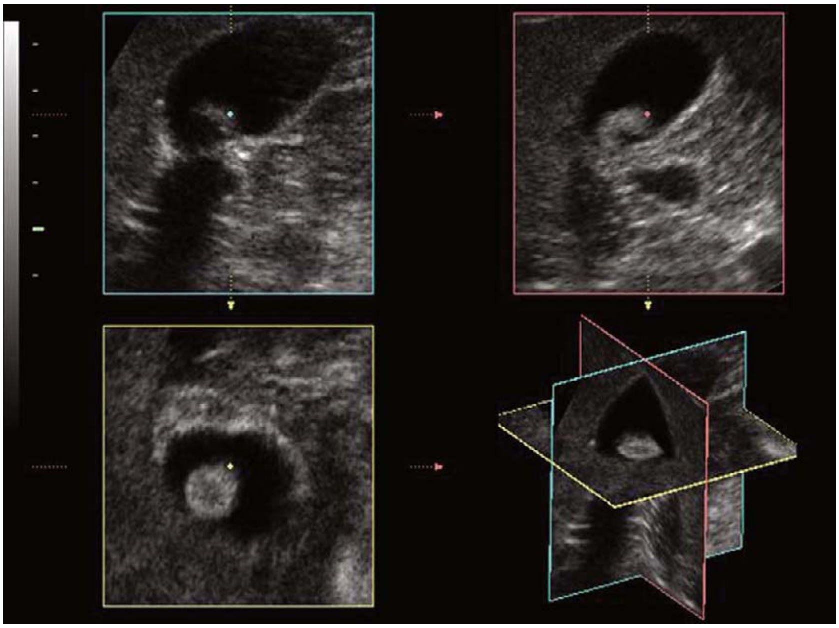

**Fig. 4.** *Three-dimensional multiplanar viewing of a gallbladder (GB) stone in a 59-year-old man. The top left image is transverse; the top right image is sagittal; and the bottom left image is coronal planar. The three displayed imaging planes are perpendicular to each other. In the bottom right image, three perpendicular planes are displayed simultaneously to show their relative orientation and intersection.*

on the screen simultaneously, with screen cues as to their relative orientation and intersection (Fig. 4). These cues facilitate orientation of the reformatted planes and help the operator conduct the examination. This technique has been successfully implemented in several commercial 3D US systems.

3. Volume-based rendering: The volume-based rendering technique can be performed using various methods, all of which present a display after it has been projected onto a 2D plane. The most widely used approach is the ray-casting technique [12,13], which projects a 2D array of rays onto the 3D image. Each ray intersects the 3D image along a series of voxels, the values of which can be weighted and then summed to form a density-weighted image showing the anatomy in a translucent manner [5]. Another common approach is to form a maximum intensity projection (MIP) image by displaying only the voxels with the maximum intensity along each ray [5]. Similarly, a minimum intensity projection (minIP) image can also be reconstructed when only the voxels with the minimum intensity along each ray are displayed. Examples are seen in Fig. 5. Recently, two new rendering techniques based on volume-rendering have been introduced. They are volume contrast imaging (VCI) and inversion mode. VCI is a new 4D US technology based on a real-time volume acquisition and has the potential benefit of contrast enhancement and speckle suppression in the 2D US image [14,15]. The main aspect of VCI is the use of a thin volume consisting of about 10 to 25 B-planes depending on the thickness setting, for example, 3, 5, 10, 15 mm instead of a single B-plane (Fig. 6). VCI technology is processed by volume rendering in which combined surface and transparent maximum gradient rendering are performed. The basic formula for volume rendering is given by:

$$I_{x,y} = \sum_i g_i \times p(g_i) \times \prod_{j=0}^{i-1} \left(1 - p(g_j)\right)$$

where $I_{x,y}$ = result pixel of the image; $g_i$ = gray value orthogonal to image plane; and p = probability (transparency) value for one gray value.

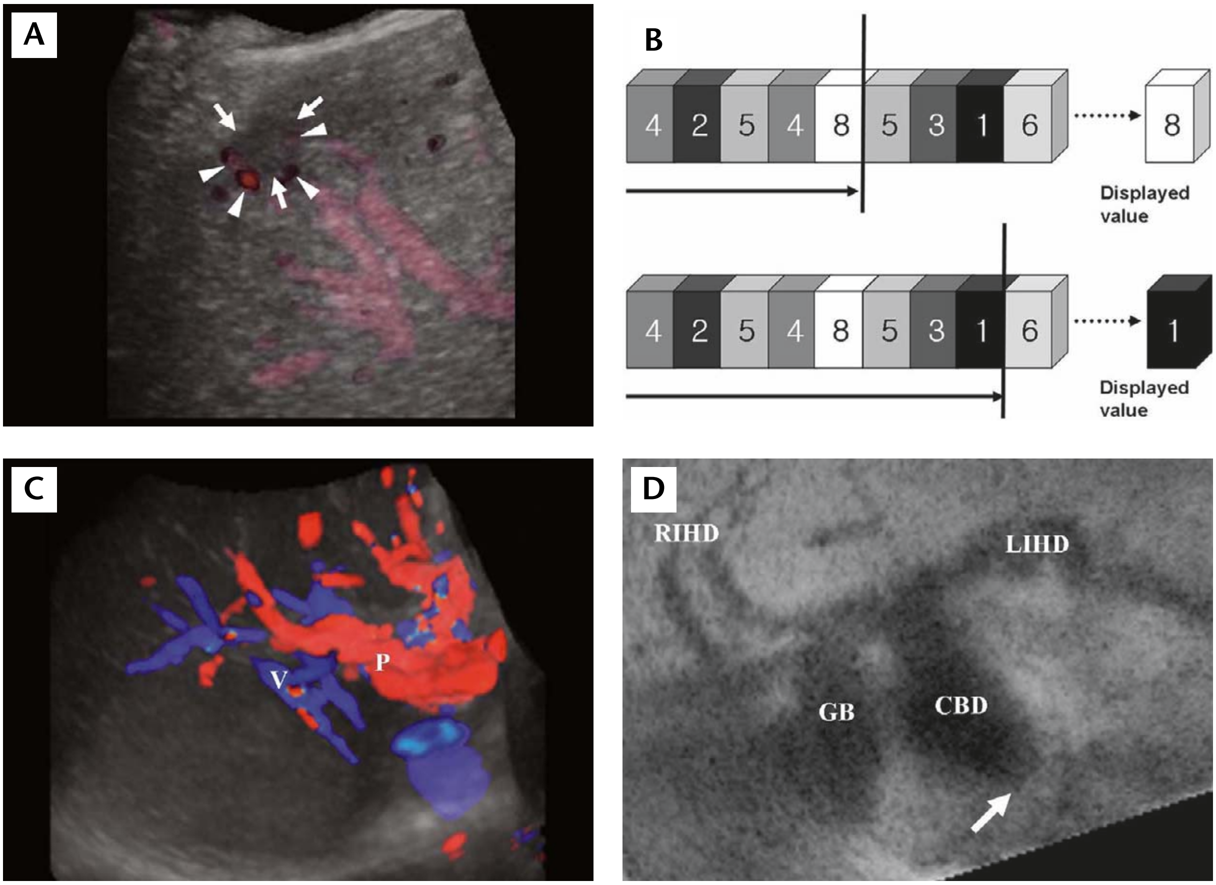


**Fig. 5.** *(A) Power Doppler three-dimensional (3D) ultrasound (US) image of a small hepatocellular carcinoma (HCC) rendered using the volume-based rendering technique. A low echoic HCC nodule (arrows) and tumor vascularity (arrowheads) are seen together in a transparent mode. (B) Schematic diagram of maximum intensity projection (MIP) (top) and minimum intensity projection (minIP) (bottom). MIP and minIP display the maximum and minimum voxel intensity along each ray, respectively. (C) MIP image of normal hepatic vasculature in 3D color Doppler US. Portal flow (P) appears as red and hepatic vein (V) as blue. (D) A coronal minIP image of malignant common bile duct (CBD) obstruction due to stomach cancer in a 57-year-old woman. Both intrahepatic duct (IHD) and CBD are markedly dilated due to severe obstruction at distal CBD level (arrow). The gallbladder (GB) is also distended. LIHD = left intrahepatic duct; RIHD = right intrahepatic duct.*

The idea behind this formula is to project a volume onto a 2D screen. In the case of US, the function given for the transparencies, $p(g_i)$, is set to a linear function, which increases with the gray values, and is set to zero beyond a certain gray threshold. The default setting of volume rendering for VCI is a mixture of 70% surface texture rendering and 30% transparent maximum gradient, which provides an amount of tissue information from the directly neighboring B-slices. This causes the suppression of the speckle pattern in VCIs without averaging, which is seen in any conventional B-mode image, creating a blurred image [14,15] (Fig. 6). A 100% surface rendering would only display the signals of the first B-slice, and only when the render ray meets a gap in the speckle pattern would it pass on the second B-slice for analysis. Furthermore, these rendering processes have a very high sample rate, meaning that the density of the rendering analysis is higher than the density of the pixels in a single B-slice, which indicates that the gaps in the speckle pattern are filled up with information from adjacent slices in the multi-slices [14,15]. Speckle suppression also produces a very smooth image while maintaining information detail, because it is not just a 2D filter.

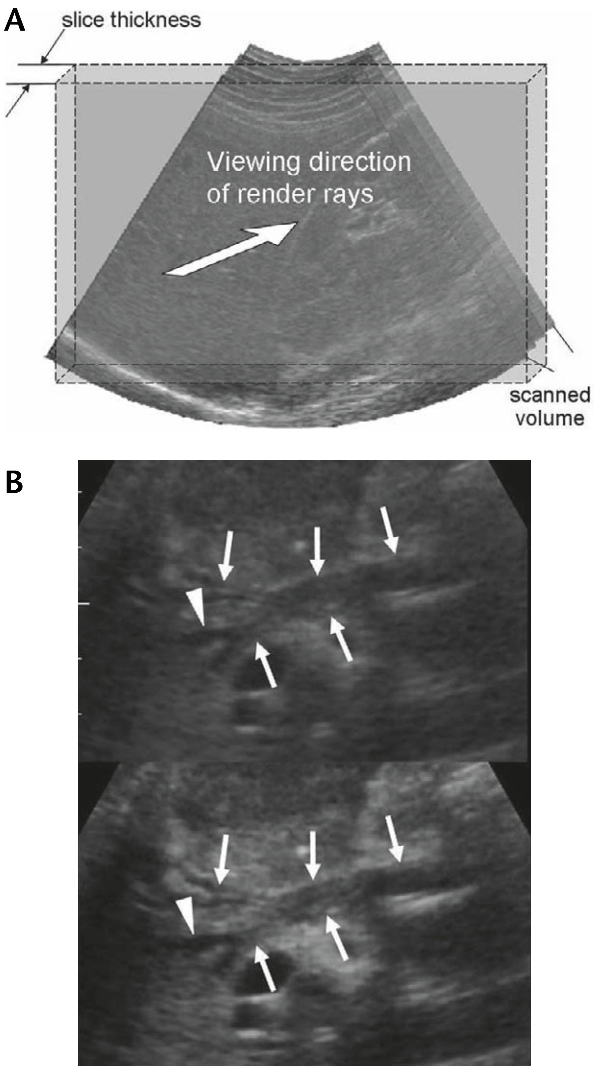


**Fig. 6.** *(A) Acquisition of a thin volume by volume contrast imaging (VCI). Within this volume, there is a render box with a large surface, but the thickness of the render box is kept small. The thickness of the rendered box can be chosen by the user as either 3, 5, 10 or 15 mm to suit the purpose. A thin volume within the render box is projected onto a two-dimensional screen in the direction of the rendering process (arrow). (B) Transverse conventional tissue harmonic (top) and VCI images (bottom) with a 3 mm slice thickness of Klatskin's tumor in a 55-year-old man. Diffuse wall thickening (arrows) of both intrahepatic ducts is well seen. VCI provides better conspicuity of thickened wall and clearer visualization of anterior wall of normal duct (arrowhead).*

Inversion mode is a new post-processing tool in the 3D analysis of fluid-filled structures [16,17]. This rendering algorithm transforms echolucent structures into solid voxels. Thus, anechoic structures, such as the heart chambers, lumen of the great

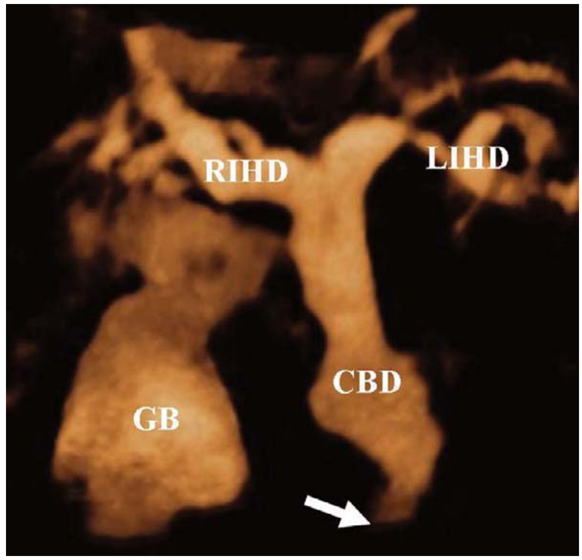


**Fig. 7.** *Inversion mode of distal common bile duct (CBD) cancer in a 70-year-old man. Both intrahepatic ducts (IHD) and CBD are severely dilated because of distal CBD cancer (arrow). The inversion mode tool transforms anechoic voxels into solid areas. LIHD = left intrahepatic duct; RIHD = right intrahepatic duct.*

vessels, stomach, bile duct, gallbladder and bladder, appear echogenic on the rendered image, whereas structures that are normally echogenic prior to grayscale inversion (e.g. bones) become anechoic (Fig. 7). This technique also avoids the inherent limitations to image reconstruction in the angle of insonation, temporal resolution, blooming artifacts, or intensity of the Doppler signal [17]. This is because it does not use color or power Doppler US as a "digital contrast" to highlight blood vessels. This feature may prove valuable in the evaluation of vascularity in an area which is frequently vulnerable to respiratory or cardiac motion. The demerits of inversion mode are the absence of information regarding the velocity or direction of blood flow, and that it may not work well in cases with poor tissue contrast between adjacent echolucent structures [17].

## Abdominal Application

Since the first attempts at 3D reconstruction on US dated back to the early 1990s [18], the areas of clinical applicability for 3D US continue to expand,

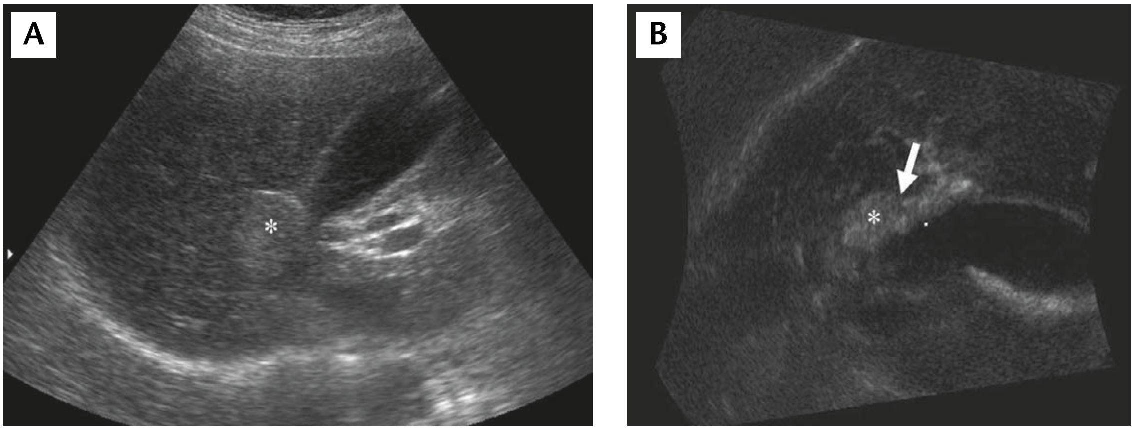


**Fig. 8.** *Coronal multiplanar reformatted image providing additional information in terms of the location of the lesion. (A) On transverse ultrasound image, an echogenic mass (*) is seen between the right lobe of the liver and the gallbladder. However, the origin of the mass cannot be determined only by this image. (B) Coronal reformatted three-dimensional image shows the presence of beak sign (arrow) between the mass (*) and hepatic parenchyma, suggesting an intrahepatic lesion. From this information, we can confidently interpret that this mass has arisen from the liver. The mass was confirmed as a hepatic hemangioma on subsequent magnetic resonance imaging.*

and many studies are in progress in the obstetric, gynecologic, vascular and abdominal areas. Several attempts at the clinical use of this technique for abdominal organs have included exact localization of lesions, volumetric assessment of solid or cystic lesions, quantification of tumor vascularity, 3D visualization of tumor with adjacent vessels, imaging of gallbladder pathology, and biliary duct visualization. In addition, the usage of 3D or 4D US in US-guided biopsy or interventional procedures has been assessed.

### *Exact localization of lesions*

Compared with computed tomography or magnetic resonance imaging, US has an advantage in that the scanning plane can be selected more freely than with other modalities. However, in clinical practice, this is sometimes not the case. For instance, true coronal plane for the liver is difficult to obtain, because some of the liver is sheltered behind the lower ribs. 3D US can provide a display of information in a manner that has not previously been possible with conventional techniques. An example of 3D coronal multiplanar viewing is shown in Fig. 8, which demonstrates an echogenic mass located between the liver, gallbladder, and right kidney. On sagittal US image, the exact location of the lesion could not be determined. However, 3D coronal multiplanar reformatted imaging depicts the presence of a beak sign between the mass and the hepatic parenchyma, suggesting an intrahepatic lesion. From this information, we can be confident that this mass has arisen from the liver. The mass was confirmed as a hepatic hemangioma on magnetic resonance imaging.

### *Volumetric assessment*

3D volumetric measurements, including fetal organ measurements to assess fetal well-being, gallbladder measurements to assess gallbladder function, and prostate measurements, have been made more accurate by recent developments in 3D US [19–22]. This improved accuracy, especially for irregularly shaped organs such as the gallbladder, also reduces the variability of serial measurements, standardizing sonographic procedures. Recently, Kim et al reported that 3D US of the gallbladder is clinically feasible and more useful than oral cholecystography or 2D US alone [22]. Their results showed an excellent correlation between gallbladder ejection fractions using 3D US and the grades of oral cholecystograms. These results indicate the superiority of 3D US, compared with oral cholecystography, for evaluating patients with gallbladder dysfunction and, moreover, demonstrated the clinical usefulness of the volumetric analysis of 3D US for gallbladder evaluation (Fig. 9). In addition, 3D US can examine intrinsic pathology as well as gallbladder function. Volumetric assessment of solid tumor burden is also important in the field of oncology, because 3D measurement of tumor volumes give a more accurate assessment of tumor burden than traditional uni-dimensional and bi-dimensional measurements [23,24]. This is also true for monitoring tumor burden after local ablation treatment, such as percutaneous ethanol injection or radiofrequency ablation. Indeed, volumetric measurement with 3D US for tumors was proved to be a more accurate tool than traditional 2D measurement in several previous reports [25,26] (Fig. 10).

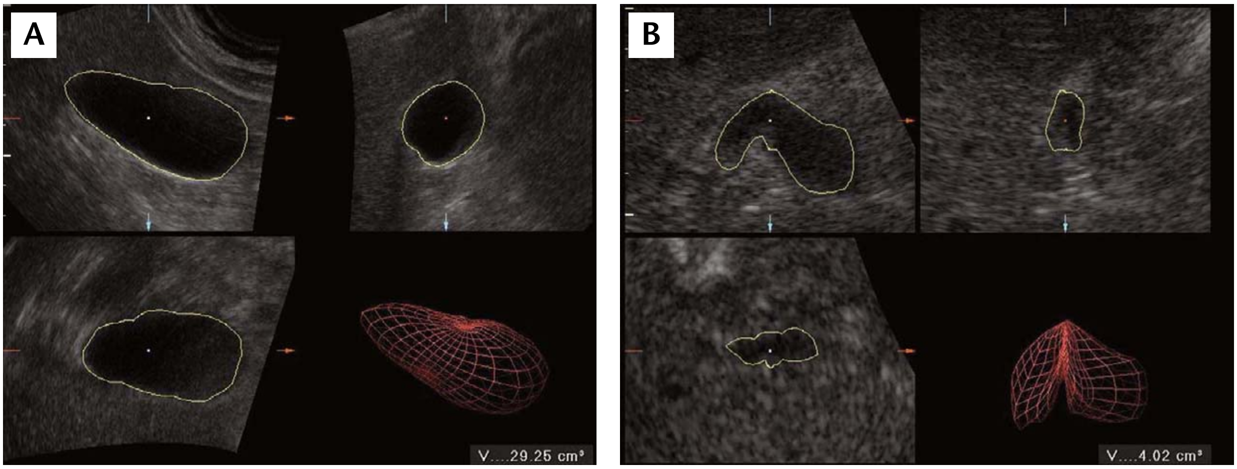


**Fig. 9.** *Volumetric assessment of the gallbladder in a healthy volunteer. On three-dimensional volumetric analysis, each calculated volume of the gallbladder (A) before and (B) after a fat-meal test is 29.25 cm$^3$ and 4.02 cm$^3$, respectively. The calculated gallbladder ejection fraction is 86.3%.*

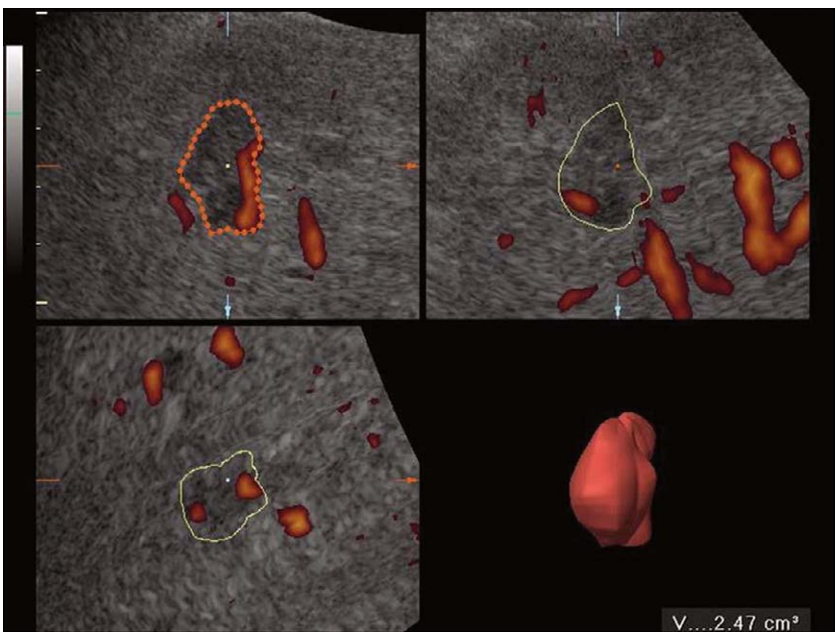


**Fig. 10.** *Volumetric assessment of a small hepatocellular carcinoma before percutaneous ethanol injection. On three-dimensional multiplanar viewing, tumor margin is carefully traced and adjusted manually not to contain non-tumorous parenchyma. The measured tumor volume is 2.47 cm$^3$.*

### 3D visualization of tumor with adjacent vessels

Exact characterization of perfusion patterns on color Doppler US can sometimes be helpful to differentiate focal hepatic lesions. Tanaka et al insisted that basket and vessel-within-the-tumor patterns were more frequently observed in hepatocellular carcinoma, and hemangioma was characterized by spot pattern and metastases by detouring pattern [27]. Vascularity itself and its spatial relationship to the tumor also give important information in treatment planning and the monitoring of treatment effects. Compared with 2D images, 3D color Doppler imaging can more clearly depict the spatial relationship between the tumor and its vascularity. An example of a 3D MIP image of a large hepatocellular carcinoma demonstrates multiple feeding arteries from the left lower portion of the tumor showing the basket pattern (Fig. 11). This 3D information regarding tumor vascularity may be helpful for planning local ablation therapy or transcatheter arterial chemoembolization.

### Imaging of gallbladder pathology

The gallbladder is one of the most appropriate organs to perform surface-rendered 3D US in the upper abdomen, because it contains echo-free bile juice. Park et al evaluated the feasibility of 3D US in the evaluation of gallbladder pathology [28]. Twenty-two of 30 patients included had gallstones, and the remaining eight had polyps. Successful 3D visualization of intraluminal gallbladder lesions was achieved in 26 patients (87%) (Fig. 12). For the remaining four patients, the cause of failure of the 3D display was due to stone-filled gallbladder in two and a contracted gallbladder in two; thereby, an appropriate sonic window for surface-rendering was unobtainable. Even though 3D surface-rendering of the gallbladder enables us to demonstrate gallbladder pathology more intuitively, additional information for correct diagnosis is difficult from 3D images. However, 3D surface-rendering display may be another method to depict gallbladder pathology, to give clearer visualization of small polyps or stones in the cystic duct or neck.

On US, reverberation or side lobe artifacts, which are intrinsic features of conventional US, make the diagnosis and differentiation of gallbladder lesions difficult. To overcome these problems, tissue harmonic image has been introduced. However, in tissue harmonic image, a bandpass filter is used to

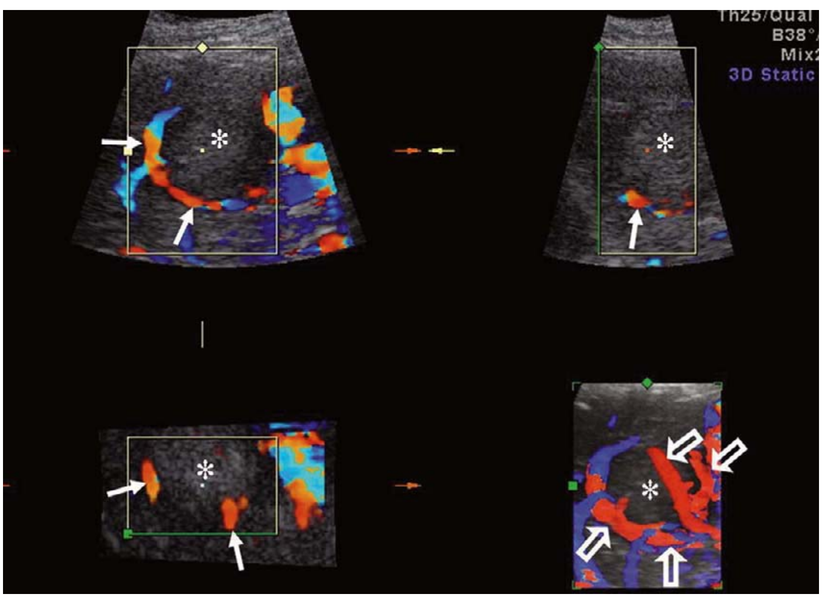


**Fig. 11.** *Three-dimensional (3D) color Doppler ultrasound image of large hepatocellular carcinoma in a 55-year-old woman. Transverse (top left), sagittal (top right) and coronal (bottom left) images of left hepatic lobe demonstrate hypervascularity around the low echoic tumor (*). 3D color Doppler image rendered by maximum intensity projection mode (bottom right) demonstrates multiple feeding arteries (open arrows) from the left lower portion of the tumor (*), showing the basket pattern.*

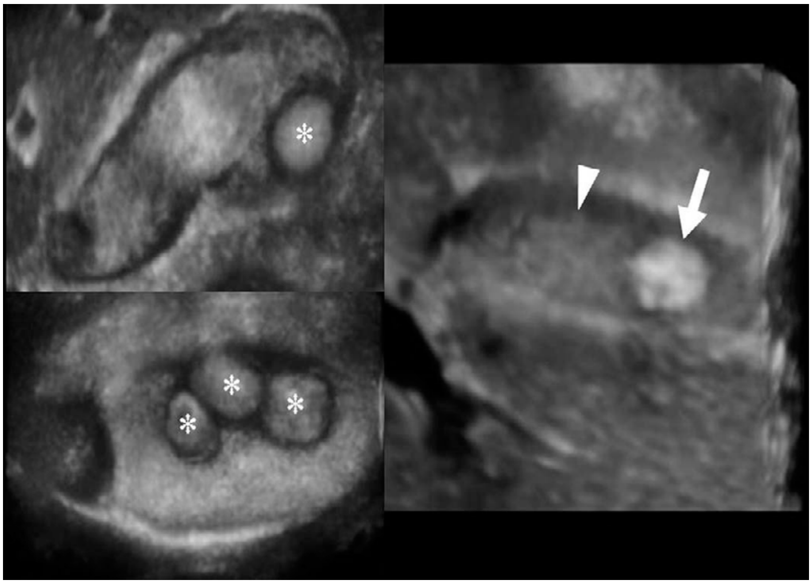

**Fig. 12.** *Three-dimensional surface-rendered images of various gallbladder lesions. Single (left top) and three (left bottom) gallstones (*) are well visualized in a fully distended gallbladder. In a slightly collapsed gallbladder (right), a highly echogenic stone (arrow) and sludge (arrowhead) are visualized.*

process the received signal so that only the returning high-frequency harmonic signal is used to produce the image. Resolution and sensitivity are thus limited by a fundamental compromise in the frequency filtering approach. Recently, VCI technology has been introduced and has the potential benefit of contrast enhancement and speckle suppression in 2D US images. Therefore, this technology is considered to be an appropriate technique for the evaluation of the gallbladder and bile duct. Indeed, in our previous report, VCI combined with the harmonic technique was proved to provide a better image quality and fewer artifacts than the conventional harmonic technique for the evaluation of various gallbladder diseases [14] (Fig. 13).

### *Biliary duct visualization*

US is the first imaging tool to be used in the diagnosis of jaundice, because it is easily accessible and noninvasive and can also be used as the guidance modality for interventional biliary drainage procedures. However, bile duct anatomy is somewhat complex, and the examiner must interpret multiple 2D ultrasonographic images and mentally integrate this information to develop a 3D impression of anatomic or pathologic structures [1]. If a radiologist can provide more intuitive 3D images for biliary pathology, it will help the clinician understand the complex biliary anatomy more easily. Lee et al investigated the feasibility of 3D ultrasonography using the minIP mode in patients with obstructive biliary disease [1] and found that the biliary anatomy was visualized more objectively on 3D images than on conventional 2D US images, because the dilated bile duct was easily displayed on one 3D minIP image. They insisted that this important advantage of 3D US using the minIP mode and the objectivity of the data provided was helpful in the reassessment, counseling, and teaching of clinical physicians and patients [1] (Figs. 14 and 15). The VCI technique is also helpful to delineate bile duct pathology [15] (Fig. 6). In addition, because VCI is a 4D US technology based on a real-time volume acquisition, the operator can obtain VCI images in a certain plane in real time, which is essential in tracing the entire course of the biliary duct (Fig. 16). The slice thickness can be chosen by the operator according to their purposes.

### *4D US in US-guided procedures*

US is a well-established means of guiding the biopsy of liver masses. It has many advantages over computed tomography and fluoroscopic guidance,

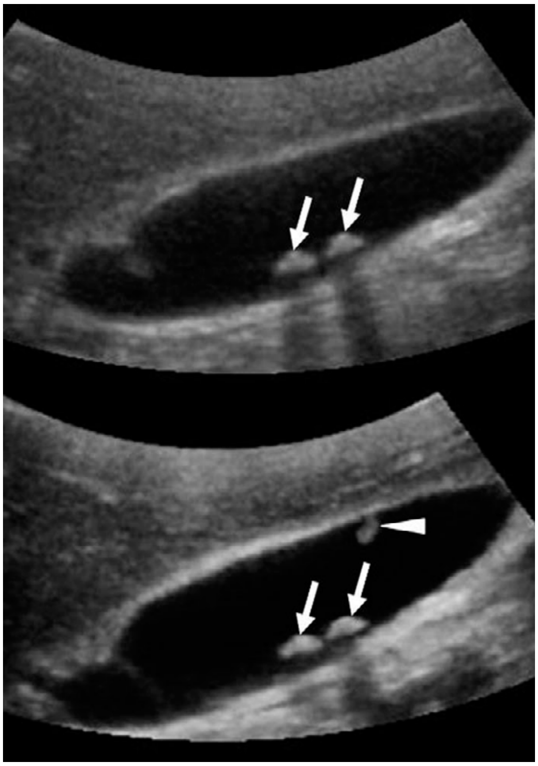

**Fig. 13.** *Transverse conventional tissue harmonic (top) and volume contrast imaging (VCI) images (bottom) with a 5 mm slice thickness of two gallstones and one polyp in a 56-year-old woman. Compared with conventional tissue harmonic image (top), VCI image shows the increased echogenicity and improved lesion conspicuity of the stone (arrows). In addition, a polyp (arrowhead) is more clearly visualized in VCI than tissue harmonic image. Internal artifacts seen in tissue harmonic image are clearly suppressed in VCI image.*

including real-time imaging with vessel visualization, decreased procedure time and cost, portability, and lack of ionizing radiation [29,30]. However, because needle visualization is limited by the planar nature of 2D US images, it is crucial the 2D US imaging plane is parallel to the needle. If the needle tract is moved out of the image plane, the operator may lose track of the needle and need to perform a rocking movement of the transducer to find it. Dynamic real-time 3D US, also known as 4D US, differentiates itself from reconstructed 3D US, which performs continuous volume data acquisition and a rendering process. In a previous study by Won et al, the real-time feature of 4D US was proved useful in guiding successful biopsy procedures by improving the depiction and understanding of the geometric relationships of biopsy needles to target lesions and other nearby structures [7]. 4D US provides additional spatial information by its ability to simultaneously show structures in three orthogonal planes in real time, so as to help the operator readjust the needles and ablative devices (Fig. 17). According to their report, the advantages of 4D US in US-guided procedures are the elimination of operator dependence in the free-hand technique, and the enabling of a more intuitive recognition of the 3D spatial relationship between the needle and the target lesion [7]. However, the disadvantages of using 4D US are

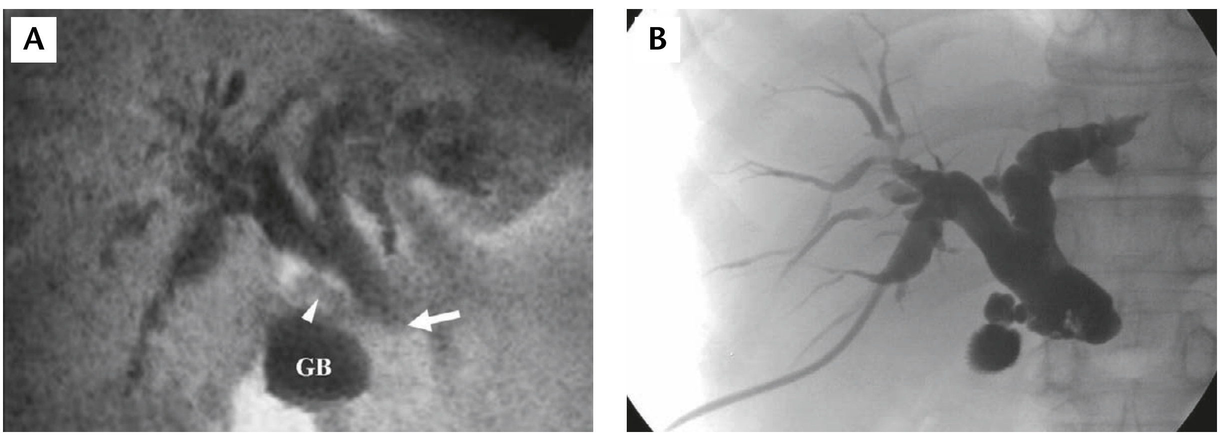


**Fig. 14.** *Distal common bile duct (CBD) cancer in a 67-year-old man. (A) Three-dimensional (3D) volume-rendered minimum intensity projection (minIP) image shows dilatation of both intrahepatic ducts and the common bile duct. Obstruction (arrow) is seen at the level of distal CBD. The gallbladder (GB) and cystic duct (arrowhead) are also distended. (B) Percutaneous transhepatic cholangiography shows good correlation with the 3D image reconstructed by the minIP mode. A pylorus-preserving pancreaticoduodenectomy was performed. Pathologic examination revealed an adenocarcinoma of the distal common bile duct.*

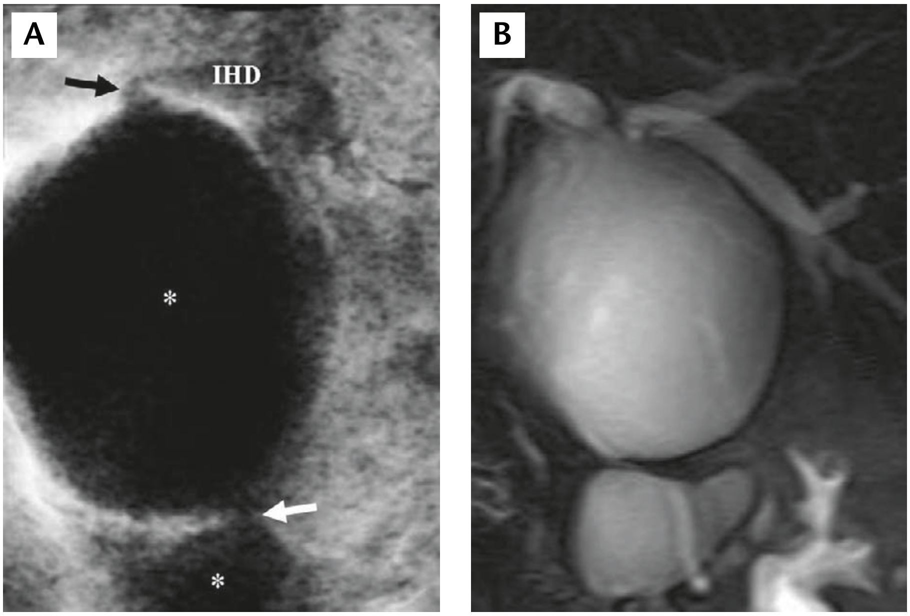


**Fig. 15.** *Choledochal cyst type IVb in a 36-year-old woman. (A) Three-dimensional (3D) volume-rendered minimum intensity projection (minIP) image shows two cystic dilatations (*) of extrahepatic bile duct with strictures (arrows). Intrahepatic bile duct (IHD) is not dilated. (B) Thick slab coronal two-dimensional magnetic resonance cholangiopancreatography shows good correlation with the 3D image reconstructed by the minIP mode.*

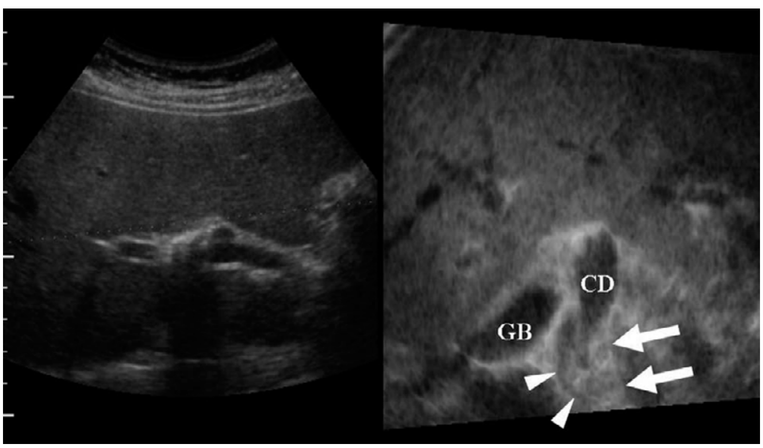


**Fig. 16.** *Real-time, coronal volume contrast imaging (VCI) image of common bile duct (CBD) and cystic duct stones in a 58-year-old man. If an operator selects the plane and slice thickness for VCI image on two-dimensional image (left), VCI image with a certain plane and thickness (right) can be demonstrated in a real-time manner. Note the multiple echogenic stones in distal CBD (arrows) and cystic duct (arrowheads) on coronal VCI image. GB = gallbladder.*

the bulkier and heavier transducer, and constant mechanical vibration during the procedure.

## Conclusion

With continuing technological improvements, including computer technology and visualization techniques, 3D US imaging is beginning to migrate from the research laboratory to the examination room. Even though a number of further advances are required before 3D US imaging has widespread routine clinical use, many investigators have proved that 3D US imaging has promise as an important clinical tool. Therefore, radiologists or sonographers should be ready to accept the paradigm shift of

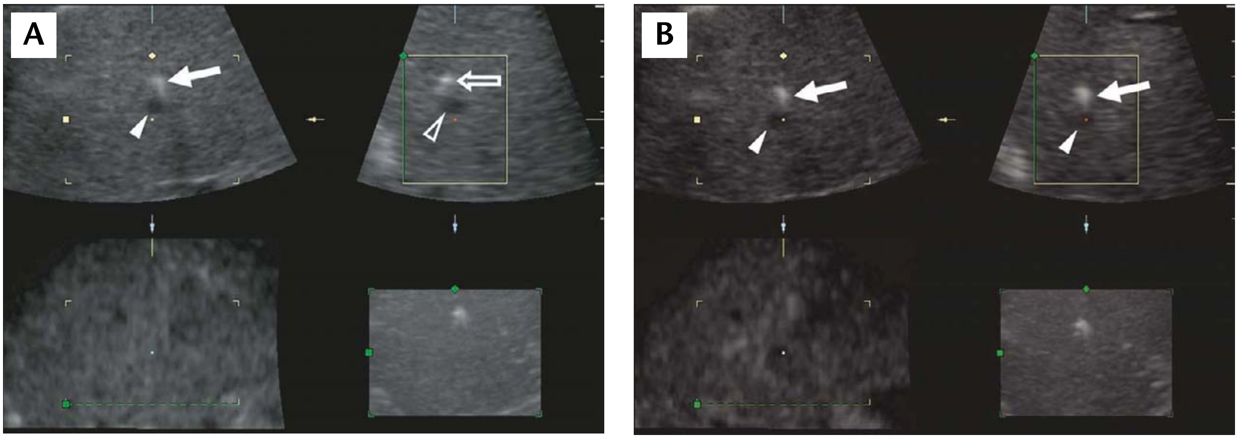


**Fig. 17.** *Four-dimensional ultrasound (US) during radiofrequency ablation for a small metastatic nodule. The top left image is transverse; the top right image is sagittal; and the bottom left image is coronal planar. The three displayed imaging planes are perpendicular to each other. The bottom right image is a three-dimensional volume-rendered image obtained by mixture of the transparent maximal and surface modes. (A) Even though the needle (arrow) seems to advance toward the center of small low echoic nodule (arrowhead) in transverse image (top left), sagittal US image (top right) shows that the needle (open arrow) is located slightly cranial to the nodule (open arrowhead). (B) After readjusting the needle slightly caudally, both transverse (top left) and sagittal (top right) US images show the needle (arrow) targeting the center of the nodule (arrowhead).*

viewing 3D images on a computer monitor rather than viewing 2D US images on the ultrasound machine and must be familiar with 3D US user interfaces. A combination of technical advances and well-prepared examiners can lead to the routine and efficient use of 3D imaging in the field of US.

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