A Phantom Study Comparing Ultrasound-Guided Liver Tumor Puncture Using New Real-Time 3D Ultrasound and Conventional 2D Ultrasound

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OBJECTIVE. The purpose of this study is to compare the accuracy of ultrasound-guided puncture using new real-time 3D (4D) ultrasound and conventional 2D ultrasound for focal hepatic masses using a liver phantom.

MATERIALS AND METHODS. A 4D ultrasound system equipped with a 5-MHz 4D probe displayed both axial and orthogonal images parallel to a puncture line plane. We used a liver phantom that contained four simulated spherical masses in an acrylic box (length × width × height, 300 × 299 × 150 mm) with two different sizes (15 and 30 mm in diameter) in two different positions (30 and 80 mm from the surface). Four inexperienced and four experienced physicians attempted punctures on these four simulated masses twice using 2D and 4D ultrasound guidance in a total of 128 punctures (eight operators, two techniques, and eight punctures per session). The error distance of the puncture was defined as the perpendicular distance from the center of a target mass (sphere) to the line of the puncture needle in the coronal plane of the target center, which was measured manually on the basis of the 3D volume data on off-line analysis.

RESULTS. On each tumor model, the average error distance with 4D ultrasound was significantly smaller than that with 2D ultrasound, except for one tumor model that was15 mm in diameter and 30 mm in depth. The average error distances for the experienced group tended to be smaller than those for the inexperienced group, with both techniques and on each tumor model, and there was a statistically significant difference between the two groups on one tumor model (30 mm in diameter and 80 mm in depth) on 4D ultrasound ($p < 0.05$).

CONCLUSION. Four-dimensional ultrasound–guided puncture for liver tumors can markedly improve puncture accuracy for both experienced and inexperienced physicians compared with conventional 2D ultrasound guidance.

Ultrasound guidance provides rapidly performed more-comfortable real-time imaging with vessel visualization, portability, and lack of ionizing radiation, compared with CT and fluoroscopic guidance. As a result, ultrasound-guided percutaneous biopsies are now the first procedure of choice for the tissue sampling of sonographically detectable liver lesions [1–3].

Moreover, percutaneous treatments, including radiofrequency ablation (RFA) [4] and percutaneous ethanol injection (PEI) [5], are currently being conducted with the use of ultrasound to guide such therapeutic procedures for the treatment of hepatocellular carcinoma; however, to completely ablate a relatively small hepatocellular carcinoma (≤ 3 cm in maximum dimension) using a 3-cm-exposed RFA electrode and to ensure a sufficient safety margin in a single intervention, an accurate puncture is imperative [6].

Current standard 2D sonographically guided puncture techniques have a number of disadvantages. In general, 2D ultrasound images show a lesion in cross-section but do not convey a spatial impression of the lesion, its location in the tissue, or its relationship with vessels. Also, needle visualization is limited by the planar nature of 2D ultrasound images. It is crucial that the 2D ultrasound imaging plane is parallel to the needle. If the needle is directed out of the image plane, the examiner can lose track of the needle and has to perform a rocking motion of the transducer to find it [7].

With recent improvements in the image-processing capacity of ultrasound systems and advancements in image-processing technology, a real-time 3D ultrasound (4D ultrasound),

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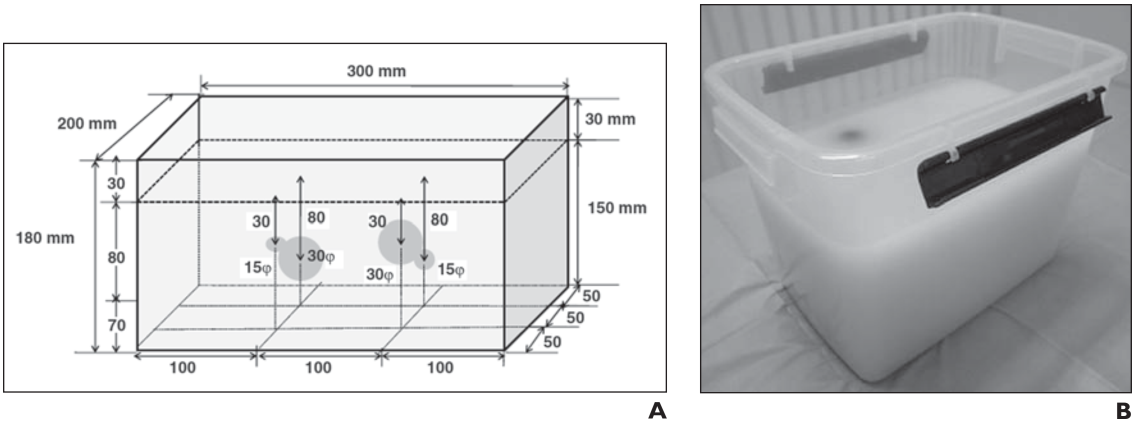

Fig. 1—Liver phantom with simulated liver tumors used in this study.
A, Illustration of liver phantom.
B, External appearance of liver phantom. Image used with permission of OST Inc.

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which enables real-time visualization of 3D images, has been developed and is being used in a clinical setting. Three-dimensional evaluation of a lesion is easier by 4D ultrasound than by 2D ultrasound, and we think that it would be possible to perform biopsy and percutaneous treatment such as RFA more accurately and safely using this method. However, not many studies have shown the benefits of using 4D ultrasound guidance in biopsies or interventional procedures.

In this study, we compared the accuracy of ultrasound-guided puncture using either a new 4D ultrasound system or a conventional 2D ultrasound system for focal hepatic masses, using a liver phantom.

Materials and Methods

Because this was a phantom study, the need for approval for ethical issues was waived by the institutional review board of our hospital.

Liver Phantom

We used a liver phantom that contained four simulated spherical masses in an acrylic box (length × width × height, 300 × 299 × 150 mm) of two different sizes (15 and 30 mm in diameter) in two different positions (depths of 30 and 80 mm from the surface). The liver phantom (brand name or model number, OST Inc.) was specially designed for the present study. A schematic illustration and an overview of the liver phantom are shown in Figures 1A and 1B. The simulated phantom liver tissue had physical properties similar to the acoustic properties of body tissue.

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Sonography Imaging System and Puncture Needle

We used an ultrasound imaging system (Aplio XG, Toshiba) equipped with a 5-MHz 4D probe (PVT-574MV, Toshiba) that can be used in either the 2D or 4D mode (Fig. 2). The 4D probe is a mechanical volumetric data acquisition probe. The piezoelectric crystals are moved mechanically in an arc with equal movements to each side of a preselected center point. We used a 21-gauge puncture needle (PEIT needle, Hakko) in this study.

Puncture Experimental Design

Four inexperienced and four experienced physicians attempted punctures of the four simulated masses, of two different sizes (15 and 30 mm in diameter) in two different positions (30 and 80 mm from the surface (Fig. 1A), twice each, using 2D and 4D ultrasound guidance for a total of 128 punctures (eight operators, two techniques, and eight punctures per session). Each experienced physician had more than 5 years of experience in percutaneous liver tumor treatments (i.e., RFA or PEI or both), and each inexperienced physician had less than 1 year of experience in such treatments, at the time of writing.

Physicians were given the following explanations and instructions before the experiments: the aim of this study was to compare puncture accuracy between 2D and 4D ultrasound; they had to attempt to puncture the center of a tumor model (a sphere); and they were not allowed to attempt to repuncture the tumor model after retracting the inserted needle. There were four tumor models, each differing in size and depth from the surface, in the liver phantom. They were instructed to puncture each model twice, eight times in total, for each technique; they could start puncturing a tumor model in any region, but they were instructed that they could not puncture the same tumor twice consecutively; and they had to puncture under 2D ultrasound guidance initially, and then subsequently under 4D ultrasound guidance. After completion of a 2D ultrasound–guided puncture, they were instructed to stop the experiment and resume the puncture procedure under 4D ultrasound guidance after an interval of 1 day or longer; there was no time limit per puncture.

After completion of each puncture, 3D volume data including the whole tumor model while the needle was still inserted were obtained, recorded on a hard disk, and analyzed off-line. To acquire a 3D volume dataset, the transducer was held stationary in one hand while the ultrasonic beam was mechanically swept across the transducer face.

Puncture Procedure With 2D Ultrasound Guidance

All puncture procedures under 2D ultrasound guidance were performed with the 2D ultrasound puncture mode of the 4D ultrasound probe. This puncture mode used a one-view display, and a conventional transverse image of one puncture line was displayed on the monitor (Fig. 3). An assistant was needed to manipulate the control panel of the ultrasound imaging system while the operator performed the puncture. All procedures were performed with a needle guide.

Fig. 2—Appearance of mechanical volumetric data acquisition (4D) probe with puncture device used in this study. Image used with permission of Toshiba.

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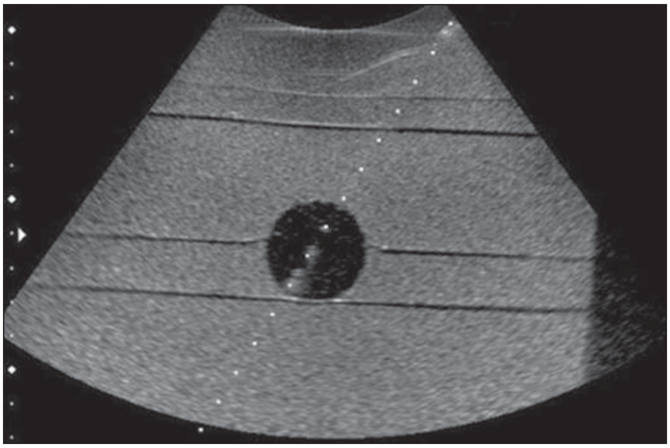

Fig. 3—Example of conventional 2D ultrasound puncture mode display. Simulated liver tumor is displayed in real time along with expected path of biopsy needle (dotted line).

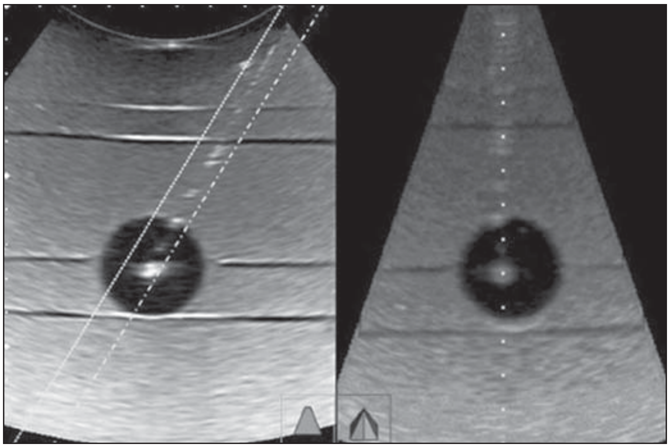

Fig. 4—4D ultrasound display used in this study (VolPure, Toshiba). Left is transverse image; right is orthogonal image parallel to plane on puncture line. Left image appears to show that puncture needle is inserted into center of tumor. However, right image shows that puncture needle is out of alignment toward left side. Image used with permission of Toshiba.

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Puncture Procedure With Real-Time 3D Ultrasound Guidance

All puncture procedures on 4D ultrasound guidance were performed with the 4D puncture mode (VolPure mode) of the 4D ultrasound probe, a new 4D puncture mode developed by Toshiba. In this system, a conventional 2D axial planar image is displayed on the left side of the monitor, while an orthogonal maximum intensity projection (MIP) image that includes the puncture line is on the right side (Fig. 4). In 4D ultrasound, the volume acquisition angle and volume rate were adjusted with a constant setting, such as 30° and 5 volumes per second, respectively. As in 2D ultrasound–guided puncture, an assistant was needed to manipulate the control panel of the ultrasound imaging system while the operator performed the puncture. All procedures were performed with a needle guide.

Assessing Puncture Results

For comparison of puncture accuracy between 2D ultrasound and 4D ultrasound, the perpendicular distance from the puncture needle to the center of the tumor model was measured in the coronal plane in the center of the tumor model in each puncture procedure (128 punctures in total), and this distance was defined as the "error distance" (Fig. 5). Although measurement of the error distance was possible in both the sagittal and coronal planes, we measured the error distance in the coronal plane in the experiments because this enabled us to better understand the error clinically and intuitively. The error distance was manually measured by one physician with an off-line software system (4D Viewer-Radiology, Toshiba) on the basis of the 3D volume data of the whole-tumor model obtained from the image at the end of each puncture procedure. To eliminate bias, the physician was blinded as to whether the technique was 2D or 4D ultrasound. To reduce any effect of intraoperator variation, we used a mean error distance of two measurements for each tumor model tested by each physician. The error distance was then compared between 2D and 4D ultrasound. In addition to the error distance, we also calculated the error ratio (percentage), which was defined as the ratio of error distance to the diameter of the target tumor. Because puncture accuracy tended to decrease when tumor size decreased, the error ratio could be used as a reliable index for puncture accuracy. Furthermore, the average errors obtained by the experienced physician group were compared with those obtained by the inexperienced group in cases with different tumor diameters and depths.

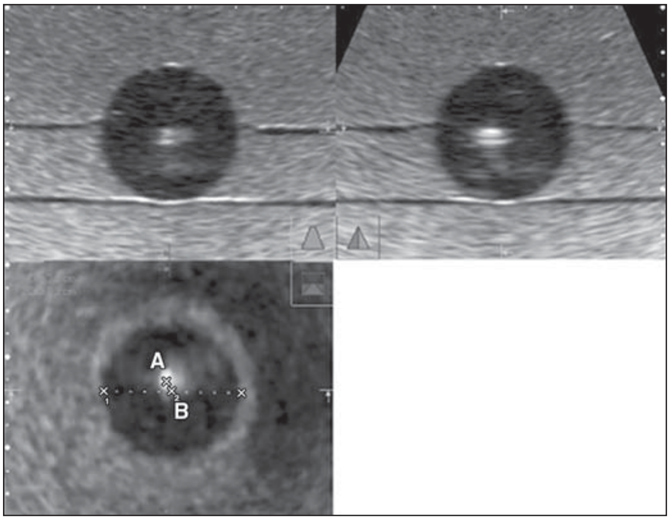

Fig. 5—4D ultrasound display used for assessing error distance. Top left image is transverse, top right image is sagittal, and bottom left image is coronal plane. Three displayed imaging planes are perpendicular to each other. Bottom left image also shows distance from puncture needle (A) to center of tumor model (B) in coronal plane containing center of tumor model in each puncture procedure; this distance was defined as "error distance."

Statistical Analysis

Student's paired t test was used to compare the average error distance among physicians between 2D ultrasound and 4D ultrasound, and a p value of less than 0.05 was considered to indicate a statistically significant difference. All statistical analyses were performed using the computer software SPSS (version 11.0, SPSS).

Results

As shown in Table 1, in all tumor models, the average error distances and their ratios obtained by 4D ultrasound were smaller than those obtained by 2D ultrasound, and all differences were statistically significant ($p < 0.05$), except in one tumor model (15 mm in diameter and 30 mm in depth). The error ratio (percentage) increased when the tumor size decreased and the tumor depth increased.

TABLE 1: Mean Error Distances and Error Ratios for Different Tumor Sizes and Locations in 2D and 4D (Real-Time 3D) Ultrasound Modes

Tumor Diameter (mm), Tumor Depth (mm)	2D Ultrasound		4D Ultrasound	
	Error Distance (mm)	Error Ratio (%)	Error Distance (mm)	Error Ratio (%)
30				
30	3.9 ± 0.4	12.9 ± 1.5	1.8 ± 0.5	5.8 ± 1.5[a]
80	4.0 ± 1.5	13.3 ± 4.9	2.2 ± 0.8	7.3 ± 2.5[a]
15				
30	2.7 ± 0.9	17.9 ± 6.2	1.9 ± 0.4	12.5 ± 3.0
80	3.5 ± 0.9	23.3 ± 5.9	2.4 ± 0.8	15.8 ± 5.6[a]

Note—Data are mean ± SD.

[a] Data were significantly different from those obtained by 2D ultrasound ($p < 0.05$)

TABLE 2: Mean Error Distances and Error Ratios for the Experienced (*n* = 4) and Inexperienced (*n* = 4) Physicians on Each Tumor by 2D and 4D (Real-Time 3D) Ultrasound

Tumor Diameter (mm), Tumor Depth (mm), Experienced vs Inexperienced Physician	2D Ultrasound		4D Ultrasound	
	Error Distance (mm)	Error Ratio (%)	Error Distance (mm)	Error Ratio (%)
30				
30				
Experienced	3.9 ± 0.5	12.9 ± 1.6	1.8 ± 0.3	5.8 ± 1.0[a]
Inexperienced	3.9 ± 0.5	12.9 ± 1.6	1.8 ± 0.7	5.8 ± 2.2[a]
80				
Experienced	3.9 ± 0.5	12.9 ± 1.6	1.6 ± 0.3	5.4 ± 0.8[a,b]
Inexperienced	4.1 ± 2.2	13.8 ± 7.2	2.8 ± 0.7	9.2 ± 2.2
15				
30				
Experienced	2.1 ± 0.5	14.2 ± 3.2	1.9 ± 0.5	12.5 ± 3.2
Inexperienced	3.3 ± 1.0	21.7 ± 6.4	1.9 ± 0.5	12.5 ± 3.2
80				
Experienced	3.4 ± 0.8	22.5 ± 5.0	1.9 ± 0.5	12.5 ± 3.2[a]
Inexperienced	3.6 ± 1.1	24.2 ± 7.4	2.9 ± 0.9	19.2 ± 5.7[a]

Note—Data are mean ± SD.

[a] Data were significantly different from those obtained by 2D ultrasound ($p < 0.05$).

[b] Data obtained by the experienced group were significantly different from those obtained by the inexperienced group ($p < 0.05$).

As shown in Table 2, the average error distances in the experienced group tended to be smaller than those in the inexperienced group, for both techniques and each tumor model, and there was a statistically significant difference between the two groups in one tumor model (30 mm in diameter and 80 mm in depth) on 4D ultrasound ($p < 0.05$).

Discussion

In the current study, 4D ultrasound–guided punctures were markedly more accurate than 2D ultrasound–guided punctures in most tumor models of different diameters and depths. This is important for the clinical application of 4D ultrasound–guided puncture, because local recurrences can be reduced and patient survival rates improved by increased puncture accuracy. In addition, the utility of 4D ultrasound was shown in both the experienced and inexperienced physician groups. This could be because 4D ultrasound allowed more intuitive comprehension of the spatial relationship of the needle and the target lesion than did 2D ultrasound.

To date, some studies have shown the utility of 4D ultrasound–guided puncture [7–9]. These studies used three orthogonal planar views, which represented transverse, sagittal, and coronal planes, with 3D-rendered images as the standard display during the procedures. In the current study, however, the VolPure mode (displaying a conventional 2D axial planar image and an orthogonal MIP image, including the puncture line) (Fig. 3) was used during the procedures.

The 4D ultrasound puncture mode used in previous studies appeared to be useful for evaluating the spatial extent of the tumor and its relationship with vessels in the liver, but it was not suitable for a puncture, because it can be difficult for an operator to see additional sagittal, coronal, or 3D volume-rendered images while simultaneously viewing the conventional 2D axial planar image during puncture procedures. Thus, these 4D ultrasound systems were considered inappropriate for puncture procedures.

However, the VolPure mode has been developed specifically for aiding the puncture procedure by displaying both conventional 2D axial planar images and an orthogonal MIP image that shows the puncture line (Fig. 3), thus enabling visualization of the needle in longitudinal directions in two images and leading to more accurate puncturing. Moreover, 4D ultrasound can constantly display volume information rather than just the planar images, thus increasing the visibility of the needle. Therefore, the operator will not lose track of the needle by moving the transducer during the operation.

The results of this study showed no statistically significant difference in the average error ratio by 2D or 4D ultrasound in one tumor model (15 mm in diameter and 30 mm in depth). These results suggest that, on relatively small (≤ 15 mm) and shallow-seated (≤ 30 mm) lesions, we can use either technique in puncture procedures.

The present results also showed that, in the inexperienced physician group, there was no statistically significant difference in the average error ratio by 2D or 4D ultrasound in one tumor model (30 mm in diameter and 80 mm in depth), whereas a statistically significant difference was observed in the experienced physician group. This finding suggests that, to precisely puncture with 4D ultrasound guidance, a certain degree of experience is necessary, especially on relatively large (≥ 30 mm) and deep-seated (≥ 80 mm) lesions. This factor, however, could be negated if the operators become familiar with 4D ultrasound–guided puncture procedures.

There are limitations to this study. First, a hyperechogenic track made by the needle remained in the phantom, and it filled with air after one puncturing session. The track could be therefore identified on ultrasound when the next puncture session was performed immediately after the previous session. However, the trails disappeared after a sufficient interval (> 24 hours) between two puncture sessions, and thus, these effects can be minimized.

Second, this was a phantom study and therefore the phantom was not completely identical to a real tumor and liver tissue and was not completely suitable for clinical situations, even though the conditions mimicked those in clinical situations and in vivo.

One of the major differences between the present phantom study and clinical situations was the absence of movement due to respiration in this phantom study, which occasionally becomes a problem in vivo. Because the 4D ultrasound mode (five volumes per second) is inferior to the 2D ultrasound mode (15 frames per second) in real time, this disadvantage cannot be ignored in the clinical application of 4D ultrasound. However, this technical restraint does not appreciably interfere with the puncture procedures, and technical innovations might solve these problems in the near future.

Third, although the operators were not allowed to adjust the needle path in this study, repeated trials of needle path adjustment are common in clinical situations. This is another limitation of this study. However, to reduce the risk of cancer cell seeding and bleeding, we believe that repeated punctures would be undesirable, and one accurate puncture per session would be ideal. Thus, adjustment of the needle path was not allowed in the study.

In conclusion, the results of this study suggest that 4D ultrasound–guided puncture had higher puncture accuracy than does 2D ultrasound–guided puncture. However, it is necessary to conduct additional clinical trials to further compare these two techniques.

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References

1. Lindor KD, Bru C, Jorgensen RA, et al. The role of ultrasonography and automatic-needle biopsy in outpatient percutaneous liver biopsy. *Hepatology* 1996; 23:1079–1083
2. Pasha T, Gabriel S, Therneau T, et al. Cost-effectiveness of ultrasound-guided liver biopsy. *Hepatology* 1998; 27:1220–1226
3. Younossi ZM, Teran JC, Ganiats TG. Ultrasound-guided liver biopsy for parenchymal liver disease: an economic analysis. *Dig Dis Sci* 1998; 43:46–50
4. Rossi S, Di Stasi M, Buscarini E, et al. Percutaneous RF interstitial thermal ablation in the treatment of hepatic cancer. *AJR* 1996; 167:759–768
5. Arii S, Yamaoka Y, Futagawa S, et al. Results of surgical and nonsurgical treatment for small-sized hepatocellular carcinomas: a retrospective and nationwide survey in Japan. The Liver Cancer Study Group of Japan. *Hepatology* 2000; 32:1224–1229
6. Tateishi R, Shiina S, Teratani T, et al. Percutaneous radiofrequency ablation for hepatocellular carcinoma. *Cancer* 2005; 103:1201–1209
7. Won HJ, Han JK, Do KH, et al. Value of four-dimensional ultrasonography in ultrasonographically guided biopsy of hepatic masses. *J Ultrasound Med* 2003; 22:215–220
8. John BS, Rowland D, Ratnam L, et al. Percutaneous renal intervention: comparison of 2-D and time-resolved 3-D (4-D) ultrasound for minimal calyceal dilatation using an ultrasound phantom and fluoroscopic control. *Ultrasound Med Biol* 2008; 34:1765–1769
9. Long JA, Daanen V, Moreau-Gaudry A, Troccaz J, Rambeaud JJ, Descotes JL. Prostate biopsies guided by three-dimensional real-time (4-D) transrectal ultrasonography on a phantom: comparative study versus two-dimensional transrectal ultrasound-guided biopsies. *Eur Urol* 2007; 52:1097–1104