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Clinical Paper

Intraoperative Navigation for Breast Cancer Surgery Using 3D Ultrasound Images

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ABSTRACT The aim of this work was to develop an intraoperative image-guidance system for breast cancer surgery using three-dimensional (3D) ultrasound imaging.

Using a 10-MHz annular array mechanical sector probe, ultrasound images were obtained from nine volunteer patients with breast cancer immediately before removal of the tumor in the operating room. A 3D tumor image was reconstructed using a workstation, then superimposed on the video image of the breast based on geometrical data. These data were obtained simultaneously by an optical 3D position sensor. The 3D images of the tumors were validated by the pathological data obtained after the surgery.

In eight cases, the superimposed images were successfully obtained in approximately 15–20 min following scanning of the tumor. Scattered lesions around the main tumor were also visualized in the reconstructed tumor images, but artifacts of the ductal lesion caused by noise could not be eliminated in some cases.

This system should be very effective in helping the surgeon to recognize the extent of a tumor within the breast itself and to determine the margin of surgical resection for breast conservation surgery. Comp Aid Surg 4:37–44 (1999). ©1999 Wiley-Liss, Inc.

OBJECTIVE

Breast conservation surgery for small cancers has become a standard operation and has produced great benefits for patients in achieving a high quality of life after surgery.[3,4,21,22] The problem with breast conservation is local recurrence, which can lead to loss of the conserved breast. The most important factor in avoiding this tragedy is thought to be ensuring that the cut-end margin of the tumor is free from cancer invasion.[5,15,16] Breast cancer often contains ductally spreading lesions around the main tumor, and this makes it difficult for surgeons to determine the region of resection.[11] Surgeons usually recognize the location of the tumor by palpation during the operation, then remove it together with some peripheral normal tissue as a safety margin because small spreading lesions are not palpable. Surgeons are thus faced with the dilemma that wider resection, which could render

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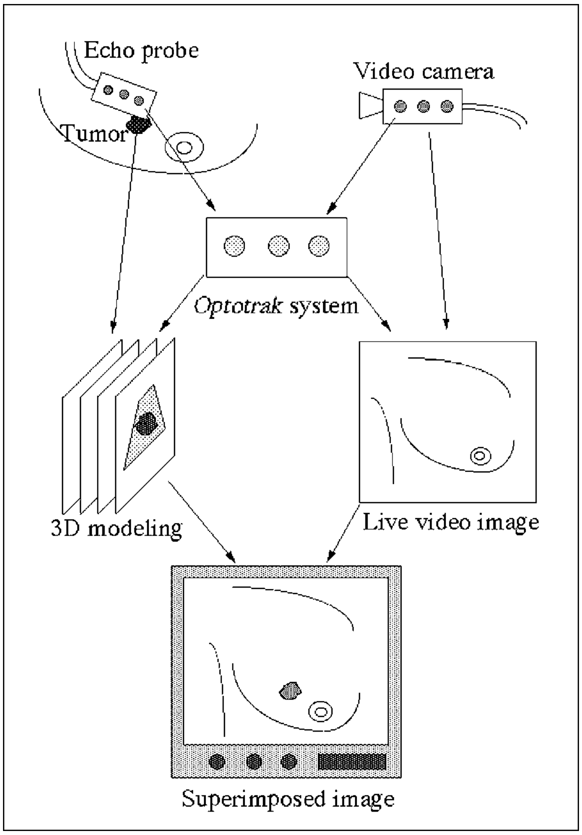

Fig. 1. Schematic outline of the system and procedure for enhanced reality visualization.

the cut end free from cancer, can diminish the benefits of breast conservation. To resolve this problem, a visualization system is needed to show the location and extension of the tumor in the breast so that the surgeon can minimize the resected region.

In this article, we describe our original image-guidance system using three-dimensional (3D) ultrasonic images and augmented-reality visualization for breast conservation surgery.

MATERIALS AND METHODS

The construction of the system and the procedure of visualization of the tumor have been reported previously.[14] The schematic outline of the procedure is shown in Figure 1.

Patients

The subjects were nine patients with breast cancer who were admitted to Osaka University Hospital from October 1997 to July 1998 and underwent surgery. A certain type of surgery, e.g., total mastectomy or breast-conserving surgery, was selected for each case on the basis of the patient's request and the clinical findings obtained through palpation by a surgeon, as well as data from mammograms and 2D ultrasound images. The patients had neither cardiovascular nor pulmonary complications, and all were given detailed information about this experiment and gave their informed consent voluntarily.

Acquisition of Ultrasound Images and 3D Geometrical Data

In the operating room, the patient was anesthetized and placed in the supine position for breast cancer surgery with her arm fixed above her face. Ultrasonic images of the tumor were obtained by scanning over the breast slowly with an SSD-2000 scanner equipped with a 10-MHz annular array mechanical sector probe (Aloka, Tokyo, Japan). The 3D motion of the probe was followed with the aid of an Optotrak system (Northern Digital, Waterloo, Ontario, Canada) which measured the position of 16 light-emitting diode (LED) markers attached to the probe (Fig. 2). These ultrasound image data and geometrical data were acquired and processed by a Sun Ultra2 Creator 3D workstation (Sun Microsystems, Mountain View, CA). The acquisition rate was about 5 frames/s, and one sequence of images contained approximately 80–150 slices, depending on the tumor size.

3D Modeling of the Tumor

The ultrasound images thus obtained were smoothed with Gaussian filtering for noise reduction. The region of interest (ROI) of the 2D image was defined manually by polygons every 10–20 slices, after which the 3D breast tissue region was composed automatically by combining the polygon images using our original tool. After one of the representative 2D images was used to determine the threshold for binary imaging, all frames were checked and 3D modeling of the binary images was performed by using the Visualization Tool Kit (vtk; Copyright: K. Martin, W. Schroeder, and B. Lorensen) (Fig. 3). The surface-rendering model was examined from every angle by rotation to distinguish the tumor from noise. Additional rearrangement was performed by means of selecting the ROI or creating binary images when too much noise masked the actual border of the lesion.

Augmented Reality Visualization

A video camera (Sun Microsystems) with LED markers was placed above the patient to take video images of the breast, and the 3D geometrical data

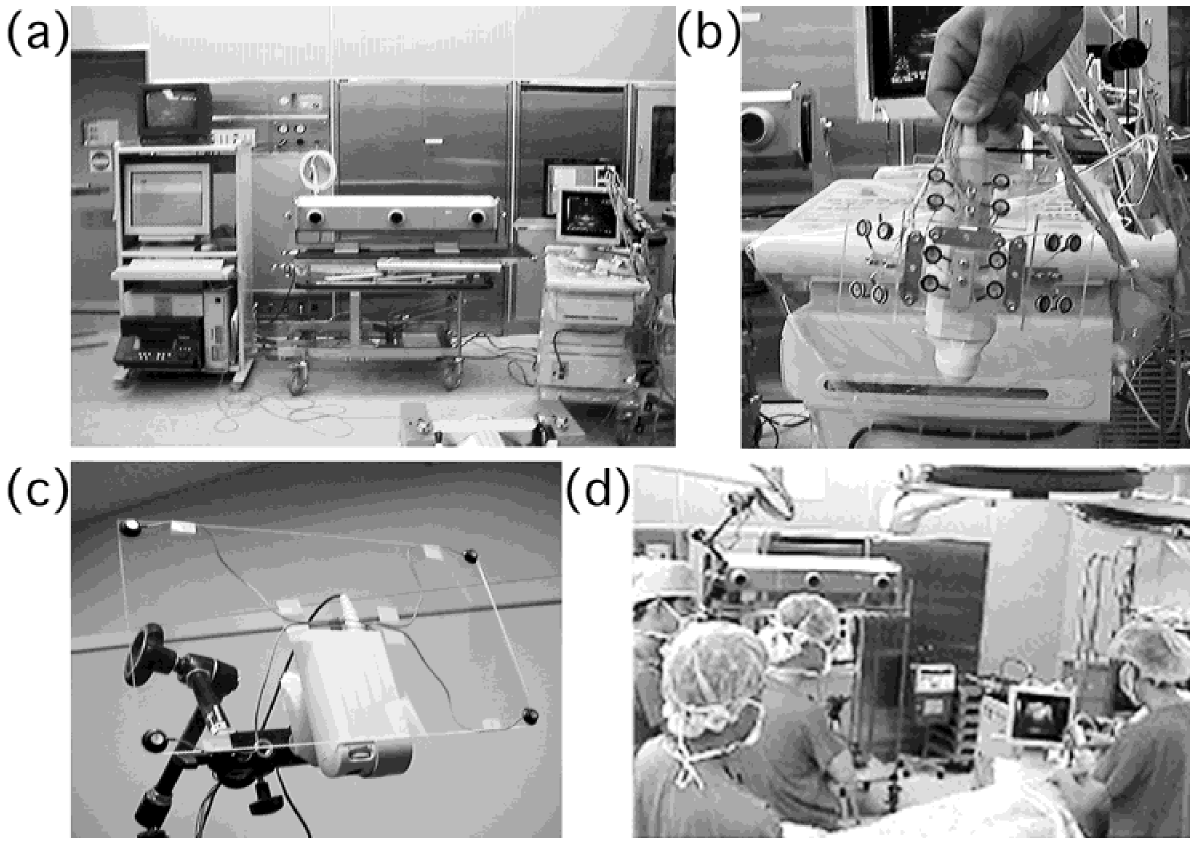

Fig. 2. Components of the system. The system consists of an Aloka ultrasound scanner, the Optotrak, a Sun video camera, and a workstation (a). The acrylic panels with LED markers are attached to a 10-MHz annular array mechanical sector probe (b) and a Sun video camera (c). A setup for acquisition of ultrasonic images in the operating room is shown in (d).

of the camera movements were obtained with the Optotrak system. The video data and the 3D tumor images were then integrated by the workstation, after which the tumor image was superimposed onto the live video of the breast. The enhanced reality images were shown on the monitor of the workstation at a rate of 1.5 frames/s.

RESULTS

The phantom tests and camera calibration had been performed previously (data not shown). The live experiments were performed on nine patients, whose clinical data are summarized in Table 1. All patients underwent successful surgery, which was planned beforehand on the basis of clinical data in the usual manner. No complications associated with either the experiment or the extended 20-min anesthesia were observed. In eight cases, the superimposed images were obtained within 20 min; the image could not be displayed in one case because of problems with the program. Complete concordance of the location of the virtual tumor and the location of the real mass (which was confirmed by the surgeon by means of palpation) was confirmed in these eight cases, while several prior tests had shown the image erroneously located 1–2 cm from the real tumor. By trial and error, it was found that this problem was caused by the camera position in the operating room: To suit the position of the patient, the camera was sometimes tilted, in which case the Optotrak could not identify the LED markers accurately. A wide acrylic wing with four LED markers was attached to the video camera in place of the old small wing (Fig. 2), and this solved the problem completely, with the difference in location being reduced to <2 mm.

Images from a case with double tumors are shown in Figure 4. A small daughter nodule appeared in the 3D image and was confirmed pathologically. However, a moderate volume of noise owing to the quality of the 2D images remained: The patient was very slender and the main tumor bulged from her breast, so the noise caused by air contamination between the probe and the skin could not be eliminated.

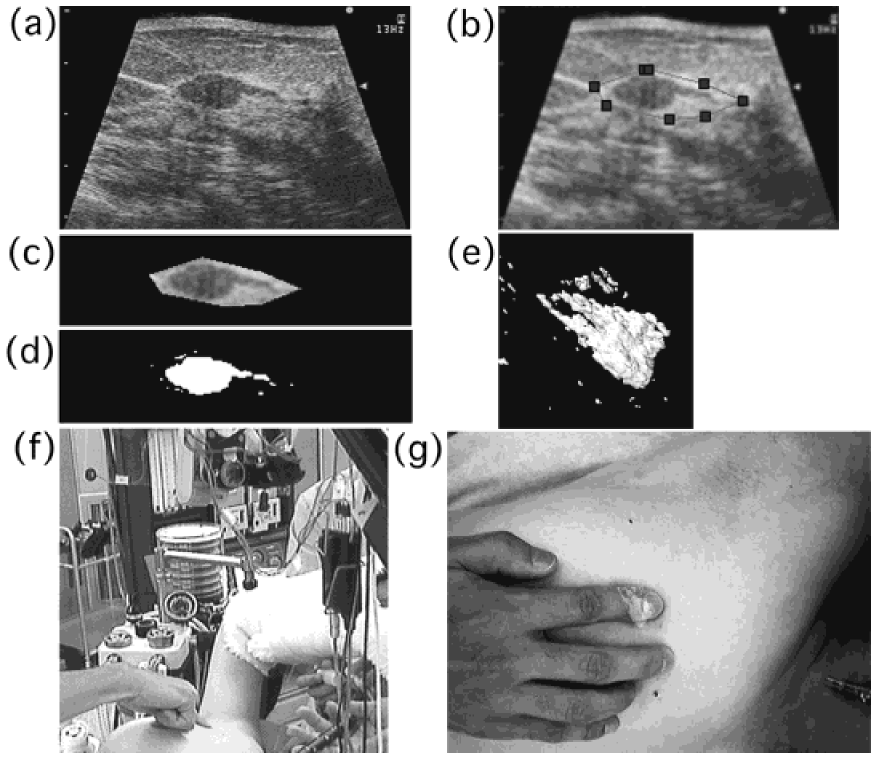

Fig. 3. Process of 3D modeling and superimposition of a tumor. (a) Original 2D ultrasonic image. (b) The ROI is defined manually by polygons on the image after Gaussian filtering. (c) Selected region. (d) Binary image of the tumor. (e) 3D model of the tumor. (f) Acquisition of the live image of the breast. The surgeon's finger is pointing to the skin over the tumor, as recognized by palpation. (g) Superimposed image on the monitor.

Figure 5 shows images from another case, in which there was complete concordance of the location of the 3D image of the main tumor and that confirmed by palpation. The superimposed image indicated a widely spreading lesion next to the main tumor, which had earlier been identified by the surgeon as a smaller lump. The pathological examination with serially sliced specimens proved that the 3D image had displayed the lesion accurately.

DISCUSSION

Displaying invisible subcutaneous lesions would provide crucial support for surgeons and would constitute a landmark development in the history of radiology. Recent developments in computer tech-

Table 1. Clinical and Pathological Findings of Patients

Case	Age	Tumor Size (cm)*	Location†	Operation‡	Histology§
1	42	2.5 × 1.5	R uoq	TM	IDC
2	55	4.2 × 3.7	L hq	TG	IDC
3	48	1.5 × 1.5	R uoq	PM	IDC
4	50	1.9 × 1.9	R uoq	TM	IDC
5	36	3.2 × 2.8,0.5×0.5	L uoq	TM	IDC
6	63	2.8 × 2.3	R uoq	TM	IDC
7	27	0.5 × 0.5	L liq	PM	NDC
8	56	2.3 × 2.2	R uoq	TM	IDC
9	29	0.9 × 0.9	R uoci	TM	IDC

* The tumor size was measured by palpation.
† R = right; L = left; uoq = upper-outer quadrant; hq = lower-inner quadrant.
‡ TM = total mastectomy; TG = total glandectomy; PM = partial mastectomy.
§ IDC = invasive ductal carcinoma; NDC = noninvasive ductal carcinoma.

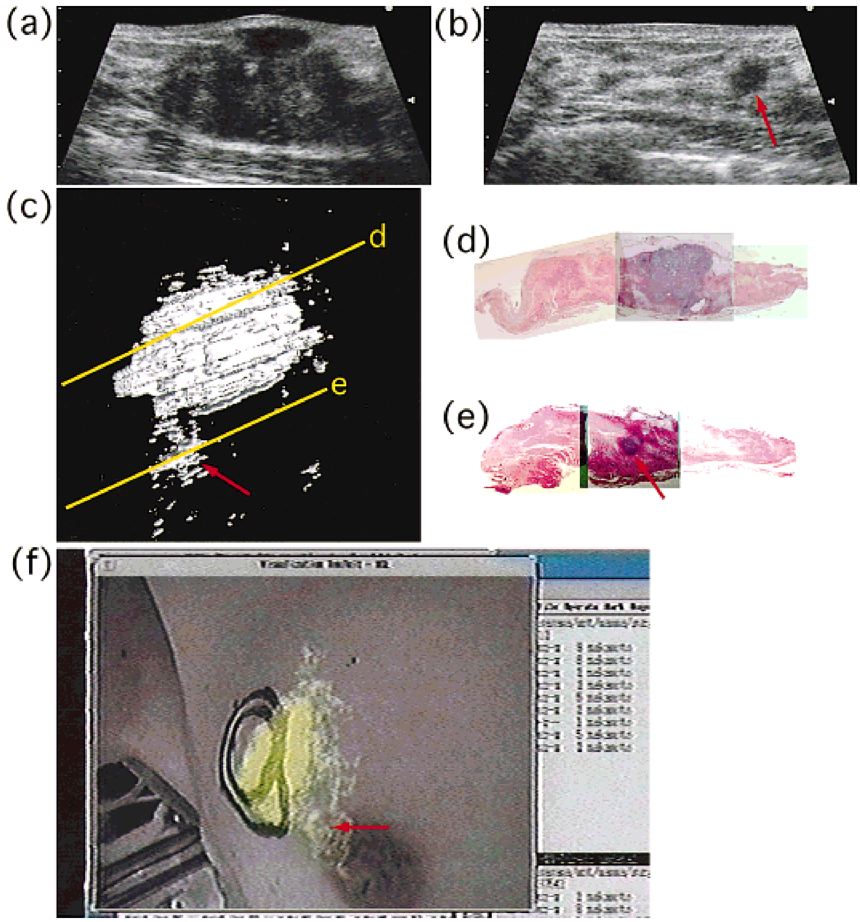

Fig. 4. Patient who had a large tumor with a daughter nodule (case 5). (a) Original 2D images of the main tumor. (b) Daughter nodule (red arrow). (c) 3D model of the tumor. (d) Section of the main tumor. (e) Section of the daughter nodule (red arrow). (f) Superimposed image of the tumors. A red arrow indicates the daughter nodule.

nology and diagnostic radiology may help realize this dream in some surgical fields.[2,20,23] The most advanced model is probably the magnetic resonance imaging (MRI) and computed tomography (CT) navigation system for brain surgery.[7,9,24] In this system, the surgeon can easily simulate the operation and identify the location of the tumor and surrounding vessels, thereby contributing to a safe and successful operation.

This article describes a navigation system for breast-conserving surgery. For this operation, the resection line is currently determined by palpation of the tumor, then the region is excised cylindrically according to the markings made with subcutaneously injected dye. The tumor is usually removed together with a large volume of normal peripheral tissue which is likely to contain ductally spreading lesions which are not palpable.[4,22] Although the surgeon's fingers may become sensitized with long-term training, excessive surgery as well as insufficient resection often occurs. Therefore, image guidance would be very helpful for surgeons in determining the resection line and marking it according to the superimposed image.

To develop an enhanced reality system for breast cancer, there are several problems to be overcome. The first is caused by the elasticity of the breast. In neurosurgery, the brain and the tumor do not move once the position of the skull is fixed on the table during the operation, so in this case there may be no problem in superimposing the virtual image onto the real image. In contrast, the breast is an elastic organ, so the 3D data of the tumor may become distorted and dislocated from the dimensions and position of the real tumor. To examine this problem, we performed an earlier experiment on the motion of the breast. According to our data, the breast skin around the tumor moved only 0.5

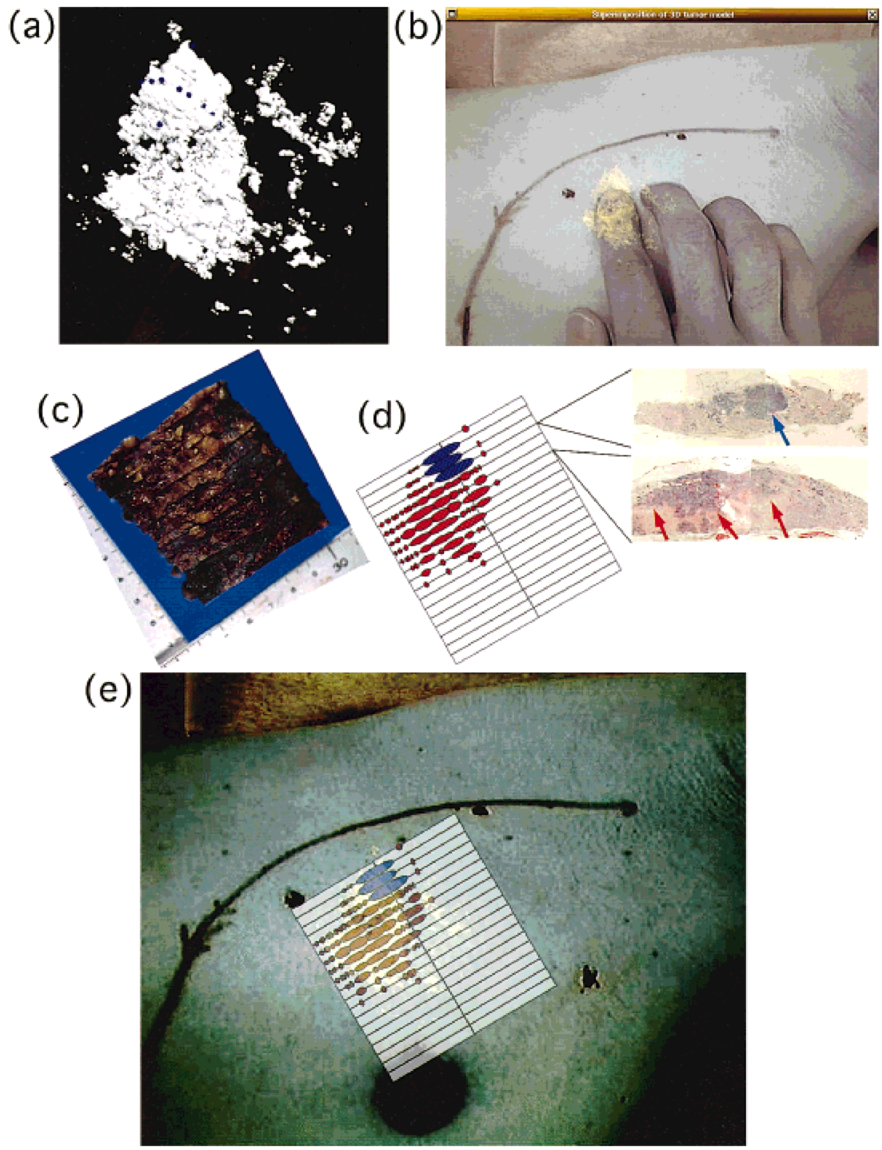

Fig. 5. Patient who had a small cancer with ductally spreading lesions (case 9). (a) 3D model of the lesion. Blue dots indicate a small main tumor. (b) Superimposed image. The surgeon did not recognize widely spreading lesions, just a small main tumor. (c) The specimen was sliced serially and examined in detail. (d) The map of the lesions shows the small main tumor indicated by blue dots and a blue arrow, and ductally spreading lesions indicated by red dots and red arrows. (e) Overlay of the lesion map onto the superimposed image of the 3D tumor model and the breast.

mm during scanning with an ultrasonic probe when respiration was suspended.[14] Most Asian women have comparatively small breasts, so a breast with a tumor is stretched sufficiently when the patient is placed in the operating position with her arm above her head. The important point was that the breast should be scanned gently and slowly, with enough jelly for ultrasound examination. Furthermore, the tumor should be placed at the highest point of the breast by controlling the angle of the operating table, so that the skin over the tumor will be stretched flat and only move minimally.

The second problem is how to determine the optimum diagnostic modality for this system. For breast cancer, CT, MRI, and ultrasound can now be easily and effectively used for diagnosis.[1,6,8,12,13,18,19] We selected ultrasound because of this system's portability and reproducibility in the general operating room. Ultrasound is considered to be the most suitable modality for the navigation system for breast cancer surgery because it can acquire real-time images of the tumor during the operation. However, ultrasound images of the breast are usually very complex because of the breast's anatomical construction and the histological diversity of the tumor.[17] Furthermore, the echo pattern of the mammary gland is often affected by menstruation.[10] Segmentation of the tumor from the ultrasound image is therefore often difficult, making validation of the 3D image unavoidable. In each case, the main tumors of our patients were correctly displayed at the site where they were confirmed to exist by both palpation by the surgeon and subsequent pathological examination. Furthermore, both 3D and 2D images of several special cases were analyzed in greater detail by comparing them with serially sliced pathological specimens. We intentionally selected tumors with complicated structures, e.g., double tumors or widely spreading ductal lesions, to confirm the reliability of the system. The lesions were displayed almost completely on the 3D images, although some noise which was indistinguishable from lesions could not be eliminated. This noise problem might have been caused by the quality of the original 2D echo images. Repeated acquisition of the image, one of the merits of ultrasound, is necessary if the image contains noise. Careful selection of the ROI, fine adjustment of the threshold for binary images, and precise checking of the 3D image from different angles can reduce noise and are thus more likely to provide accurate images of the tumor. However, more data need to be obtained from a greater number and variety of patients, including those with large breasts, to develop this system further.

The time required to create a 3D image is also an important factor when considering its clinical use. In this series, approximately 15–20 min was required to display the superimposed image on the monitor. Most of this time was used for Gaussian filtering, repeated determinations of the threshold, and surface rendering from over 100 frames of 2D images. However, this problem of time required can be expected to be solved by further advances in computer technology: We believe that it will be possible to perform the procedure in 5 min in the not too distant future.

The recent development of medical imaging devices for diagnosis and screening of breast cancer has improved the detection of nonpalpable but echo-detectable small breast cancers. Our enhanced-reality image-guidance system is expected to become a reliable tool for breast surgeons in the future and will provide patients with a better quality of life by facilitating minimum resection of the cancer with maximum therapeutic effect. We are continuing to obtain pathological data on the surgical margins from a larger number of specimens, resected in accordance with navigational data to estimate the reliability of our system. Furthermore, we are now developing more interactive processing tools, and are planning to use a faster computer in conjunction with a downsized system.

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