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Augmented Reality Applied to Ultrasound-Guided Breast Cyst Aspiration

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INTRODUCTION

The purpose of this paper is to introduce the augmented-reality guidance technology for breast cyst aspiration to the medical community. The technical details of our approach have been described in detail previously (1–4). The first part of this paper, up to and including "Equipment Specifications," summarizes some of the work presented in these papers, including the contents of Figures 2, 3, and 4. The second part of the present paper, starting with "Phantom Studies," presents the phantom and human subject experiments from the perspective of the radiologist and contains a medically-oriented discussion of the preliminary results and the potential of this technology.

CLINICAL BACKGROUND

In recent years, ultrasound-guided biopsy of breast lesions has been used for diagnostic purposes, partially replacing open surgical intervention (5–7). Ultrasound guidance also is often used for wire localization prior to open surgical biopsy, as well as for cyst aspiration. However, ultrasound guidance for such interventions can be somewhat difficult to learn and perform, especially for very small lesions, for women with very large breasts, or for lesions that lie very close to the chest wall (8–11).

Successfully completing these interventions requires good hand-eye coordination and three-dimensional visualization skills to guide the biopsy needle to the target. Typically, the ultrasound image is viewed on a conventional video monitor. The operator must learn to alter the position and orientation of the needle with respect to the lesion location in real time. Part of the difficulty in guiding the needle is keeping both the needle and the lesion simultaneously in view, that is, within the ultrasound image slice, as the needle approaches the lesion. Also, both position and orientation of the needle (5 degrees of freedom) must

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be ascertained in part from a two-dimensional ultrasound image. The position and orientation of the ultrasound image within the patient must be determined by the physician using only visual and tactile feedback. Thus, establishing correspondence between the biopsy needle and the patient's body is a two-step, indirect process. With the chest wall, pleura, and pericardium in close proximity to the breast, and with lesion size ranging down to only a few millimeters, the needle must be accurately positioned, both to avoid complications and to obtain the correct diagnosis (5,12).

In addition, sonographic is preferable to stereotactic mammographic guidance in some circumstances because ionizing radiation is not used; the guidance is utilized in "real time," which can shorten the procedure significantly, and stereotactic guidance is impracticable for some parts of the breast (i.e., in lesions directly against the chest wall and in the superficial subareolar region) (13). Some cases, such as mammographically detected calcifications of the breast, are not visible by sonography and thus are not accessible to sonographic-guided biopsy.

TECHNICAL BACKGROUND

We believe that the use of augmented reality (AR) technology that would allow the image to be displayed in three dimensions at its actual location within the patient might significantly simplify both the learning and performing of ultrasound-guided interventions. Although three-dimensional ultrasound acquisition systems are available commercially, they are not widely used. These systems are not ideal for applications such as breast biopsy because the cumbersome hardware might obstruct the physician's access to the patient. Because two-dimensional acquisition systems are likely to remain commonly used for many years to come, it would be useful to develop a tool that would display the images obtained with this device in three dimensions.

While the development of Head-Mounted Displays (HMDs) and affordable real-time computer graphics engines has given rise to much work in Virtual Reality (VR), comparatively less work has been done in the field of "Augmented Reality" (AR). A VR system immerses the user into a totally synthetic, computer-generated environment. On the other hand, an AR system combines computer-synthesized images with the observer's view of real world surroundings (14).

An AR system typically has the following requirements:

1. Accurate registration between synthetic and real objects: a virtual object must appear in its proper place relative to the real world, otherwise the user cannot correctly determine three-dimensional relationships. Dynamic registration is important so that the user can move around in his/her environment, and the relative positions of the real and synthetic object remains constant and accurate.
2. Reasonable image generation rate (10 Hz) and stereopsis so that there is good depth perception and believability of the object in space, which require kinetic or stereoscopic depth cues.
3. Simple initial set-up procedures so that AR applications are easy to pick up and use without tremendous technical understanding of how the systems function, much as two-dimensional display systems are currently used by radiologists and technologists.
4. Minimal constraint on the user's mobility so that, ideally, the user is able to move without significant restriction.
5. Low latency, that is, minimal delay between the user's movement of the image acquisition device and the image display update needed for smooth and effective interaction with the system.

In the application, developed by the computer scientist coauthors of this paper (HF,

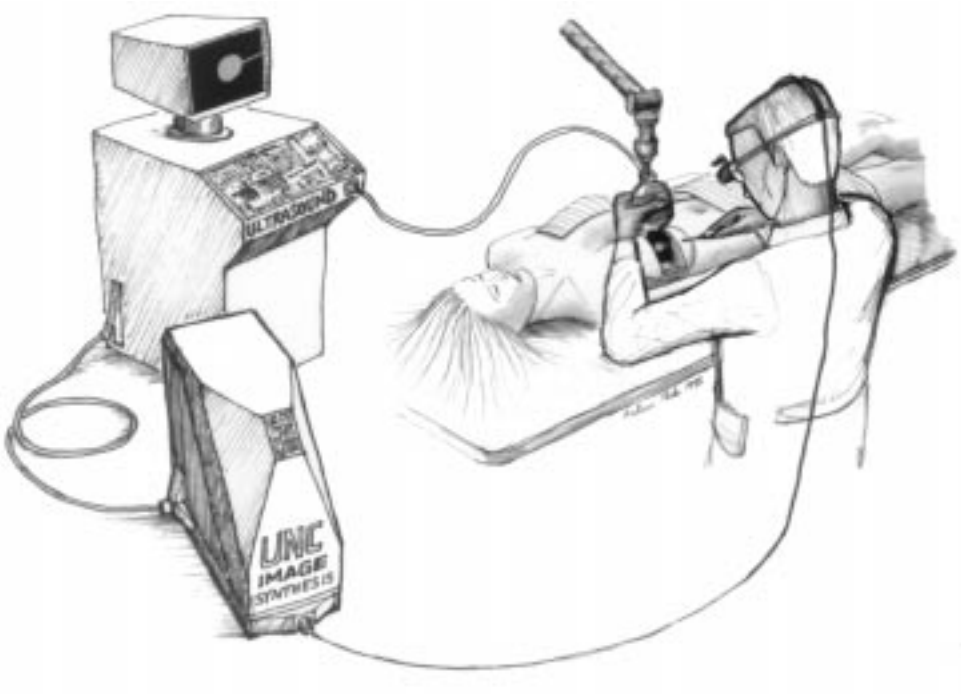

Fig. 1. Artist's rendition of ultrasound-guided needle biopsy scenario using AR guidance. The physician wears a head-mounted display (HMD) with a camera looking at the breast; the left hand controls the ultrasound transducer while the right hand operates the biopsy needle. The synthetic "pit" inside the breast, to more easily view the ultrasound images and other data, is seen by the physician in the head-mounted display, or by others viewing a conventional video monitor which shows the HMD point-of-view.

AS, ML, MW, and GH), the synthetic imagery consists of computer-processed sonography data, acquired through ultrasound imaging, superimposed over the real-world surroundings or the physician's view of the breast biopsy patient. The latter view is acquired by high-quality miniature video cameras mounted on the physician's head. Tracking systems are used to acquire position and geometry information for the patient and physician. High-performance graphics computers are used to generate the combined imagery in real time. The composite images are presented to the physician via a Head-Mounted Display (HMD). The physician views the ultrasound imagery "in place," registered with the patient (Figure 1). We report here on preliminary experiments with phantoms (Figure 2) and with four human subjects (Figures 3 and 4).

To our knowledge, no other group has applied this technology to this task. The computer scientist coauthors of this paper have demonstrated previously one of the first augmented-reality ultrasound visualization systems (15), real-time visualization of a live fetus within a pregnant subject (16), and on-line rapid volume reconstruction (17) using the experimental graphics engine that they have developed, Pixel-Planes 5 (18). More recently, they have demonstrated an experimental system designed to eventually provide AR guidance for ultrasound-guided breast biopsies (1–3,19,20). Other groups have used three-dimensional reconstruction of ultrasound data to display arteries *in vitro* (21,22). Cline et al. have used noninvasive MR blood flow data to reconstruct three-dimensional display of flow that resembles cineangiography (23). Altobelli et al. have used three-dimensional displays of surface reconstructions from CT data to plan complex craniofacial surgery in 20 patients (24). Gleason et al. have used combined three-dimensional reconstructed CT or

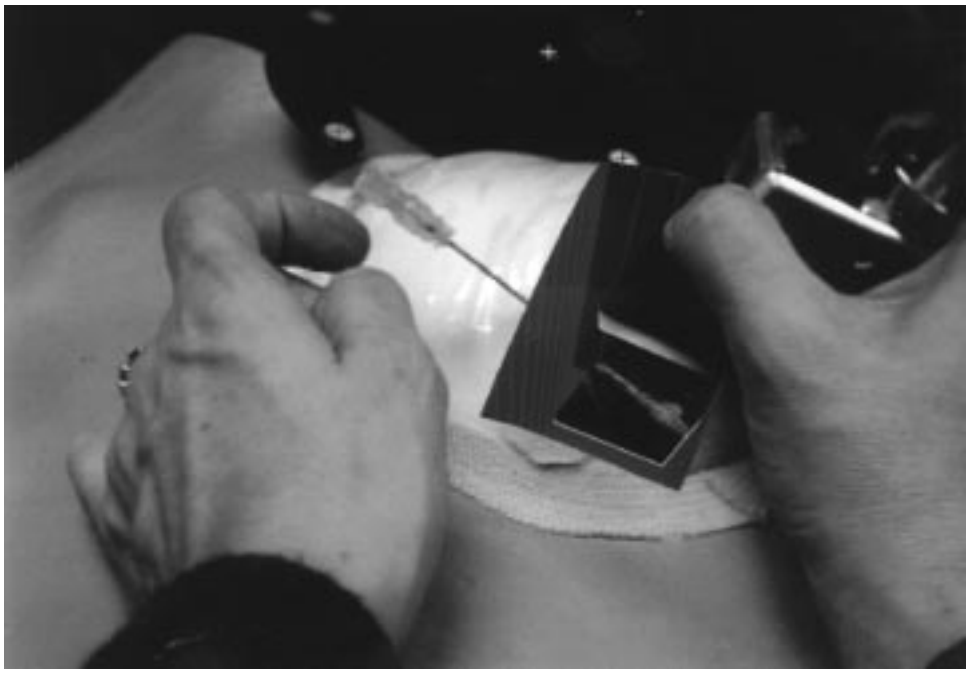

Fig. 2. View inside the head-mounted display during one of our preliminary experiments with a breast phantom. The (square) ultrasound transducer slice images a lesion within the breast phantom. A biopsy needle has been inserted into the breast and is also visible within the ultrasound slice.

MR scans registered with live video images of the patient to assist stereotactic nuerosurgery (25). We believe our group is the first to use the three-dimensional ultrasound data registered in real time with the patient's body to guide an intervention.

METHODS

Equipment Specifications

The system uses an array of tools suitable for both real-time acquisition and visualization, as well as for off-line reconstruction and visualization. The principal components (all commercial off-the-shelf technology) for the UNC augmented reality system used for the experiments to be described later are:

1. A Virtual Research VR-4 Head-Mounted Display (HMD)
2. Two Panasonic GP-KS102 CCD video cameras with Cosmicar F1.8 12.5 mm lenses with 28° field of view attached to the head-mounted display
3. A PIE Medical Scanner 200 ultrasound machine, equipped with a 7.5 MHz linear transducer
4. An Ascension Flock of Birds® magnetic tracker with Extended Range Transmitter mounted on the head-mounted display, for tracking the head of the observer
5. A FARO Technologies Metrecom IND-01 mechanical arm for precise (tethered) tracking of the ultrasound transducer
6. A Silicon Graphics Onyx InfiniteReality® (SGI IR) graphics workstation equipped with 4 high-capacity raster managers and 2 GB of main memory, as well as a Sirius Video real-time video capture device used for both HMD video acquisition and image-processing and for ultrasound video acquisition and image processing
7. A precision x-y motion-control platform that is used for transducer calibration.

In subsequent refinement of the system, the HMD has been replaced by a lightweight, cus-

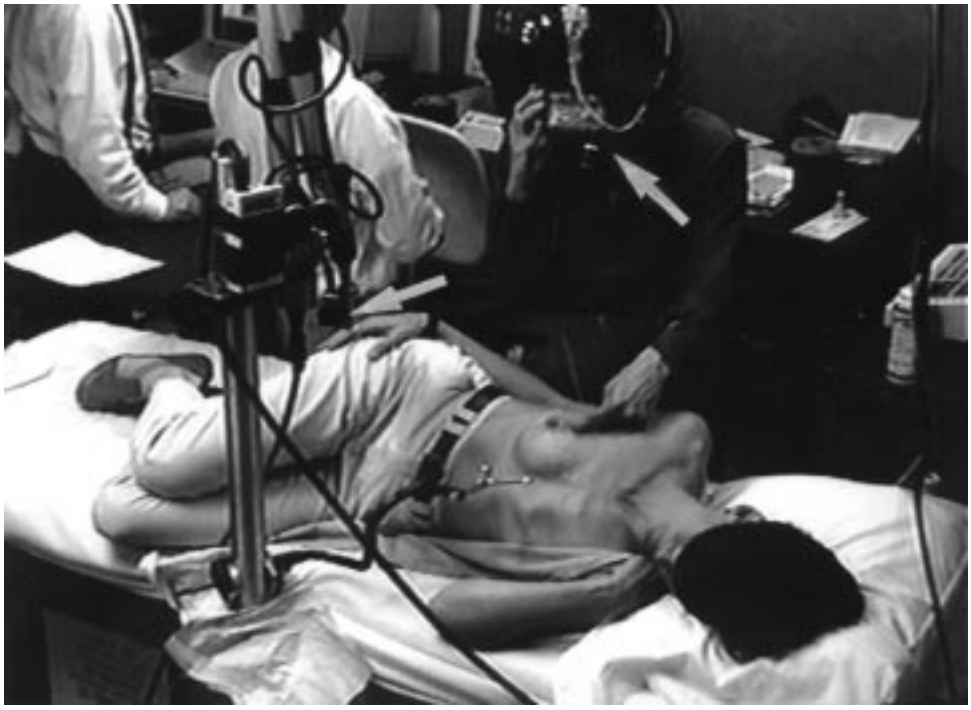

Fig. 3. Preliminary human subject experiment. The physician (EDP), wearing an HMD (marked by top-right arrow) is examining the subject's right breast. The left arrow points to PIE Medical 7.5 MHz ultrasound transducer, attached to FARO Technologies mechanical arm for precise 6 degree-of-freedom tracking. This has been replaced by a less cumbersome system using a Flashpoint 5000 3D localizer to track the transducer without encumbering the physician.

tom-designed video-see-through head-mounted device with built-in stereo video cameras. The Panasonic video cameras have been replaced with Toshiba IK-UM42A miniature cameras cameras built into the custom-designed head-mounted device. The Ascension Flock of Birds® magnetic head tracker has been replaced by a large-area ceiling tracker designed and built at UNC. The FARO Technologies Metrecom IND-01 mechanical arm has been replaced by a Flashpoint 5000 3D localizer from Image-Guided Technologies. Phantom experiments have been completed using this new system, but no patient studies have yet been undertaken with it.

The HMD-mounted video cameras are 64 mm apart — a typical interpupillary distance for humans — and are oriented with a convergence angle of 4° for sufficient stereo overlap in a tabletop working environment. The 28° field of view was selected for minimal optical distortion.

This system makes heavy use of the high-speed image-based texturing capability available in the SGI IR. The Sirius video capture subsystem acquires both HMD camera video and ultrasound video simultaneously and transfers the data to the graphics frame buffer and the main memory of the SGI IR. The display presented to the user resembles that of an earlier on-line volume reconstruction system, but the images obtained are vastly superior to those generated by the older system. The new system can sustain a frame rate of 10 Hz for both display update and ultrasound video grabbing and also can provide high-resolution ultrasound slice display and rendering for up to 16 million ultrasound pixels. It also uses a technique designed to correct registration errors (due to lack of precision in the electromagnetic head-tracking device) dynamically, by tracking strategically placed, colored dot targets in the video image (these

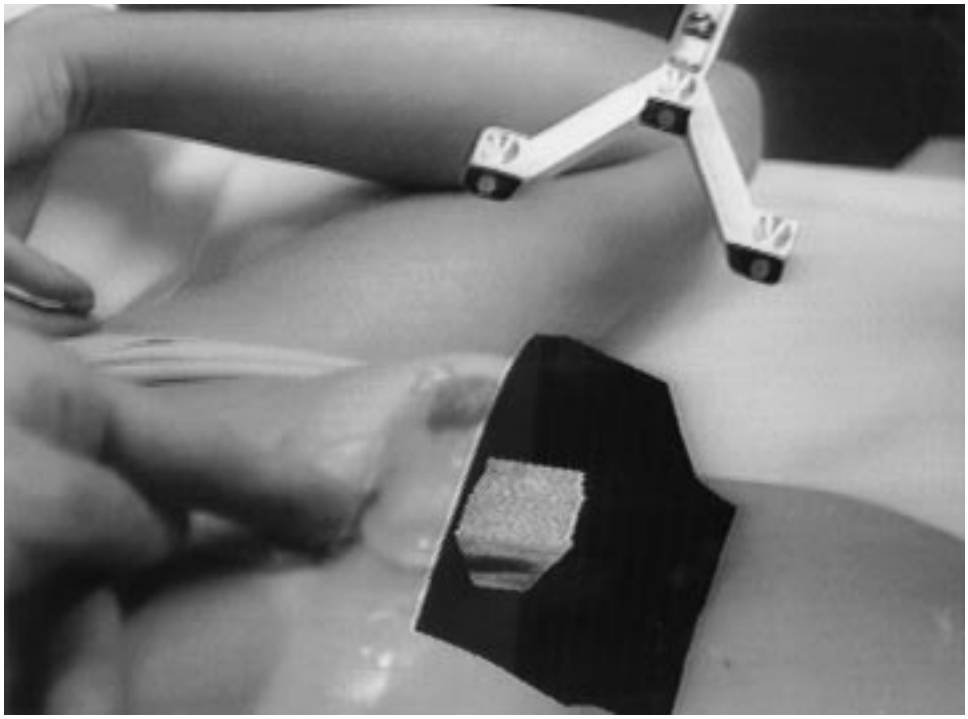

Fig. 4. View presented inside the user's head-mounted display in real-time during the experiment depicted in Figure 3. The synthetic opening covering the bottom half of the breast contains a volume of 2D ultrasound slices, showing a cross-section through a liquid-filled cyst inside the breast. The physician's left index finger points to the location of the cyst as she perceives it via tactile feedback, verifying correct enhanced imaging registration.

are visible in Figures 2 and 4). Furthermore, compositing of live video and computer graphics elements is done digitally, eliminating artifacts introduced by the external chroma keyer used in the previous systems.

Each ultrasound slice is presented in its proper location and orientation at the moment of acquisition and is displayed properly intersecting with other slices. Old slices dim and fade in time, controlled by a user-definable decay parameter. This "3D radar display," expected to be useful in scanning moving structures such as fetuses or biopsy needles, reflects decreasing knowledge about imaging targets that have not been "visited" recently by the scanner. A Binary-Space-Partition (BSP) tree algorithm handles intersecting slices properly (26). A large number of such directly rendered ultrasound slices can give the appearance of a volume dataset.

Two different rendering modes are supported by the system: Maximum Intensity Projection (MIP) and Opacity Accumulation, a rendering method derived from Levoy rendering. Ultrasound probe tracking was performed for the human experiments with a high-precision, rigidly tethered device — a mechanical arm manufactured by FARO Technologies (indicated in Figure 1); it provides sub-millimeter positioning accuracy and thus considerably improves registration between individual ultrasound slices when compared with earlier systems. The system also is capable of acquiring patient geometry for a specific area of the skin surface. This is currently done via a manually assisted "sweep" phase; after that, the acquired geometry is used to render a synthetic opening in the patient, within which the ultrasound data (consisting of slices) can be viewed.

Phantom Studies

To test system feasibility, a breast phantom with hypo- and echogenic "lesions" was

mounted on a mannequin. The radiologist, expert in breast imaging (EDP), used the system to perform needle biopsies of this phantom until she was sure that she could achieve the same accuracy of needle placement as she ordinarily could in her clinical practice. This endeavor required approximately three hours. Multiple passes were made, both with a 22-gauge spinal needle and a 14-gauge needle, into multiple lesions within the phantom. The radiologist could check the placement of her needle by removing the HMD helmet and viewing the needle location in the traditional way — by viewing a video monitor that displayed the sonographic data.

Patient Studies

Four patients who were already scheduled for ultrasound-guided cyst aspiration as part of their regular clinical care were recruited for testing of the AR system. These patients underwent the necessary procedures over the course of a 12-month period. Patients signed a study specific consent form and had their interventions performed in the graphics laboratory at the Computer Science Department at UNC-CH. Two Advanced Cardiac Life Support-Certified emergency medical technicians were available in the room in case of life-threatening complications. This project was approved by the University of North Carolina Institutional Review Board.

RESULTS

The phantom and patient studies have demonstrated the feasibility of this system in the performance of percutaneous interventions involving small lesions in the breast.

Phantom studies revealed that the needle could be placed accurately into the phantom lesions using the system. Three-dimensional location of the needle tip was confirmed by scanning the phantom in two orthogonal planes and visualizing the needle tip within the phantom lesion in both planes (see Figures 2, 5a and 5b).

For the first patient, the AR system was utilized only to locate the lesion within the patient's breast and to determine an appropriate skin entry point. The lesion, a large cyst, was then aspirated using traditional visualization methods. A 22-gauge needle was introduced into the lesion, and approximately 10 cc's of clear fluid was drained (see Figure 4).

For the second, third, and fourth patients, the system was utilized to locate the breast lesion and to place the needle within the breast. The lesions were then punctured and aspirated using traditional visualization methods. For the second patient, fluid was not obtained when the 22-gauge needle was introduced, so three passes with a 14-gauge core biopsy needle were performed. The lesion proved to be sclerosing adenosis. Small quantities of cyst fluid was drained from patients three and four. Needle placement was not altered significantly after removal of the HMD for final puncture of the lesion for any of the three patients.

Table 1 shows the target lesion sizes and the location of the lesions in three planes within the breast for these first four patients. There were no apparent complications to these interventions.

DISCUSSION

Potentially, this technology is extremely useful, not only in the breast but also in visualizing pathology and interventions involving other organ systems. Specifically, the breast was selected as a test organ because of the following: it is superficial; patients who have breast lesions tend to be healthy and are not at high risk for complications if their biopsies are not performed at the hospital; and life-threatening complications are unlikely. Shortly, we will be testing the system on more women in a controlled study, comparing it to the standard technology in order to prove its feasibility in this setting. We have been able to determine those aspects that need

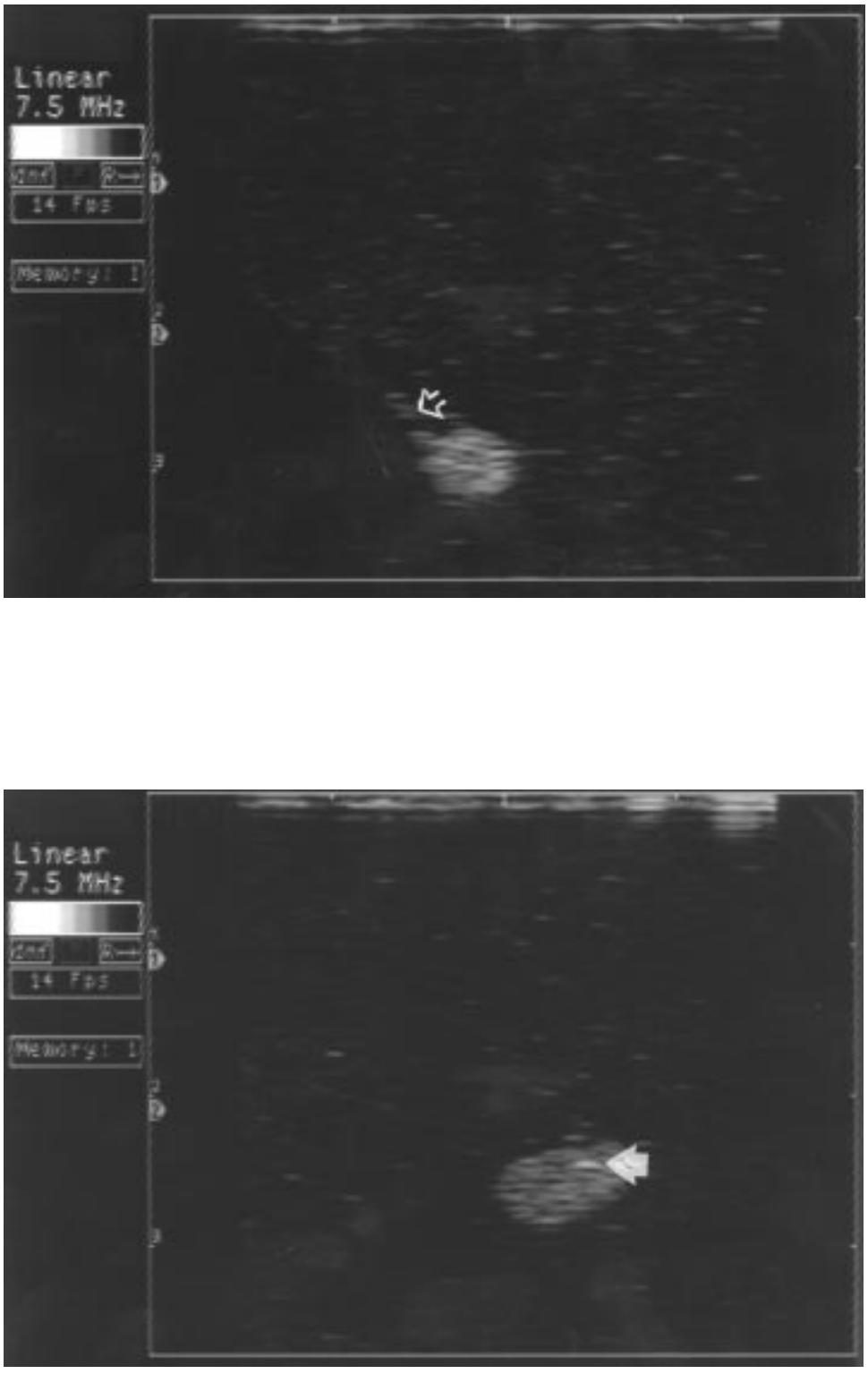

Fig. 5. 2D sonographic images of the same needle and lesion as seen in Figure 2. These images confirm in two planes (arrows), using traditional technology, that the needle is in fact traversing the phantom lesion.

refinement before using it in an organ system where patient risk is higher if technical problems occur. Many changes made to the system, described above in detail, came about because of limitations discovered during the four procedures involving patients.

On the other hand, the breast is a somewhat challenging organ for development of this technology because patient motion does influence the success of the system. Also, breast lesion size is often less than 1 cm, which is smaller than lesions that are biopsied in other organs. The planned clinical studies of the system will compare the accuracy and speed of needle placement with standard display methods.

The system has some limitations in its current configuration. Originally, the HMD helmet was too bulky and heavy for most physicians to use for more than a few minutes at a time. We now have a custom-designed lightweight head-mounted device. In addition, the spatial resolution of the ultrasound video provided through the head-mounted display is not as fine as would be expected by most radiologists using the images as a means of keeping track of a needle and a breast lesion. This limitation is being addressed in the next version of the system.

In addition, the image displayed within the patient is the actual size of the objects being examined. To use this system, radiologists will have to become accustomed to seeing what will seem to be miniaturized images, compared to the greatly magnified images they are used to viewing. This might mean retraining in the performance of interventions at a closer working distance than usual. Similarly, with current technology, the examiner does not have to attend to the location of his/her scanning hand relative to the location of the image. When the image of the lesion to be biopsied is registered with respect to the breast, the scanning hand might obstruct the scanner's view of the lesion and the needle. The radiologist will need training to learn how to hold the transducer during a biopsy to achieve optimal viewing of the lesion and the needle.

We are enthusiastic about the future use of this technology, both in the breast and in other organ systems. We predict that this technology will be used widely for minimally invasive interventions in deep organs that are accessible by sonography. Specifically, we expect that diagnostic and therapeutic interventions involving the liver, pancreas, kidneys, and central nervous system will be able to utilize this technology in the future.

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