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Automated Breast Sonography Using a 7.5-MHz PVDF Transducer: Preliminary Clinical Evaluation

Work in Progress[1]

Breast ultrasound imaging performed with an automated machine was carried out in 89 patients, and images obtained with a conventional ceramic single-focus 4-MHz transducer and a 7.5-MHz polyvinylidene fluoride (PVDF) transducer were compared. The 7.5-MHz PVDF transducer improved overall image quality in 77% of patients and had equal penetration in 83%. It yielded greatly increased diagnostic information in 43% of 81 masses and improved visualization of calcification in 57% of 14 lesions in which calcium was visible on mammograms.

Index terms: Breast, diseases • Breast, US studies, 0.12 • Breast neoplasms, US studies, 0.3 • Ultrasound (US), technology

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SEVERAL studies have shown that the combined use of ultrasound (US) and x-ray mammography in selected patients increases the rate of detection of benign and malignant breast masses (1–6). Present automated breast US machines in the Western world use relatively low-frequency transducers (3–4.5 MHz) to penetrate the naturally attenuating breast tissue (7). Drawbacks to current breast US examinations performed using various instruments include difficulty in imaging small solid masses, especially in fatty breasts (8–19), difficulty in reliably differentiating benign from malignant solid masses (11–13), rare visualization of microcalcifications (14), and occasional difficulty in differentiating fat lobules from tumors (6, 13). In a 1-year period, we examined 89 patients with a supine automated breast US unit and compared images obtained with a sharply focused (f/2) ceramic 4-MHz transducer and those obtained with a sharply focused (f/3) 7.5-MHz polyvinylidene fluoride (PVDF) transducer. The PVDF transducer has a number of advantages over ceramic transducers of the same frequency, including better axial resolution. Although the PVDF transducer has been used for breast sonography in Japan (15–18), to our knowledge it has not been used in commercially available breast US equipment in the United States.

There were two major questions to be answered in this study: (*a*) whether the higher frequency PVDF transducer produced images of adequate quality, showing complete penetration of the breast by the US beam, when used with our supine breast US unit, and (*b*) whether the resulting images contained more diagnostic information than images obtained using the sharply focused 4-MHz transducer.

PATIENTS AND METHODS

Patients were selected for this study from the population referred to the breast imaging service of the Indiana University Medical Center. Of the 89 patients in the study, 68 were referred for evaluation of a symptomatic breast mass and 21 were referred for screening mammography. The patients ranged in age from 18 to 83 years. Preliminary x-ray mammograms were obtained in 74 patients, and each showed a mass or residual density in the breast thought to warrant US evaluation. The 15 patients who did not undergo x-ray mammography were all under the age of 30 and had a large amount of fibroglandular tissue; in these patients US findings were thought to be sufficient for diagnosis.

All sonograms were obtained using a dedicated supine breast US unit (Labsonics Inc., Mooresville, Ind.), designed for examination of the symptomatic patient. This B-mode linear scan unit produces static images of the breast in supine patients with compression provided by a water-filled, optically transparent, semicompliant plastic bag. A unique aspect of the design of the Labsonics breast scanner is that the water bag (with indwelling transducer) does not simply couple the sound and apply pressure to the breast. It also allows an advantageous angle of incidence of the US beam to both the skin surface and to internal masses. The manually manipulated, delicately controlled angular and vertical motions of the water bag, when used in conjunction with appropriate patient positioning, can yield an angle of sound beam entrance that minimizes refraction and the associated beam defocusing. If a mass is not adequately visualized during a specific scanning procedure, it is sometimes possible to improve visualization of the region of interest by altering the angle of incidence of the US beam and placing the center of focus of the transducer within this region. In this respect, the instrument combines, to a limited degree, the advantages of a hand-held probe and an automated scanner.

US scans were obtained at 3–5-mm intervals longitudinally and/or transversely and at 1-mm intervals through the area of interest. Whenever possible, identical scan planes were used for imaging the

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breast with the 4-MHz and 7.5-MHz transducers. These transducers could be switched without moving the water bag. All images were recorded on x-ray film using a multi-image camera.

The standard transducer in this breast US system is a conventional ceramic f/2, 4-MHz transducer (Etalon or Panametrics), which has a tightly focused beam. The single-focus f/3, 7.5-MHz transducer (Kreha Corp. of America, New York) is made of PVDF, a piezoelectric polymer material that has an acoustic impedance value closer to that of water and biologic tissues (19, 20). As a result of this impedance match, a sound wave can be effectively transmitted into tissue and it exhibits a broad frequency bandwidth. Additionally, this material has a sharp mechanical resonance, that is, it exhibits less ringing than ceramic materials. Because of these combined characteristics, excellent axial resolution can be achieved. It is also possible to design these transducers so that they provide a narrow beam width and thus good lateral resolution. As expected, however, the measured 6-dB beam width of the 7.5-MHz transducer (0.65 mm) was only slightly less than that of the 4-MHz transducer (0.8 mm). Modifications of the transducer pulser system were carried out by the engineering staff of Labsonics Inc. to elicit the full 7.5-MHz center frequency.

X-ray mammograms were obtained using a dedicated low-dose screen-film unit (Pfizer RSI [Columbia, Md.], now manufactured by Elscint [Boston]). Oblique mediolateral and craniocaudal views were obtained and recorded on Kodak (Rochester, N.Y.) Ortho M film using Kodak Min-R screens.

All x-ray mammograms and US scans were independently reviewed by two radiologists experienced in breast imaging (V.P.J., P.A.R.). The following characteristics of masses detected on US were recorded for both transducers: border characteristics (smooth, irregular, mixed), shape (round, oval, indeterminate), internal echo texture (homogeneous, inhomogeneous), internal echo brightness (anechoic; less than, equal to, or greater than subcutaneous fat), posterior shadowing or enhancement (absent, mild, moderate, strong), lateral shadow signs (absent, present), and calcification (absent, present). The depth of breast tissue penetrated by the US beam with each transducer was measured on the scans. In addition, the film reviewers subjectively judged which of each pair of sonograms contained the most diagnostic information and which had the best overall image quality. Factors evaluated in image quality were resolution, depth of beam penetration, smoothness, and subjective diagnostic information in the image.

Pathology reports on the 40 masses subjected to surgical or fine-needle aspiration biopsy were reviewed. In selected cases, the slides were reviewed with the pathologist (S.A.C.) for better correlation with the breast imaging studies.

RESULTS

Of the 89 patients examined by US, 17 had normal examinations (confirmed by normal mammography and/or by clinical follow-up) and 72 had one or more breast masses. The diameter of the cysts ranged from 0.4 to 2.5 cm (mean, 1.25 cm), and the diameter of the solid masses ranged from 0.6 to 6.5 cm (mean, 1.88 cm). There were 17 solid tumors 1 cm or less in diameter. Table 1 gives the number and sizes of tumors detected by x-ray mammography and/or US.

The overall image quality was thought to be superior with the 7.5-MHz transducer in 77% of patients (Table 2). The depth of penetration of the US beam was equal for the two transducers in 83% of patients. In the 16% of cases in which penetration was poorer with the 7.5-MHz transducer, the limitation was mild: on average, there was only 1.1 cm less depth penetration when the 7.5-MHz was used, and there was no case of severe beam attenuation at the higher frequency. As expected, attenuation of the US beam by the nipple was greater with the higher frequency transducer, but this was mild and did not seriously affect the overall scan quality in most patients.

Of the 81 masses in this study, 20 were cystic. Eight of the 20 cystic masses were subsequently proved to be simple cysts or abscesses by aspiration or excisional biopsy. The remaining 12 cystic masses were considered sonographically typical for simple benign cysts, and clinical follow-up was elected by the patient and referring physician. Although overall image quality, particularly resolution of wall structure, was thought to be improved in 15 of the cysts with use of the 7.5-MHz transducer, the higher frequency transducer yielded additional diagnostic information as to whether a mass was cystic or solid in only two cases (Table 2). Use of the higher frequency transducer did not allow the examiner to identify any cysts smaller than those seen on the 4-MHz images, although ducts were occasionally better seen on the 7.5-MHz scans. There were two cases of suspected intracystic masses; both were seen equally well with the 4-MHz and 7.5-MHz transducers.

The 7.5-MHz scans were diagnostically superior in 33 of the 61 solid masses (54%). Fourteen solid tumors, including two infiltrating ductal carcinomas, were identified at 7.5 MHz but were poorly seen or not visible at 4 MHz.

X-ray mammography provided evidence of calcification in 14 lesions. There were six degenerated fibroadenomas with calcifications ranging from 0.6 mm to 1.8 cm in diameter. In one fibroadenoma the calcification (1.8 × 1.1 cm) was seen equally well with both transducers. Four fibroadenomas contained calcifications ranging from 0.6 to 5 mm in diameter that were visible with both transducers but seen much better on the 7.5-MHz sonograms. One additional fibroadenoma contained 1–2-mm branching calcifications that were seen only on the 7.5-MHz US scans. Two cysts had faint, 0.5-mm peripheral calcifications, seen equally well with the two transducers. There were four malignant-appearing masses containing multiple microcalcifications, all less than 0.6 mm in diameter. These microcalcifications were imaged equally well with the 4-MHz and 7.5-MHz transducers in one case but were visible only on the high-frequency scans in the remaining three cases. There were two cases of calcifications (less than 1–2 mm) without associated masses; we were unable to image any of these calcifications with either transducer.

To date, biopsies were done on 32 solid masses. Three patients in this group had palpable masses and abnormal mammograms but normal US scans at both frequencies, even on retrospective review. One patient had a 1.5-cm fibroadenoma in a predominantly fatty breast. The second patient had diffuse microcalcifications with mild residual density on the mammogram. The US scan showed only fibroglandular tissue and fat. Biopsy revealed fibrocystic disease without macroscopic cysts. The third patient had a 6.5-cm spiculated mass compatible with carcinoma on x-ray mammography. The breast tissue in this patient was unusually attenuating, and there was very poor penetration with both transducers, leading to nonvisualization of a discrete mass, and a clearly nondiagnostic sonogram.

Of the 28 sonographically visible solid masses that had undergone biopsy, 22 (79%) were less echogenic at 7.5 MHz than at 4 MHz; nonetheless they were more apparent on the higher frequency images because of increased contrast in relation to the surrounding tissue. Additionally, four masses were not visible on the 4-MHz scans but were easily seen on the 7.5-MHz scans by virtue of their hypoechogenicity relative to fat. These masses consisted of a 2.8-cm fibroadenoma, a 1-cm area of localized fibrocystic disease without macroscopic cysts, a 6-mm area of fat necrosis, and a 3.5-cm infiltrating ductal carcinoma.

Table 1
Comparison of Lesion Detection by X-Ray Mammography and US

Results	Cysts (Size Range)	Solid Masses (Size Range)	Calcifications (Size Range)
XRM pos., 4 MHz pos., 7.5 MHz pos.	11 (0.5–2.5 cm)	28 (0.6–6.5 cm)	8 (0.5–18 mm)
XRM pos., 4 MHz neg., 7.5 MHz neg.	0	3 (1–6.5 cm)	2 (<1–2 mm)
XRM pos., 4 MHz neg., 7.5 MHz pos.	0	13 (0.6–3 cm)	4 (≤0.5–2 mm)
XRM neg., 4 MHz pos., 7.5 MHz pos.	6 (0.4–2 cm)	3 (0.9–4.5 cm)	0

Note.—XRM = x-ray mammography, 4 MHz = sonography with 4-MHz transducer, 7.5 MHz = sonography with 7.5-MHz transducer.

DISCUSSION

The role of US in the evaluation of the breast remains controversial. While some investigators advocate the use of hand-held high-frequency transducers for evaluation of the breast, these examinations are extremely operator-dependent, often poorly reproducible, and to date largely limited to "lumpography" of palpable masses (21, 22). Automated breast US has the advantages of reproducibility, utility in surveying large areas of the breast, and diminished operator dependence. At its present level of development, however, automated breast US has several important limitations. Some investigators have found it difficult to see small solid tumors on US scans, particularly in predominantly fatty breasts (8–10). Differentiation of fat lobules from tumors is a frequent source of frustration with this modality, and microcalcifications usually cannot be visualized. For these reasons, present US equipment does not permit US to be used as a sole screening modality, and preliminary x-ray mammography is essential in all but young patients (less than 25–30 years old).

Although for many years high-frequency hand-held transducers have been used for evaluation of palpable breast masses, dedicated automated breast US units have used relatively low frequencies (in the range of 3–4.5 MHz), in order to penetrate adequately the highly attenuating fat and fibroglandular tissue of the breast (7). The recent availability of 7.5-MHz PVDF transducers has allowed investigation of whether sound at this frequency can adequately penetrate the average-sized breast of an American woman and whether the improved resolution of these transducers would be evident in deep regions of the breast. The use of this transducer in scanning compressed breast phantoms and the in vivo breast has been previously described (23, 24). While it was anticipated that the images obtained with the 7.5-MHz transducer would exhibit greater resolution, our major question was whether use of this transducer would yield increased diagnostic information about the breast that would justify the expense of the examination.

The overall quality of the images obtained with the 7.5-MHz PVDF transducer, including resolution, "smoothness" of the image, and other subjective qualities, was thought to be greatly superior to the quality of the 4-MHz images in 77% of patients. In only 15% of examinations was the image quality better with the 4-MHz transducer; any decreased image quality with the 7.5-MHz unit was generally caused by mildly increased attenuation of the US beam. The depth of penetration with the 7.5-MHz transducer was equal to that with the 4-MHz transducer in 83% of patients, even in large breasts of up to 6 cm of compressed thickness. While there was a slight increase in small shadows from fibrous tissue on the 7.5-MHz sonograms, this was of little consequence and did not detract from the overall image quality in the majority of patients.

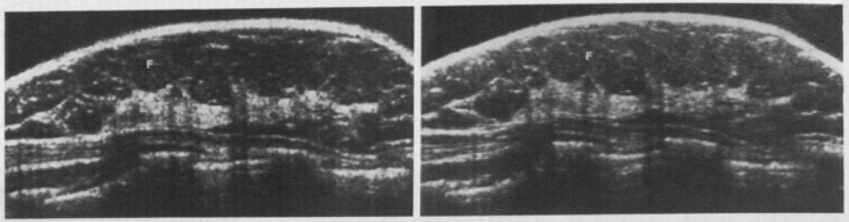
The most obvious change in the sonograms obtained with the 7.5-MHz transducer was an overall increased echogenicity of the fat of the breast when compared with the standard 4-MHz scans (Fig. 1). This "filling in" of the fat is associated with increased backscattering of the sound that occurs at high frequencies. There was excellent differentiation of fat from fibroglandular tissue of the breast with both transducers. Of the solid tumors, 79% appeared less echogenic with the 7.5-MHz transducer than the 4-MHz transducer, and all were considerably less echogenic than fat at the higher frequency. This enhanced contrast allowed much easier differentiation of the mass from surrounding fat and therefore markedly improved recognition of these tumors. There were 14 cases in which a solid mass was "invisible" or poorly seen on the 4-MHz scans but easily detected on the 7.5-MHz scans (Fig. 2). Therefore, 23% of the solid tumors in this series would likely have been missed on conventional 4-MHz scans alone.

Our findings of increased image contrast between fat and solid masses imaged at high frequencies may corroborate the preliminary investigations of Foster et al. (25). Using a sharply focused (f/1) 13-MHz polyvinylidene difluoride polymer transducer, these investigators obtained very high-resolution images as well as quantitative data on velocity and

Table 2
Comparison of Breast US Performed Using 4-MHz and 7.5-MHz Transducers

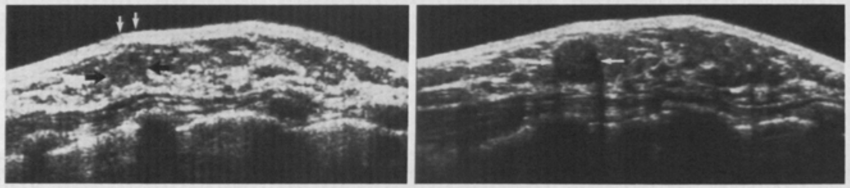
Parameter	4 MHz Better Than 7.5 MHz	4 MHz = 7.5 MHz	7.5 MHz Better Than 4 MHz
Overall image quality (89 patients)	13 (15)	7 (8)	69 (77)
Beam penetration (89 patients)	14 (16)	74 (83)	1 (1)
Diagnostic information (81 masses)	5 (6)	41 (51)	35 (43)
Cysts (20)	2 (10)	16 (80)	2 (10)
Solid masses (61)	3 (5)	25 (41)	33 (54)
Lateral shadows (37 masses)	2 (5)	15 (41)	20 (54)
Posterior shadowing (20 masses)	1 (5)	9 (45)	10 (50)
Posterior enhancement (25 masses)	6 (24)	16 (64)	3 (12)

Note.—Numbers in parentheses indicate percentages.



a. b.

Figure 1. Longitudinal 4-MHz **(a)** and 7.5-MHz PVDF **(b)** sonograms of the lateral aspect of the right breast in a healthy woman. Note the overall increased echogenicity of the fat (*F*) on the 7.5-MHz scan, with excellent differentiation between fat and fibroglandular tissue. The penetration of this "B-cup" breast is equal with the two transducers.



a. b.

Figure 2. Longitudinal sonograms over a palpable mass in a 37-year-old woman. The 4-MHz scan **(a)** shows slight mass effect (white arrows) over the tumor (black arrows), which has the same echo texture as the adjacent fat. With the 7.5-MHz transducer **(b)**, this 1.4-cm biopsy-proved fibroadenoma is clearly seen (arrows), because the internal echo texture is slightly less than that of the surrounding fat.

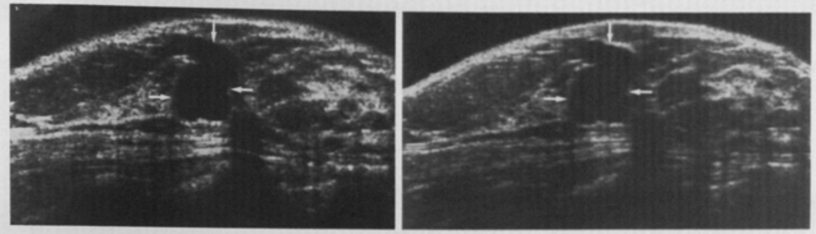
attenuation backscatter values of fat, parenchyma, and skin. They found a significant difference in the backscatter coefficient value between fat and infiltrating ductal carcinoma in the two masses examined. Since these investigations were carried out at only a single frequency, it is not possible to evaluate frequency-dependent characteristics. Based on the preliminary results described in our study, however, it can be postulated that the frequency-dependent backscatter coefficient of breast fat may be considerably greater than that of some malignant and benign breast masses. Continued investigation of the frequency-dependent characteristics of US breast imaging, including our current studies on the use of transducers that have multiple frequency output (3.5–10 MHz) (26), may lead to further improvements in this modality.

The border characteristics of solid masses were most improved in cases in which the 4-MHz scan did not show the tumor well. For the remaining masses, while the wall structure was better seen, no additional diagnostic information for determining the etiology of the mass was gained using the higher frequency transducer. Similarly, while the internal echo texture was often better seen with the higher frequency transducer, this feature was of little help in determining the etiology of the masses. This is opposed to the findings of Kobayashi et al. (17), who thought that improved visualization of wall structure and internal echo texture was helpful in differentiating benign from malignant solid tumors. Early in our study carcinomas appeared to be less echogenic than fibroadenomas, but as the study progressed it became apparent that there was overlap between the internal appearances of benign and malignant tumors. Only expansion of this series will determine whether the internal echo texture and its brightness relative to fat are useful in diagnosing malignancy.

Lateral shadow signs were seen in 37 masses. These shadows were more apparent on the 7.5-MHz images in 20 cases (54%). Lateral shadows were seen in a variety of benign and malignant processes and were of no help in the US determination of the etiology of a mass. In this series, 25 masses displayed posterior acoustic enhancement, and in 64% of these the degree of enhancement was judged to be the same at both US transducer frequencies. In only 12% was the enhancement more apparent on the 7.5-MHz scans. The presence of lateral shadow signs and enhancement is so dependent on variable factors of the sound field that their absence is not thought to be diagnostically significant.

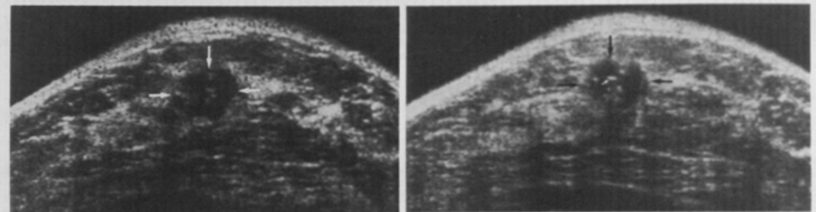
Although the 7.5-MHz transducer produced better-defined images of cysts in 75% of cases (Fig. 3), it yielded increased diagnostic information in only 10%. In only one instance were the 4-MHz scans of a cyst significantly better than the 7.5-MHz scans, and this was primarily because of a patient positioning problem. Thus, the 7.5-MHz PVDF transducer can be used to identify and diagnose cysts, but this task can be adequately carried out with the 4-MHz transducer.

A comparison of the performance of x-ray mammography and US at both frequencies (Table 1) indicates that although high-frequency US improves lesion detection, not all tumors are visualized. In our study, US at either frequency was better than x-ray mammography for the detection



a. b.

Figure 3. Longitudinal 4-MHz **(a)** and 7.5-MHz **(b)** sonograms of a 2-cm lobulated cyst (arrows) lateral to the right nipple. Although the image quality is improved with the higher frequency transducer, there is no additional diagnostic information present on the 7.5-MHz scan.



a. b.

Figure 4. Transverse 4-MHz **(a)** and 7.5-MHz **(b)** sonograms over a 2-cm invasive ductal carcinoma with microcalcifications. On the 4-MHz scan, the tumor (arrows) is very similar in echo texture to the surrounding fat and the microcalcifications are poorly seen. On the 7.5-MHz scan the carcinoma (black arrows) is much less echogenic than the adjacent fat, and the brightly echogenic calcifications are easily identified (white arrow).

of cysts. As expected, all patients with positive sonograms but negative mammograms had residual fibroglandular tissue obscuring the cyst on the x-ray study. The majority of solid tumors were detected on both mammography and US, with the 7.5-MHz transducer improving US performance considerably. Three masses were found only on x-ray mammography, but an equal number were seen only on US, again because of residual density on the mammogram. It must be noted, however, that Table 1 represents a skewed subpopulation, because young patients did not undergo x-ray mammography if we thought the US examination was sufficient for diagnosis. This group of patients would be most expected to have nondiagnostic mammograms. A larger series of patients studied with both modalities will be necessary before we can determine the true efficacy of US in tumor detection.

One criticism of breast US is that it is not capable of detecting microcalcifications. Microcalcifications in benign and malignant tumors are small, usually ranging from 100 to 300 μ, but rarely they may be as large as 2 mm in size (27). It is not surprising that these small-sized particles cannot be detected at frequency ranges on the order of 4 MHz. However, Kasumi and Tanaka (28) have demonstrated that microcalcifications within masses can be detected at 7.5 MHz. In our series, calcifications ranging from less than 0.5 mm to 5 mm were easily visualized within masses (Fig. 4). Diffuse microcalcifications in the breast tissue, outside of masses, were not recognized. The clinical utility of US visualization of calcifications is presently limited except in young patients, in whom US may be the sole imaging modality used, or in patients with prostheses, in whom large portions of the breast may be obscured on x-ray mammography. For the rest of the patient population, the role of US is purely adjunctive to x-ray mammography, a modality that easily demonstrates microcalcifications. However, unless unforeseen US findings of minimal breast cancer are discovered, visualization of microcalcifications is essential if US is to be used in the future as a screening modality. It is obvious that the use of higher frequency transducers is a step in the right direction.

The disadvantages of the use of the 7.5-MHz PVDF transducer were minor. The decreased beam penetration found in 16% of the patients was regarded as mild. Small focal shadows occurred behind fibrous tissue in some patients on the 7.5-MHz scans, but these shadows did little to diminish the overall quality of the images. In a few very large masses, lateral shadow signs were much more prominent on the 7.5-MHz scans, making visualization of the wall structure and internal detail of the lateral portions of the mass difficult. Initially, we also had difficulty with an overly bright skin–water bag interface; this problem was eliminated by design changes initiated by Labsonics Inc., in the preamplifier and amplifier systems.

CONCLUSION

Based on our preliminary study, the detection of solid masses and microcalcifications is greatly improved with the 7.5-MHz PVDF transducer compared with the standard ceramic 4-MHz transducer, primarily because of improved contrast between fat and solid tumors. Because of the excellent image quality of most examinations, we believe that the f/3, 7.5-MHz PVDF transducer can be used with our US instrument for routine scanning. However, there is no ideal frequency for breast US, and therefore lower frequency transducers should be available for special cases. Only additional investigation will show whether use of the higher frequency transducer will improve the differentiation of benign from malignant solid masses. Unfortunately, because of the considerable overlap in the gross pathologic characteristics of these two groups, such differentiation may be too much to expect from any anatomic imaging modality. ■

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