IMPROVING ULTRASOUND MAMMOGRAPHY INSTRUMENTATION: INVESTIGATION OF DEFOCUSING AND USE OF COMPRESSED BREAST PHANTOMS*

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INTRODUCTION:

The success of future innovative approaches to the design of clinical pulse echo breast examination instrumentation may be largely dependent on the ability of the new instrumentaion to distinctly image small solid masses located in the deep regions of average to large sized breasts. The terms "small" has varying connotations when used in association with breast tumors. Breast masses as large as 2 cm, categoried as T1 in the TNM classification system are generally considered small, in comparison to the average size of breast tumors generally found at the time of surgery. In terms of minimal breast cancer, a tumor of 5 mm or less is small (1).

Efforts to improve ultrasound instrumentation designed for detecting and diagnosing tumors of the T1 size are aided by the availability of symptomatic patients with tumors in this size category since scanning such patients can prove or disprove the efficacy of the new design. The task of improving ultrasound instrumentation which allows detection and diagnosis of malignant masses less than 1 cm in size (and, in particular, those less than 0.5 cm) is more difficult due to the unavailability of a sufficient number of patients that can act as test subjects on the basis of prior identification of a solid breast mass which is less than 1 cm and apparently is malignant. At Indiana University, this problem is partly solved by the use of specially designed breast phantoms containing masses less and greater than 5 mm as instrument test objects.

The phantom discussed in this paper is designated a "compressed breast phantom" since it is designed to simulate acoustic and architectural properties of a human breast which is compressed during ultrasound visualization. (2-5) Theoretical and experimental evaluations of such phantoms, solely in terms of the known values of the depth of each phantom tissue layer and its associated acoustic parameters, can be used to determine the extent of defocusing due to refraction (6) and that occuring as the result of absorption. Subsequent to such evaluations they can be used to test the efficacy of a particular instrument design in terms of detection of different types and sizes of masses located at various depths in the phantom.

BACKGROUND:

In respect to continuing improvement of ultrasound breast examination instruments, specifically in terms of image resolution, the

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investigations on the use of 7.5 and 10 MHz frequencies, underway in Japan, are of particular interest. (7-12) Most of the high frequency transducers used in recent breast imaging studies in Japan are constructed of the polymer material, PVDF, i.e. polyvinylidene fluoride. In contrast to conventional ceramic materials this polymer film has an acoustic impedance which is close to tissue and other properties that make it a good piezoelectric element. Both experimental and theoretical studies have shown that the low acoustic impedance of this material results in less reverberation or ringing of the piezoelectric assembly, the transducer can operate with broad bandwidth characteristics and thus transmit short duration acoustic pulses. Consequenly, both good range and lateral resolution can be achieved. Although the electromechanical coupling factor of PVDF is not as large as that of PZT, sensitivities which are within a few dB of that of PZT have been achieved and transducers with frequencies ranging from 2-20 MHz have been manufactured. (12)

It is of particular interest that Kasumi and Tanaka, with the use of a single focus, F/3, 7.5 MHz, PVDF transducer, identified microcalicifications, ranging in size between 100 and 400 microns, embedded within malignant breast tumors. (11) The microcalcifications appeard as fine bright spots, without shadowing. Calcifications present in diffuse, benign lesions could not be identified because they did not produce strong echoes. Using an agar phantom with embedded glass beads and the same F/3, 7.5 MHz transducer, these investigators found that it was possible to image and identify glass beads as small as 110 microns.

As a follow up on the work of Kelly-Fry (13-15) on the advantages of breast compression when combined with application of transducers of half amplitude intensity beam widths of the order of 0.8 mm, and the work of Madsen et al (16-18) on anthropomorphic breast phantoms, which simulate an uncompressed breast in a prone position, Kelly-Fry and Madsen initiated investigations on the development of compressed breast phantoms. A number of compressed breast phantom models were constructed. These varied in respect to the values of speed of sound, density and attenuation coefficient of the glandular parenchyma, the depth of the glandular parenchyma and the presence or absence of a layer of subcutaneous fat (4). Ultrasound images of these model phantoms were compared to in vivo breast images obtained with the same instrumentation (4). As a result of these studies and the earlier studies of Madsen et al, the compressed breast phantom described in the following section of this paper was fabricated at the University of Wisconsin under the direction of E.L. Madsen. A unique aspect of this phantom is the presence of fat spheres distributed within the glandular parenchyma. These are included to act as beam distorting, refractory elements (16).

INSTRUMENTATION:

The instrument used in the studies discussed in this paper is a Labsonics, B-mode, linear scan ultrasound breast scanner, designed to examine a patient in the supine position. A specially designed water bag with associated housing is hand manipulated in terms of placement on the breast surface, angulation and pressure (as controlled by its vertical motion.) This water bag unit can be used (in addition to its sound transmission function) to interact with the breast in respect to compression and manipulation of the compliant breast tissues in order to allow the most appropriate angle of entrance of the sound beam. The instrument is designed for easy interchange of transducers. The transducer currently used in clinical applications of this instrument is an F/2, 4 MHz ceramic unit. The broad bandwidth 7.5 MHz, PVDF transducer used in the study reported here has an active diameter of 2.5 cm and a focal length of 7.5 cm.

Figure 1 shows a photograph of the phantom used in these investigations. The tissue mimicking components contained within the housing are fabricated from water-based gels impregnated with solid or liquid microscopic sized particles (16). The overall dimensions of the internal structure (from skin to rib) is 24 x 10 x 6.5 cm, with the 10 x 24 cm dimension representing the scanning window area. The scanning window consists of a 0.25 mm thick teflon surface which prevents fluid loss. The depth of each of the tissue mimicking layers are as follows: A 3 mm skin, 9 mm subcutaneous fat, 25 mm glandular, 5 mm retromammary fat and 20 mm muscle. Twenty-five percent of the volume of the glandular tissue consists of fat spheres ranging in diameter from 2.5 mm to 6.3 mm. Also included in the simulated glandular tissue are twenty spherical cystic and solid masses with approximate size ranges of 13, 9.5, 6.0 and 3.0 mm. These are located at varying depths within the glandular region. Table 1 lists the measured values (at 22°C) of speed of sound, ratio of attenuation coefficient and frequency, and density of the compressed breast phantom tissue layers and the cystic and solid masses within the glandular tissue region. A more complete description of the subject phantom will be presented in an upcoming publication (2).

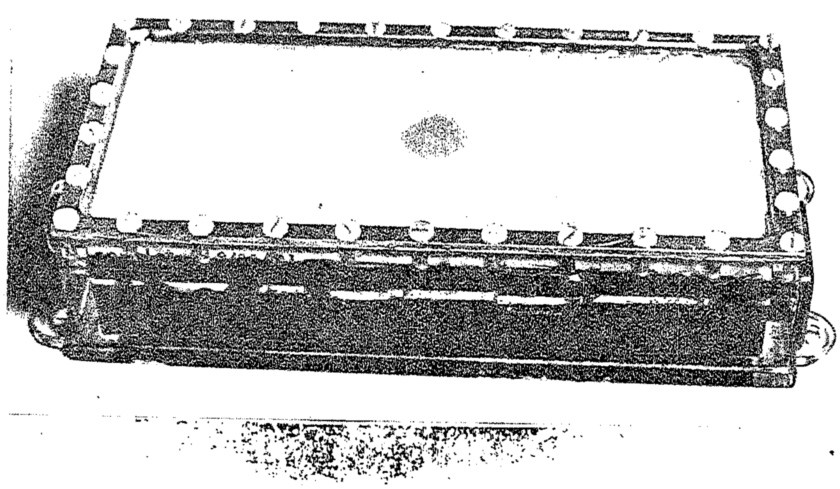

Fig. 1. Photograph of Compressed Breast Phantom

TABLE 1

SIMULATED BREAST TISSUE	SPEED OF SOUND C(M/S)	ATTENUATION α/F (dB/cm/MHz)	DENSITY ρ(GM/CM^3)
SKIN	~1570	~0.6	~1.05
SUBCUTANEOUS FAT	1456	0.47	0.94
GLANDULAR PARENCHYMA	1569	0.34	1.03
FAT SPHERES COMPOSING 25% OF GLANDULAR REGION	1445	0.3	0.92
RETROMAMMARY FAT	1458	0.54	0.94
PECTORAL MUSCLE	~1540	~0.4	~1.12
CYSTS	1568	0.1	1.02
13 MM DIAM. FAT SPHERE	1458	0.54	0.94
SIMULATED FIBROADENOMA MASSES	1564	0.34	1.03
SIMULATED ATTENUATING MALIGNANT MASSES	1508	8.7	1.05

METHODS:

The procedures followed in the studies outlined in this paper were based on determining: (1) Whether it is possible to image, in terms of full peneration, the pre and post menopausal breasts, of brassier size C, when using the PVDF 7.5 MHz transducer in the ultrasound visualization unit described under Instrumentation; (2) whether the 0.6 mm (3 dB intensity amplitude) beam width of the PVDF, 7.5 MHz transducer provides a significant advantage over the 0.8 mm beam width of th 4 MHz ceramic transducer, in terms of:lateral resolution; detecting small (6 mm and 3 mm) attenuating masses within the breast phantom; and overall image quality; (3) whether the improved axial and lateral resolution of the PVDF transducers provide significantly greater information on the internal structure of the commonly encountered benign masses found in symptomatic patients and, in particular, the fibroadenoma. Plans for use of the 7.5 MHz transducer to image breast masses which appear malignant either on the basis of x-ray mammography or, ultrasound visualization via the standard clinical transducer, are dependent on results obtained in the above outlined ongoing studies. Other, specially designed, ceramic transducers with beam widths of the same order as that of the 7.5 MHz PVDF unit were also used in these investigations. However, these studies are still underway and the results are not reported here.

RESULTS:

The investigations reported in this paper are ongoing. The results reported here should be viewed in that context.

Initial efforts to image average size breasts using the PVDF 7.5 MHz transducer were not completely successful. After completing cooperative studies with the Labsonics engineering staff on diffe-rent aspects of the pulsing regimes, excellent images were obtained. Figure 2 shows an image of the breast of a 55 year old normal sub-ject (Bra 44C) obtained with use of the PVDF 7.5 MHz unit. The ex-ceptional resolution of Cooper's ligaments, of individual structural components within the fat and of muscle fibers should be noted.

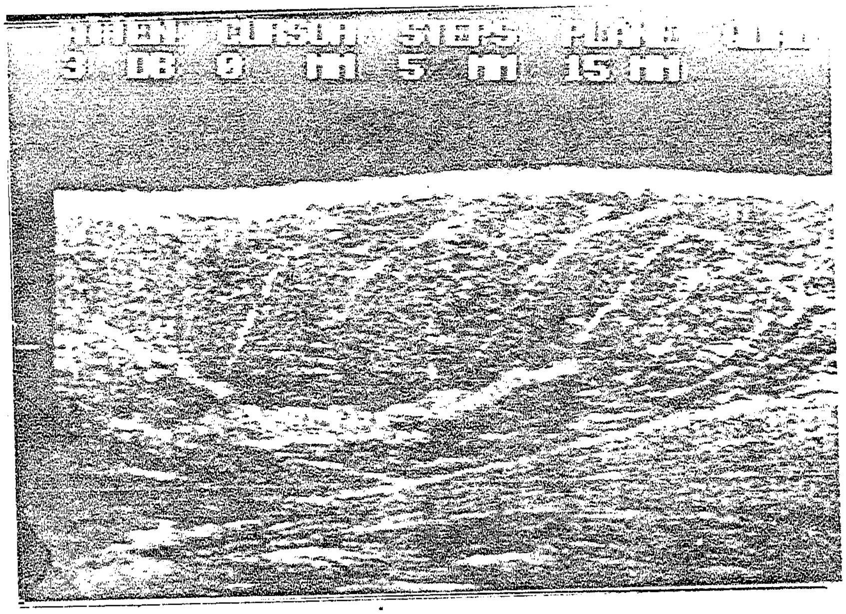

Fig. 2. Image of normal breast of 55 year old woman obtained with use of F/3, 7.5 MHz, PVDF transducer. Mag. 1:1.

Figure 3, an image of the breast of a 26 year old subject (Bra 36C) also illustrates that excellent resolution, for both shallow and deep regions of the breast can be achieved with use of the 7.5 MHz PVDF probe. On the basis of surgical biopsy, the solid mass imaged in Figure 3 (indicated by arrows) was diagnosed as a fibroadenoma. Comparison of the image shown in Figure 3 to that obtained, (not shown here) for the same patient, with application of a standard ceramic transducer, indicates that wall structure and internal components of the fibroadenoma are more clearly imaged by application of the 7.5 MHz PVDF transducer. Of particular interest is that the small cystic like structures shown within the fibroadenoma image were not imaged with use of a standard ceramic transducer.

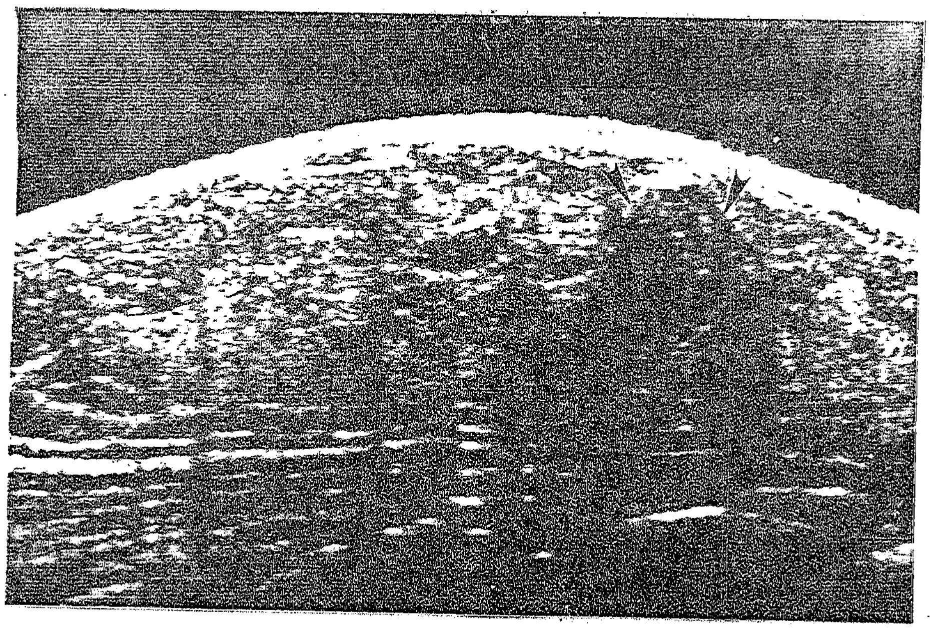

Fig. 3. Image of Breast of 26 year old woman obtained with use of F/3, 7.5 MHz, PVDF transducer. Mass outlined by arrows is a fibroadenoma.

An image, obtained with a standard ceramic F/2, 4 MHz transducer, of the simulated breast tissues and indwelling masses, for the phantom described under Instrumentation, is shown in Figure 4A. The image shown in 4B was obtained with use of the 7.5 MHz, PVDF unit. The wall structure of the 9.5 mm cystic and solid mass is more precisely delineated in Figure 4B. The 3 mm mass is well resolved in both images but is slightly more sharply defined in 4B. However, it should be noted that in terms of differentiating between individual tissue layers within the phantom, the image pattern shown in Figure 4A is an improvement over that shown in 4B.

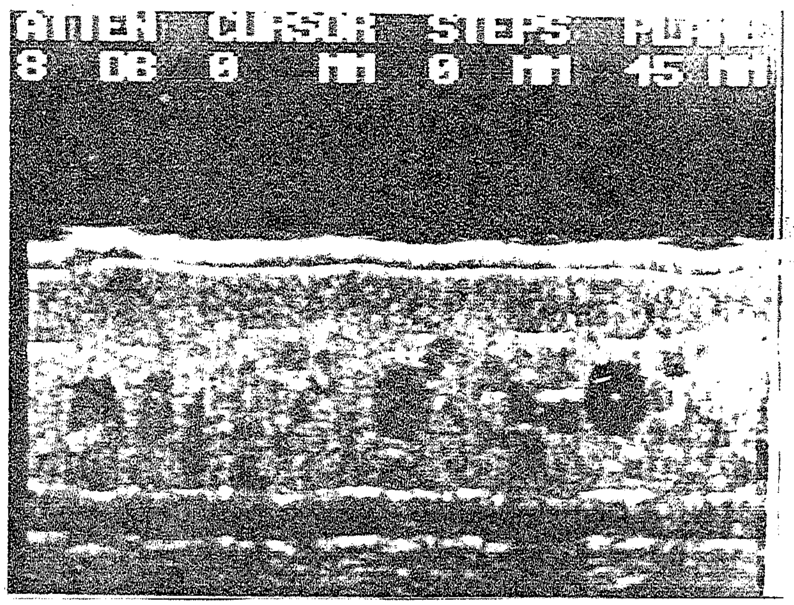

Fig. 4A. Image of Compressed Breast Phantom obtained by longitudinal scan using a F/2, 4 MHz, ceramic transducer. Location of 3 mm attenuatin mass and simulated fibroadenoma is indicated by cursor cross symbol.

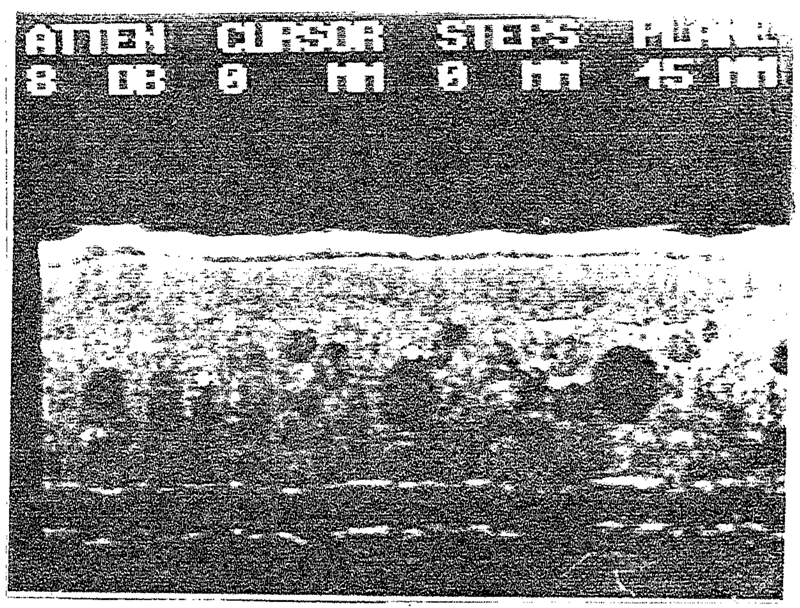

Fig. 4B. Image of Compressed Breast Phantom obtained by longitudinal scan using a F/3, 7.5 MHz PVDF transducer. Location of 3 mm attenuating mass and simulated fibroadenoma is indicated by cursor cross symbol. Mag. 1:1.

The three sharply defined shadows shown in the image in Figure 5, obtained with use of the 7.5 MHz PVDF transducer, represent attenuation from three 6 mm diameter masses located at different depths within the glandular tissue region of the phantom. These same masses can be as clearly identified with use of the ceramic F/2, 4 MHz transducer.

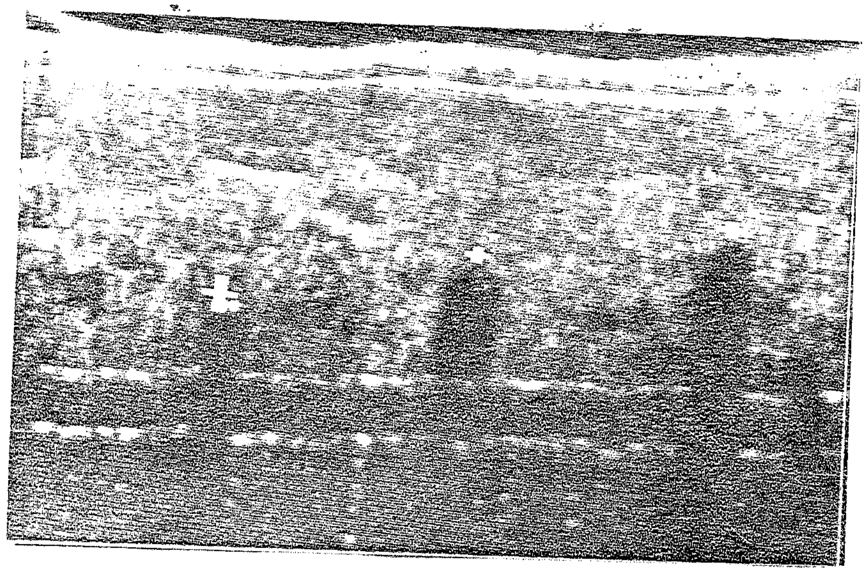

Fig. 5. Image of Phantom-region of 3 att. 6 mm masses, transverse scan F/3, 7.5 MHz PVDF transducer. Mag. 1.1:1.

The three shadows shown in Figure 6 represent attenuation associated with 3 mm diameter masses. This image was obtained with use of the 7.5 MHz PVDF unit. As shown in Figure 4A, a 3 mm mass located 20 mm deep in the phantom can be well defined with use of the F/2, 4 MHz transducer. However, the most deeply ≈40 mm located 3 mm mass is better defined with use of the 7.5 MHz transducer. Investigations are continuing on these specific comparative studies.

Fig. 6. Image of Phantom-region of 3 att. 3 mm masses, transverse scan F/3, 7.5 MHz PVDF transducer. Mag. 1.1:1.

DISCUSSION:

For the studies carried out, to date, the slightly narrower beamwidth of the PVDF transducer, in combination with its excellent axial resolution, is advantageous in terms of resolving fine tissue components and, in particular, the wall and internal components of fibroadenoma masses. This conclusion is based on the image data obtained on breasts of patients rather than with the phantom. To determine whether use of the F/3, 7.5 MHz PVDF transducer provides better detection of small (less than 1 cm) breast masses than a sharply focused lower frequency unit, reliance must be placed on the phantom data (for the reasons outlined in the Introduction). Since the architectural features of the phantom are based on knowledge gained in examining the in vivo compressed breast and, since the acoustic parameters of the simulated tissues in the phantom are primarily based on knowledge and experience gained in fabrication and application of an earlier uncompressed breast phantom (16-18) this appears to be a reasonable approach to a complex imaging problem. (The attenuation coefficient value for the simulated malignant mass in the phantom is based on FFT data for an excised breast with an intact malignant tumor) (19).

Under ideal circumstances, it would be of benefit to have three phantoms i.e. one that is representative of the dense, breast of many young subjects; one that simulates the post-menopausal breast, namely, a breast that is composed largely of fat. (Figure 2 is an example) and, finally a phantom which is representative of the breast of a pre-menopausal, middle age subject, namely, a breast which has a large component of subcutaneous fat, a somewhat decreased glandular tissue in comparison to the young breast, with the decreased glandular tissue areas replaced by globules of fat. The phantom pictured in Figure 1, is essentially a simulation of the breast tissue of a young subject which has a large deposition of subcutaneous fat, (similar to the breast shown in Figure 3). The fat distribution within the glandular tissue of an in vivo breast would not be precisely the same as the 25% volume distribution of fat globules in the compressed breast phantom. However, the fat deposits are useful for investigating refraction effects. Images of the phantom (obtained within just a few dB of the same gain settings used for the in vivo breast) are similar in brightness and gray scale levels to that of the in vivo breast.

Based on acceptance of the phantom as a tissue equivalent model of an in vivo breast, the results found for detection of 6 mm (Fig. 5) and 3 mm (Fig. 6) masses are of interest. It is clear from Figure 5 that for any depth within the breast such a mass can be identified with the PVDF 7.5 MHz transducer and as previously indicated, these masses can also be distinctly imaged with the F/2, 4 MHz ceramic transducer. It is reasonable to conclude, therefore, that a malignant mass which has an attenuation coefficient of the order of 8 dB/cm and is approximately 6 mm in size should be readily detectable in all regions of a breast, when using a sharply focused, 4 MHz transducer and breast compression. Further, as shown in Figure 4A, (magnification 0.7:1), a 3 mm attenuating mass located almost 3 cm below the skin line can also be distinctly imaged with a F/3, 4 MHz transducer. However, for the same size mass located almost 4 cm below the skin line, use of the more sharply focused PVDF transducer provides better detection than the lower frequency unit. As indicated under Methods other narrow beamwidth transducers are being used in continuing evaluation of this problem.

A new compressed breast phantom has been designed. This includes a simulated malignant mass with scattering characteristics similar to some malignant masses, a jagged wall and variable attenuation across the mass volume.

Based on results of earlier studies on use of multiple frequencies for breast examination (14) and some of the data discussed in this paper, it appears that, for breast imaging, ultrasound examination should not be limited to a single frequency. Instrumentation is now been designed which provides for examination of the compressed breast with a single, sharply focused transducer which can be energized to emit either higher or lower center frequencies (20).

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KEYWORDS:

Ultrasound Mammography Instrumentation; Breast Phantoms; PVDF Transducers; Defocusing; and Refraction.