Variation of Transducer Frequency Output and Receiver Band-Pass Characteristics for Improved Detection and Image Characterization of Solid Breast Masses

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ABSTRACT

A new approach has been used for ultrasound detection of small benign and malignant breast masses, namely, control of scattering in such a manner that a small mass can be easily recognized because of the effect of the scattering on the contrast between the mass and the surrounding normal tissue. Maintenance of good resolution as scattering is varied is an essential aspect of this approach.

Image contrast is dependent on a number of instrumentation parameters but, in a fundamental sense, it is related to differences in the amount of scattering between a solid breast mass and the surrounding normal tissue. In the subject studies, modification of image contrast is accomplished by varying either the center frequency output of the transducer or the band-pass of the receiver. These approaches take advantage of differences in the frequency dependence of scattering coefficients of solid breast masses and normal tissue.

A unique technique for varying center frequency without switching transducers was developed, namely, use of a wide bandwidth, co-polymer PVDF transducer, in combination with certain instrumentation conditions which allow the center frequency output of a single ultrasound transducer to vary over a relatively wide frequency range. Using this technique, an automatic B-mode ultrasound imaging breast instrument which allows emission of 3.5, 4.5, 6.5 and 11MHz ultrasound frequencies from the same co-polymer transducer was used to examine patients with solid breast masses. Both a wide band-pass receiver, similar to that commonly used in clinical ultrasound systems and a tunable receiver (which allows variation of the band-pass from wide to narrow) was used with this automated system.

Using the standard receiver system, it was found that there are advantages to having a range of transducer frequencies immediately available for breast examination. These include: (1) improved detection of masses located in highly attenuating regions of breast (by decreasing frequency); (2) availability of diagnostically relevant information at some one frequency which may not be apparent at other frequencies.

Using the multiple frequency system and the standard receiver, it was found that the most appropriate examination frequencies for detection and diagnosis of fibroadenomas are higher frequencies (8 to 11MHz). This is particularly true in the case of fibroadenomas in fatty breasts.

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By using higher frequencies (10 MHz and above) along with band-pass filtering of the transducer receiver, it was possible to produce a significant difference in scattering between a mass and the surrounding normal tissue, while maintaining or improving resolution. Images obtained under these circumstances show intense backscattering from normal breast tissues and significantly less scattering from breast masses, whether benign or malignant. This technique may have significant potential for detection of small breast masses since it allows such masses to be sharply outlined in high contrast to their surroundings. Preliminary data also indicates that this technique may provide image characterization of benign and malignant breast masses.

**Key Words**
breast ultrasonography, ultrasound technology, early detection of breast masses, control of image contrast, image characterization.

**INTRODUCTION**

The aim of this research is to develop clinically practical techniques for multiple frequency scanning, in combination with control of receiver band-pass characteristics, and to apply these techniques to ultrasonic mammography. The primary purposes of this approach are to evaluate its potential in terms of: (1) control of image contrast between a mass and surrounding tissue, and (2) improved visualization in highly attenuating regions of the breast, and (3) improved recognition of diagnostically significant, qualitative differences in the image scattering characteristics of benign and malignant breast masses.

Using a broad bandwidth, co-polymer PZT transducer in combination with specific transducer pulsing conditions, a technique for modifying the center frequency output of a single ultrasound transducer, without significantly-changing transducer sensitivity, was developed. As a follow-up to this research, an ultrasonic imaging breast instrument which provides for the emission of 3.5, 4.5, 5.5, and 8.0 MHz ultrasound frequencies from the same transducer, the same sensitivity, was developed. Subsequently, a higher frequency transducer which, under specific pulsing conditions, allows frequency emissions of approximately 3.5, 4.5, 5.5, and 8.0 MHz, was applied. A 10 MHz transducer is also being evaluated. A tunable receiver system which allows selection of band-pass center frequency and width (wide to narrow) was designed and used with this multiple frequency scanner.

All of the above outlined features were applied in combination with a new bi-plane scanning, namely, the ability to scan breast masses at any of the available transducer frequencies or receiver band-pass positions, for two mutually perpendicular tissue planes.

**IMPLEMENTATION AND TECHNIQUE**

Instrumentation used in this study is a modified Lasonics, Inc., Norcrossville, GA, automated tomographic ultrasound scanner designed for examination of symptomatic patients. With the patient in a supine position and the transducer coupled to the body by use of a water bag, an ultrasound transducer, this 33-ball, linear scan unit produces static images of the breast. The optically-transparent, semi-transparent water bag is manually controlled in terms of: (1) amount of pressure put on the breast, (2) angular orientation and thus the angle of entrance of the sound, and (3) transverse, longitudinal, or diagonal scanning modes. Ultrasonic scans are automatically carried out at spatial intervals as seen in the image of the plane selected for image gathering and can be repeated at any chosen smaller interval that is in turn selected by the operator. The data are then stored in the computer. Data is transferred to a television monitor, and can be stored on a floppy disk for later viewing.

**Figure 1.** Top sketch: Representation of breast tissue imaged by a longitudinal scan. The gray scale through the mass represents the automatic motion of the transducer. The data was recorded during a dynamic bi-plane scanning. Bottom sketch: Representation of tissues imaged during a dynamic bi-plane scanning. The image is superimposed over one region of the original longitudinal scan image. See Figure 11, page 145.
For the research patients who were found to have confirmed carcinoma, analysis of the images indicates that, in some cases, multiple frequency examination can be a factor in the detection of a mass and it may also provide valuable diagnostically relevant information on tumor characteristics. When this data is applied along with mammographic information, it may improve diagnostic accuracy. Those cases of multiple frequency examination of patients with confirmed carciomas are presented here. Two of these patients were less than thirty-five years old at the time of examination.

Figures 3A,B demonstrate that, in this specific type of case, a lower frequency may be more effective for tumor detection than a higher frequency. On mammography, the breast of this thirty-one-year-old woman appeared bilaterally dense; no microcalcifications or overt masses were palpable. However, possible retraction of glandular tissue was observed. Ultrasound scanning at a frequency of 3.0MHz (Figure 3A) detected an overt hypoechoic mass. Although visible at a frequency of 8.0MHz (Figure 3B), the mass is less easily recognized because the tissue structures located deep to the nipple areola area are more attenuated at the higher frequency. As a result, there is poor contrast between the hypoechoic mass and hypoechoic surroundings. A biopsy image of another area of the same case (Figure 3C), at a frequency of 8.0MHz, demonstrates a jagged wall structure for the transverse scan marked Right-Left) and reveals (on the longitudinal scan marked L-R) extension of the tumor into surrounding tissue. There is a similarity of echoes from within the mass, when scanned at this higher frequency, but a bi-plane scan at 4.0MHz (Figure 3D) for this same tissue region, indicates the mass is solid and includes an overt region of fibrous (arrow). Biopsy revealed an infiltrating and invasive lobular carcinoma with extensive invasion in a mass, as-called Indian File fashion, within some areas a proliferation of fibrous tissue.

Figure 3A

Figure 3B

Figure 3C

Figure 3D

Figure 3A,B. Transverse scan: thirty-one-year-old patient with a mass located close to the areola. A, high frequency transducer was used to yield a center frequency of 3.0MHz. B, 8.0MHz transducer was used to yield a center frequency of 8.0MHz. Line marks on margins of all breast images were used for separation.
Figure X. Bi-plane longitudinal image (represented by the region marked S-L) is overlaid on a section of the original transverse scan image (Right-Left). Transducer pulsed to yield a frequency of 8.0MHz.

Figure XI. Same scanning conditions as that shown in Figure X, except transducer pulsed to yield a frequency of 3.5MHz.

The next case is of particular interest, because this sixty year old subject received a mammogram examination as part of a screening procedure. The mammogram showed an asymmetric nodules of density in the right breast, greatest in the retroareolar region. Each of the 3.5, 4.5, 6.5, and 8.0MHz ultrasound examination revealed the presence of a 2cm, hypoechoic, attenuating mass. Note, as shown in Figure 4A (8.0MHz) and 4B (4.5MHz) the anterior and lateral walls of this mass appear bright, i.e., have a "halo", at both of these frequencies. Although a portion of the posterior wall was partly imaged at the low frequencies, the wide, dark shadow that extends throughout the whole image, at both the high and low frequencies, (Figure 4A,B) reveals the highly attenuating character of this mass. It is also of interest to note that, in this particular case, the low frequency image apparently reveals a reactive process, imaged as bright reflections from the tumor wall to the skin. This is more easily observed in the lower frequency image because, at lower frequencies, there is less scattering of the sound by the fatty tissue. As a result, the image of the subcutaneous fat is relatively dark thus providing a good contrast with the bright, reactive process image. On biopsy, the tumor was diagnosed as an intraductal and infiltrating carcinoma.

Figure 4A, B. Images from longitudinal scans, at a frequency of 8.0 and 4.5MHz, of the breast of a 45 year old woman with a biopsy proven carcinoma. Note the difference in backscattering from fatty tissue at frequency is decreased.

Figure 4A. An image of a transverse scan, at 8.0MHz, over the region of a palpable mass in the breast of a twenty-eight year old woman. The presence of a non-attenuating, solid mass with relatively homogeneous internal echoes and a thickened anterior wall is apparent. A mammogram revealed microcalcifications and an abnormal density. A bi-plane scan at 8.0MHz (Figure 5A) indicates that this solid mass has a cystic component (resolvable in the longitudinal scan, marked S-L). In addition, images recorded at 8.0, 6.5, 4.5, and 3.5MHz, the tumor wall appeared relatively smooth in some areas and jagged in others. (Figure 5C) in this case, it is the fluid component and jagged wall feature, observed at all of the examined frequencies that makes this mass suspicious for carcinoma. Biopsy revealed an invasive, poorly differentiated adenocarcinoma with scattered, heterogeneous areas measuring up to 4mm in diameter and, in some areas, a fibroplastic, desmoplastic tissue response. For this specific case, areas carried out at frequencies less than 8.0MHz only confirmed the information obtained at the higher frequencies.
Figure 5A. Image from transverse scan, at a frequency of 8.8 MHz, of breast of a twenty-eight year old subject with a biopsy proven carcinoma.

Figure 5B. Bi-plane image of same mass shown in Figure 5A. Note the cystic regions, apparent in the longitudinal bi-plane scan.

Figure 5C. Image from transverse scan, at a frequency of 4.5 MHz, over another region of mass illustrated in Figures 5A, B. Note jagged wall and hypoechoic center.

Our results on the relationship between frequency and detectability of fibroadenomas are of particular interest. We have found that fibroadenomas located in dense breasts can usually be detected at any frequency between 1.5 and 11MHz. However, in the case of fatty breasts detection can be more difficult or, in some cases, impossible if lower frequencies (<3 MHz) are used. For example, Figure 6A shows an ultrasonic, 10MHz image of a solid mass in the breast of a twenty-eight year old subject. This slightly atrophing mass exhibits a smooth wall, fine internal echoes and lateral acoustic shadowing, characteristics often observed with fibroadenomas. As shown in Figure 6B, when examined at a frequency of 4.5MHz, the mass is less readily detectable. At a frequency of 3.5MHz (Figure 6C) the mass is not evident. Biopsy indicated a fibroadenoma accompanied by tissue fibrosis.

Figure 6A. Longitudinal scan of fibroadenoma in breast of a twenty-eight year old woman. (10MHz transducer pulsed to yield a center frequency of 11MHz)

Figure 6B. Same as 6A except 10MHz transducer pulsed to yield a center frequency of 4.5MHz.

Figure 6C. Same as 6A except 10MHz transducer pulsed to yield a center frequency of 3.5MHz.
Based on analysis of qualitative imaging parameters such as that shown in Figures 6A, 6B, and our data on multiple frequency examination of fibroadenomas in dense breasts, it can be conjectured that at lower frequencies (e.g., 3MHz), the backscattering coefficients of fat and fibroadenomas are not significantly different in value than that of fibroadenomas and glandular tissue at the same lower frequency. At higher frequencies (10MHz or above), this phenomenon would likely explain why fibroadenomas in dense breasts were not readily detected at higher frequencies. A further factor of poor detection is the decreased resolution at low frequencies which obscures macrostructural tissue differences between fat and fibroadenomas. This problem can be compounded by image-gain settings which may additionally decrease resolution and further obscure the low contrast differences between a fibroadenoma and surrounding fatty tissue.

We have found, in most cases, that fibroadenomas are not significantly attenuating at frequencies as high as 7.5 to 10MHz. In that regard, our routine clinical scans of fibroadenomas are carried out at a frequency of 8.0MHz while 6.0 or 10MHz is applied in our research investigations. Calcified fibroadenomas attenuate the sound at all clinically applied frequencies. A non-calcified fibroadenoma which is complicated by the presence of fibrosis may show some attenuation at both high and relatively low frequencies. However, in most cases, the smooth wall character of these masses and their internal architecture usually give evidence that they are probably not malignant.

**RESULTS: Tunable Receiver**

As indicated under Instrumentation and Techniques, a tunable receiver which allows control of both band-pass center frequency and width is available for examination of mammographic images. Using this receiver, it has been found that when transducer frequencies of the order of 10MHz and above are combined with a novel band-pass filter, there is significant backscattering from the normal tissues of the breast, but significantly less scattering from both malignant or benign breast masses. As a result, these images exhibit high contrast between a breast mass and the surrounding tissue. Since excellent resolution of masses is maintained, this technique provides images which are uniquely appropriate for detection of breast masses less than 1 cm in diameter in size.

Additionally, tunable receiver systems may allow more precise differentiation between fibroadenomas and benign masses (in particular, lobular carcinomas) than is now provided by standard receiver system. To date, 25 symptomatic patients have been examined with this new receiver technique. This population included six biopsy proven fibroadenomas and four confirmed carcinomas. Images of five of the confirmed carcinomas and one of the confirmed fibroadenomas are presented here.

Figure 7A is an image obtained by use of a 10MHz transducer and the wide band-pass (+1MHz at 3dB) receiver system, for examination of a palpable breast mass. A small mass is imaged in Figure 7A, but because other image structures have a similar appearance there is uncertainty regarding its reliability. A prior clinical scan at a frequency of 10MHz did not detect this palpable mass. X-ray mammography indicated the presence of a lobulated, solid nodule which was suspicious for malignancy. Using the same 10MHz transducer, in combination with the tunable receiver set for a narrower band-pass (4.0MHz at 3dB), the images shown in Figure 7B was obtained. Extensive backscattering from all regions of the breast, except the 5mm mass and the nodule is now apparent. As

![Figure 7A](image)

**Figure 7A.** Longitudinal scan image over region of palpable breast mass in breast of sixty-eight year old woman, using 10MHz transducer and a standard receiver system (10MHz transducer pulsed to yield center frequency of 10MHz)

![Figure 7B](image)

**Figure 7B.** Same as 7A except tunable receiver (set for narrow band-pass). BIOPSY revealed sclerosing and microlobular adenocarcinoma.

Figure 8 is an image of a palpable mass in the breast of a forty year old subject, obtained with the 10MHz transducer and tunable receiver system used as a standard clinical scan. I.e., the bandpass was only slightly narrower (4.0MHz at 3dB) than that used in the standard clinical scan. (X-ray mammography only revealed a dense breast.) Note the reverberation of the echoes from the dense particles within the mass. Biopsy indicated a well differentiated carcinoma tubular and intraductal. Since this low mass was so sharply delineated, it can be conjectured that smaller masses with similar characteristics could be clinically detected with use of a high frequency transducer and an amplifier tuned to provide full penetration and high contrast.
Figure 9, a bi-plane image of a palpable mass in the breast of a fifty-three-year-old patient, was obtained with application of a 10 MHz transducer and a tunable receiver set for a wide bandwidth (~10 MHz at 3 dB). The clinical scans essentially revealed the same image information except that the fine echoes from the center of the mass were not detected. Mammography indicated an ill defined, spiculated mass corresponding to the palpable abnormality. Figure 10 is a bi-plane image of the breast of a twenty-two-year-old subject, obtained under the same transducer and receiver conditions as those indicated for Figure 9. The clinical scans of this subject did not provide any information on the internal echo pattern of this mass. Note that neither of the masses in Figures 9 and 10 are highly attenuating, although a 10 MHz frequency is used for both examinations. It is evident, however, that the wall structure of the mass in Figure 9 is jagged and there is a scarcity of internal echoes. By comparison, the walls of the mass shown in Figure 10 are much smoother, but they are not as classically smooth as that observed for most fibroadenomas. These image characteristics were consistent across the full volume of each mass. For Figure 11 (an image of the same breast as that shown in Figure 9) and for Figure 12 (an image of the same breast shown in Figure 11) the 10 MHz transducer and tunable receiver were used, but the band-pass was narrowed to 10 MHz for Figure 11, and to 5 MHz for Figure 12. There are now clear differences between the images of these two masses, namely, the image in Figure 11 is hyperechoic and attenuating while that in Figure 12 is hypoechoic and has a distinctive internal echo pattern. These image characteristics were consistent across the full volume of each mass. The mass in Figure 11 is a biopsy proven, medullary carcinoma; that shown in Figure 12 is a biopsy proven fibroadenoma. It may be diagnostically significant that medullary carcinoma was found to be attenuating as the bandwidth was decreased while this was not true for the fibroadenoma.

Figure 9. Bi-plane image of breast of a fifty-three-year-old woman with a biopsy proven medullary carcinoma, using a tunable receiver controlled for a wide band-pass and a 10 MHz transducer pulsed to yield a center frequency of 10 MHz.

Figure 10. Bi-plane image of breast of a twenty-two-year-old woman with a biopsy proven fibroadenoma, using a tunable receiver controlled for a wide band-pass and a 10 MHz transducer pulsed to yield a center frequency of 10 MHz.

Figure 11. Longitudinal scan image of medullary carcinoma in same breast as that shown in Figure 9, using the same high frequency but controlling the tunable receiver for a narrow band-pass.

Figure 12. Longitudinal scan image of fibroadenoma in same breast as shown in Figure 10, using the same high frequency but controlling the tunable receiver for a narrow band-pass.

It is not implied here that all fibroadenomas examined with a high frequency transducer and a tunable receiver system, will have an internal echo pattern which is as distinctive as that of Figure 12. However, based on the image data from three of the other four biopsy proven fibroadenomas (two fibroadenomas were associated with sclerosing adenosis and fibroadenomas), it appears that the images of many fibroadenomas, obtained by means of a high frequency transducer and a tunable receiver set for an appropriate bandwidth, are sufficiently distinctive that they can be differentiated from medullary carcinomas and possibly other types of malignant masses. This conclusion does not apply to fibroadenomas that are calcified, fibrous or massive in size.

Similarly, in our clinical scans, a high frequency (~3 MHz) transducer and a wide band-pass (~10 MHz at 3 dB) receiver provides adequate information on the internal echo pattern of fibroadenomas. Occasionally, however, this is not the case. For example, Figure 13A is an image of a biopsy proven fibroadenoma in the breast of a nineteen-year-old subject, obtained by application of the standard clinical scanner using a 7 MHz transducer. Note that despite the excellent imaging of all of the other breast tissues, it was difficult, in this particular case, to define the internal structure of this mass at any of the scanning planes. Figure 13B is an image of the same breast using a 10 MHz transducer and the tunable receiver set for a band-pass (10 MHz at 3 dB) that is decreased but still relatively wide. Although, under these circumstances, the internal echo pattern of the mass remained difficult to image, nonetheless, it was sufficiently defined to show that it exhibited the same general characteristics as the fibroadenoma in Figure 12.
Figure 13. Longitudinal scan image of breast of nine-year-old woman obtained with a 7.5 MHz transducer using the standard clinical breast scanner. Note that despite the excellent quality of this breast image, the internal character of the mass could not be demonstrated. (Transducer pulse to yield 8.0 MHz.)

Figure 13b. Longitudinal scan image of same breast shown in Figure 13a obtained with a 10 MHz transducer (pulsed to yield 10 MHz) and the tunable receiver set for a narrow band-pass. (The designation MHz is not a quantitative figure; it refers to a dial setting.) Note that the internal echo pattern is now discernible. Biopsy indicated a fibroadenoma.

Figure 14a is an image of a biopsy proven fibroadenoma in the breast of a forty-five year-old subject, obtained with a 10 MHz transducer and the standard, wide band-pass (10 MHz to 3.5 MHz) non-tunable receiver system. The posterior enhancement, lateral shadows and heterogeneous internal pattern are obvious. Figure 14b shows an image of the same breast obtained with the use of a 10 MHz transducer and the tunable receiver set for a band-pass of 10 MHz at 8 MHz. Note the sharply resolved 2 cm cyst within the fibroadenoma, the increased resolution of the internal echo pattern and the similarity between this internal echo pattern and that of the fibroadenoma shown in Figure 13.

Figure 14a

Figure 14b

Figure 14c, d. Transverse scan image of breast of a forty-five year-old woman. 14a was obtained using a 7.5 MHz transducer (pulsed to yield a center frequency of 8.0 MHz) and a standard receiver. 14b was obtained with a 10 MHz transducer (pulsed to yield 10 MHz) and the tunable receiver set for a narrow band-pass. Biopsy indicated a fibroadenoma.

Discussion

For breast, images of specular reflectors such as skin, Cooper's ligaments, and other smooth surface structures in terms of wavelengths may provide indirect signs of the presence of a malignant mass by demonstrating skin retraction or architectural distortion. However, the fine, usually lower intensity echoes backscattered from tissue structures which are comparable in size to the wavelength of the incident beam are generally of more importance in both detection and diagnosis of breast masses. A quantitative parameter for such reflections, designated the backscattering coefficient, defined as the ultrasound intensity (power) scattered in the backward direction per unit volume of tissue scatterers per unit angle of incident beam, has been evaluated for various biological tissues, such as liver, breast, pancreas, kidney, spleen, myocardium, brain, and aortic wall.4-10 On the basis of such investigations, it appears that, for any one frequency, the value of the backscattering coefficient varies according to the type of biological tissue examined, the size and spacing of tissue components and their acoustic impedance. The degree of scattering is related to frequency in terms of some specific power dependence.3-8

Although most quantitative studies of backscattering have been carried out with biological tissues which are less complex than breast tissue, some data on values of backscatter coefficients of normal and pathological breast tissues is available.11-13 Porter et al. found that, for in vitro examination of breast tissues at a frequency of 10 MHz, the value of the backscatter coefficient of fat is significantly greater than that of normal mammary.12 Since a large difference in backscatter values between adjacent tissues will result in increased contrast, these authors proposed that it may be easier to detect malignant breast masses in a fatty breast by use of higher ultrasound frequencies. A subsequent clinical study by Jackson et al. comparing breast images recorded at 4.0 and 7.5 MHz using separate transducers for each frequency confirmed that solid breast masses in a fatty environment are more readily detected at a higher frequency because of increased contrast between the mass and surrounding normal tissues.14 In the basis of these multiple frequency investigations, Jackson et al. postulated that the frequency dependence of the backscatter coefficient of breast fat may be considerably greater than that of some benign and malignant masses. In subsequent "in vivo" studies of the values of backscatter coefficients of breast fat, parenchyma and infiltrating ductal carcinomas, over the frequency range of 3 to 100 MHz, D'Aoust and Porter contrasted the Jackson et al. suggestion regarding a probable difference in the frequency dependence of the backscattering coefficient of breast fat and carcinomas.11 D'Aoust and Foster found that at low frequencies the value of the backscatter coefficient of ductal carcinomas is almost the same as that of fat, thus accounting for the difficulties sometimes encountered in detecting such tumors at low examination frequencies. Specifically, they determined that the frequency dependence of backscatter from infiltrating duct carcinomas is approximately one and that of breast fat is approximately two. On the basis of this data, they postulated that it may be possible to differentiate these two tumors in images obtained at frequencies between 8 and 100 MHz.

Many Japanese investigators have carried out clinical studies on scattering and, in particular, on the type of scattering which forms a "halo" around a breast mass.15-18 In some of these studies, it was found that the frequency dependence of tissue wall scattering may be used to improve differential diagnosis.19 Inferences on this type of "halo scattering" are not included in the studies discussed in this paper.
in the current studies, emphasis has been placed on developing practical techniques for clinically applying sono information on the frequency dependence of attenuation, resolution, and scattering. For example, although we have known from our previous investigations that there are advantages to examination of breasts at more than one frequency, multiple frequency examinations were not generally carried out in the clinic because of time delays associated with changing transducers. The development of a technique for providing selected center frequencies from a single transducer allows essentially instantaneous change of frequency. Thus, a technologist can readily switch to a lower frequency when an isolated region of high attenuation is encountered. Additionally, image data on effects of frequency variation was readily be obtained under normal clinical conditions. For example, Figures 15A,B graphically illustrate some of the quantitative data of D'Aoust and Marston on the comparative values of the backscattering characteristics of breast fat and parenchyma over a frequency range of 3 to 7.5 MHz, i.e., (1) there is more backscattering from the breast parenchyma than from the fatty tissue at both a low and high frequency and (2) that scattering increases for both the fat and the parenchyma as the frequency is raised, but the greatest increase takes place in the fatty tissue. The high frequency dependence of scattering for fat tissue is also illustrated in Figures 4A,B. Since the hypoechoic, malignant mass in three Figures is almost 2 cm in size and is attenuating, its detection is not dependent on high contrast between the mass and the fatty tissue.

Figure 15A. Longitudinal sonogram of normal thirty-two-year-old woman obtained with a 7.5 MHz transducer, pulsed to yield a center frequency of 3.7 MHz and a standard widebandwidth receiver.

Figure 15B. Same conditions as 15A except the transducer is pulsed to yield a center frequency of 8 MHz.

Figure 5A,B,C illustrate that some regions of a malignant mass may be hypoechoic while others are not, and this shows the value of biplane scanning. A dramatic example of the advantage of multiple frequency examination is shown in Figures 4A,B,C. Figure 5B specifically illustrates that a solid mass may be imaged within the environment of a fatty breast, but because of insufficient contrast between the mass and the surrounding tissue, its presence may not be recognized.

The tunable receiver studies represent an attempt to take further advantage of the variability of the frequency dependence of backscattering coefficients of normal and pathological tissues. In considering the frequency dependence of any factor that affects imaging, it is relevant to emphasize that transducer bandwidth, per se, is a frequency parameter. The unusually wide bandwidth of the 3:1:5:10 MHz transducer used with our tunable receiver system is particularly appropriate for investigations concerned with the frequency dependence of scattering. It is a significant advantage to have the ability to selectively filter the frequency distribution output in order to determine the most appropriate frequency components for high contrast imaging. Since specular is a phenomena that is dependent on interference between reflected sound waves, it can be expected that variations of band-pass will influence this undesirable image characteristics. Specular and other image texture characteristics are associated with complex wave interactions which are affected by multiple system factors, including transducer characteristics.

The investigations discussed here were not directed toward altering this image phenomena. As previously indicated, our first priority was to increase contrast without sacrificing resolution in order to achieve improved detection of small masses. We also planned to investigate new approaches to differentiating benign and malignant masses.

Our primary efforts were directed toward decreasing the effects of the lower frequency components of the reflected sound in imaging. Decreasing the low frequency components (via the band-pass) reduced the presence of large, low frequency echoes and thus allowed use of increased gain. Additionally, since a decrease in band-pass provided an improved signal-to-noise ratio, gain could be further increased without the characteristic blooming of skin and other specular reflectors which usually accompanies a simple increase in gain.

As the center frequency of the receiver system is increased and the band-pass narrowed, a dramatic increase in the relative brightness and number (in a small fixed area) of scattering components and a decrease in amplitude of large specular components is evident. Such an effect can be partially associated with logarithmic amplifier responses to operator applied increases in gain. It may also be related to the delimitation (via the band-pass restriction) of some of the lower frequency components of the specular reflectors i.e., as these components are removed, the amplitudes of the high frequency portions of the specular components and that of scattering components may be more comparable. This effect should be helpful in terms of image characterization of solid masses. On a practical clinical scale, the use of a high frequency systems, accompanied by control of receiver band-pass, appears to offer a possibility of improved detection of small masses. It also appears that this technique can provide sufficient information on the internal echo pattern of fibroadenoma to differentiate them from medullary carcinomas and other malignant masses. Further, since a mass is detected and examined using a narrowed band-pass, it can also be readily scanned, with all the advantages of an appropriate gray-scale, by simply moving the receiver to a wider band-pass.

It should be noted that in most cases, the above outlined effects associated with band-pass limitations, are accomplished without severely limiting band-pass.
Further investigations of both asymptomatic and non-asymptomatic patients are required before the above conclusions can be completely validated. The approaches outlined in this investigation are not restricted to automated breast scanners. With further development, they can be applied to other ultrasound mammography systems.

A technique has been developed which allows more than one center frequency to be excited from a single transducer. Clinical application of this technique in ultrasound mammography allows improved detection and diagnosis of breast masses. This enhanced detection is associated with an increase in contrast between a solid mass and surrounding fatty tissue, because of differences in their frequency dependence of scattering. An additional technique for increasing contrast between a breast mass and surrounding tissue has also been developed. This consists of the design and application of a tunable receiver in conjunction with a high frequency, wide bandwidth transducer. Preliminary data indicates that this technique may also provide improved detection and, in addition, image characterization of benign and malignant masses.

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