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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 (10MHz and above) along with band-pass filtering of the tunable 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 ultrasound 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, (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 PVDF 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.[1-3] As a follow-up to this research, an ultrasound imaging breast instrument which provides for the emission of 3.5, 4.5, 6.5 and 8.0MHz ultrasound frequencies from the same sensitive, co-polymer transducer was developed. Subsequently, a higher frequency transducer which, under specific pulsing conditions, allows frequency emissions of approximately 3.5, 4.5, 6.5 and 11MHz, was applied. A 12MHz 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 automatic 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.

INSTRUMENTATION AND TECHNIQUES

Instrumentation used in this study is a modified Labsonics, Inc. (Mooresville, IN) automated tomographic ultrasound scanner designed for examination of symptomatic patients. With the patient in a supine position and the ultrasound coupled to the breast by means of a water bag with an indwelling transducer, this B-mode, linear scan unit produces static images of the breast. The optically transparent, semi-compliant 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. Ultrasound scans are automatically carried out at spatial intervals as small as 1mm or any chosen larger interval that is compatable with the width of the water bag. Automatically controlled, mutually perpendicular scans (bi-plane scanning) may be carried out over a region of interest without reorientation of the water bag or the patient's position (Figure 1). The Labsonics, Inc. breast scanner was modified to allow (under operator control) center frequency outputs of 3.5, 4.5, 6.5 and 8.0MHz from a single focus, co-polymer, PVDF, F/3 transducer.[1-3] This transducer, originally designed for a center frequency of 7.5MHz (Kreha Corporation of America, New York), has a fractional bandwidth of 56% at -6dB and 65% at -10dB. Currently, an F/3.75, 10MHz co-polymer PVDF transducer which, under specific pulsing conditions, can emit center frequencies of approximately 3.5, 4.5, 6.5 and 11MHz, is in use. This unit has a fractional bandwidth of 72% at -6dB and over 100% at -10dB. A 12MHz transducer has also been applied, but is not in routine use.

Two separate receiver systems are available for this instrumentation. System one is designed for a wide band-pass frequency spectrum (> 15MHz at 3dB) and is comparable to the receiver used in the standard Labsonics clinical scanner. System two, a tunable receiver, has been designed so that both the center frequency response and the width of the band-pass can be controlled by means of a continuously variable dial. Center frequency response may be varied from 3.5 to 15MHz. Spectrum analyzer recordings of band-pass responses, (when the receiver center frequency response was set at 10MHz) are shown in Figure 2. Similar calibrations were carried out for other center frequency settings of the receiver. To date, emphasis has been placed on using the tunable receiver at high center frequency settings (10MHz and above) and then observing changes in image characteristics as the width of the band-pass is varied. (Second Author designed both receivers.)

Mammograms are obtained using dedicated, low-dose screen-film units (Pfizer RSI, Columbia, Maryland now manufactured by Elscient, Boston or Mammo Diagnost U-M, Philips Medical Systems, Inc. Shelton, Connecticut).

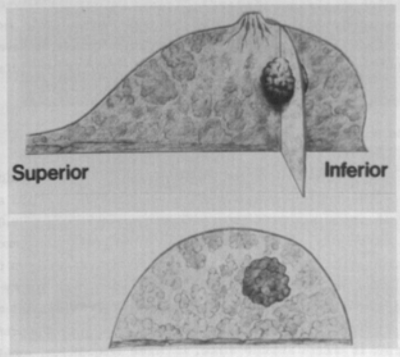

Figure 1. Top sketch: representation of breast tissues imaged by a longitudinal scan. The 90° plane drawn through the mass represents the automatic motion of the transducer during bi-plane scanning. Bottom sketch: representation of tissues imaged during a bi-plane scan. On the display system, the bi-plane image is superimposed over one region of the original longitudinal scan image. (See Figure 3C,D)

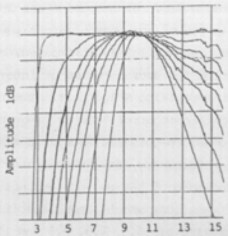

Figure 2. Spectrum analyzer recordings of tunable receiver responses for various manual control dial positions. The receiver was adjusted to a center frequency band-pass of 10MHz. The amplitudes are not comparable, i.e., the reference level was adjusted for each trace so the peaks are at the same level. The dynamic range measured at the detected output was 60dB for unity signal/noise level. Only initial 7dB responses are shown here.

<u>PATIENT PROTOCOL</u>

The majority of patients for this study are selected on the basis of prior knowledge (by x-ray or ultrasound mammography) of the presence of a solid mass within their breast. A small number of subjects whose breasts contained cysts were initially included in the study. Following research investigations to determine the advantages and feasibility of multiple frequency examinations, this modality was added to the standard clinical instrument system. For clinical patients the technologist determined the examination frequency that was most appropriate for a specific patient. For research patients, scans are carried out at 11, 6.5, 4.5 and 3.5MHz under controlled receiver band-pass conditions. Generally, bi-plane scanning of the mass is also performed (Figure 1) with the mutually perpendicular scanning planes imaged at the same frequency or at one or more of any of the other available frequencies, or under different receiver conditions.

An informed consent statement is signed by the patient after a full explanation of the experimental nature of the investigation. To date, 71 patients have been examined with this system, including 10 biopsy confirmed carcinomas and 13 cases diagnosed as fibroadenomas.

<u>RESULTS</u> Non-Tunable Receiver

As indicated under Instrumentation and Techniques, for standard clinical scans, the technologist has available an operator controlled system which allows a center frequency output, from the same transducer, of either 3.5, 4.5, 6.5, or 8.0MHz. Based on experience with 490 clinical patients examined in a one year period immediately following the installation of this multiple frequency system, it has been found that technologists most often choose a frequency of 8.0 or 6.5MHz. A frequency of 3.5 or 4.5MHz is generally chosen to scan a massive size tumor or a tumor distal to the attenuating nipple-areola area. From the technologists viewpoint, the preference for the higher frequencies is understandable since, at these frequencies, excellent range and lateral resolution is provided. For most patients, the full volume of the breast can be imaged at these frequencies when using the previously mentioned coupling technique. Additionally, at these higher frequencies detection of breast masses is improved due to the greater contrast between the mass and the surrounding tissue.

For the research patients who were found to have confirmed carcinomas, 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 subtle diagnostically relevant information on tumor characteristics. When this data is applied along with mammogram information it may improve diagnostic acuracy. Three cases of multiple frequency examination of patients with confirmed carcinomas are presented here. Two of these patients were less than thirty-two years old at the time of examination.

Figures 3A,B demonstrate that, if 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 micro-calcifications or overt masses were imaged. However, possible retraction of glandular tissue was observed. Ultrasound scanning at a frequency of 3.5MHz (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 bi-plane image of another area of this same mass (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 S-I) extension of the tumor into surrounding tissue. There is a scarcity of echoes from within the mass, when scanned at this higher frequency, but a bi-plane scan at 4.5MHz, (Figure 3D) for this same tissue region, indicates the mass is solid and includes an overt region of fibrosis (arrow). Biopsy revealed an infiltrating and in-situ lobular carcinoma with extensive invasion in a linear, so-called Indian File fashion, evoking in some areas a proliferative fibrous response.

Figure 3A

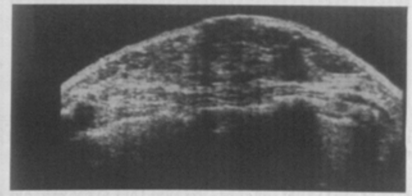

Figure 3B

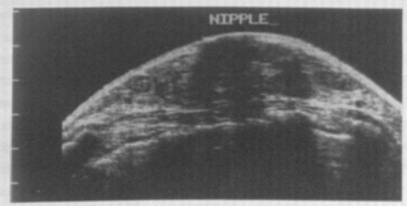

Figure 3A,B. Transverse scan; thirty-one year old patient with a mass located close to the areola. A. High frequency transducer pulsed to yield a center frequency of 3.5MHz. B. Same transducer pulsed to yield a center frequency of 8.0MHz. Line marks on margins of all breast images represent 1cm separation.

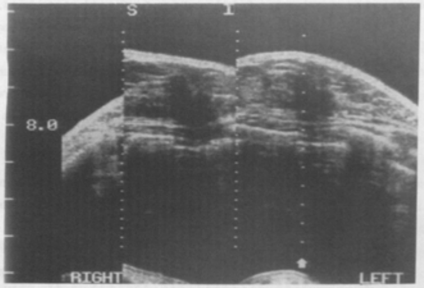

Figure 3C. Bi-plane of another region of same breast shown in Figure 3A,B. The bi-plane longitudinal image (represented by the region marked S-I) is overlayed on a section of the original transverse scan image (Right-Left). Transducer pulsed to yield a frequency of 8.0MHz.

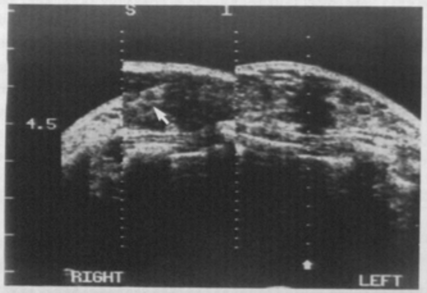

Figure 3D. Same scanning conditions as that shown in Figure 3C, except transducer pulsed to yield a frequency of 4.5MHz.

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 nodule of density in the right breast, greatest in the retro-areolar region. Each of the 3.5, 4.5, 6.5, and 8.0MHz ultrasound examinations 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 muscle 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

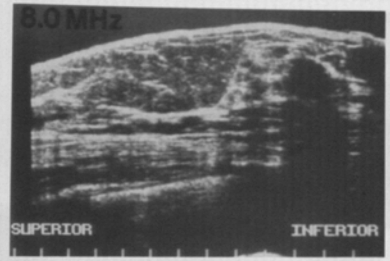

Figure 4B

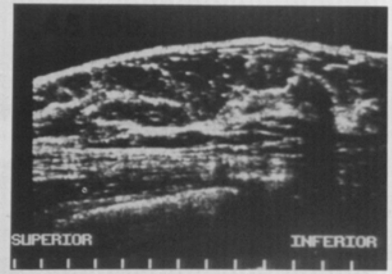

Figure 4A,B. Images from longitudinal scans, at a frequency of 8.0 and 4.5MHz, of the breast of a 60 year old woman with a biopsy proven carcinoma. Note the difference in backscattering from fatty tissue as frequency is decreased.

Figure 5A, is 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 5B) indicates that this solid mass has a cystic component (observable in the longitudinal scan, marked S-I). In additional 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 examination frequencies that makes this mass suspicious for carcinoma. Biopsy revealed an invasive, poorly differentiated adenocarcinoma with scattered, hemorrhagic areas measuring up to 4mm in diameter, and, in some areas, a fibroblastic, desmoplastic tissue response. For this specific case, scans carried out at frequencies less than 8.0MHz only confirmed the information obtained at the higher frequencies.

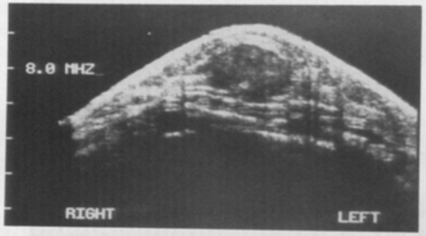

Figure 5A. Image from transverse scan, at a frequency of 8MHz, of breast of a twenty-eight year old subject with a biopsy proven carcinoma.

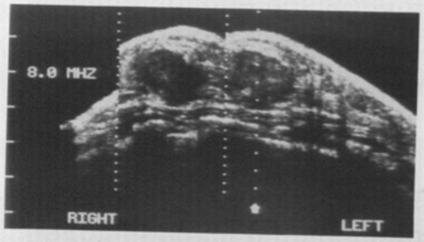

Figure 5B. Bi-plane image of same mass shown in Figure 5A. Note the cystic regions, apparent in the longitudinal bi-plane scan.

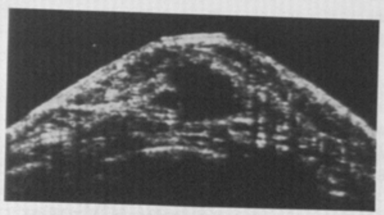

Figure 5C. Image from transverse scan, at a frequency of 4.5MHz, over another region of mass illustrated in Figures 5A,B. Note jagged wall and hypoechoic center.

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 3.5 and 11MHz. However, in the case of fatty breasts detection can be more difficult or, in some cases, impossible if lower frequencies (< 5MHz) are used. For example, Figure 6A shows an ultrasound, 10MHz image of a solid mass in the breast of a twenty-eight year old subject. This slightly attenuating mass exhibits a smooth wall, fine internal echoes and lateral corner 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.

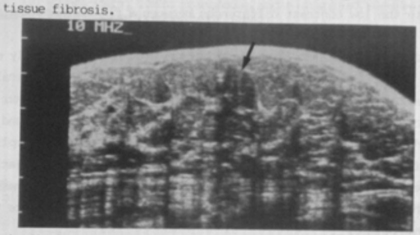

Figure 6A. Longitudinal scan of fibroadenoma in breast of a twenty-eight year old woman. (10MHz transducer pulsed to yield a center frequency of 11MHz)

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,B,C and our data on multiple frequency examination of fibroadenomas in dense breasts, it can be conjectured that at lower frequencies (< 5MHz) the backscattering coefficients of fat and fibroadenomas must be significantly closer in value than that of fibroadenomas and glandular tissue at the same low frequency or that of fat and fibroadenomas at high frequencies (10MHz or above). This phenomena would partly explain why fibroadenomas located in fatty breasts are more readily detected at higher frequencies. A further cause of such poor detection is the decreased resolution at low frequencies which obscures macrostructural tissue differences between fat and fibroadenomas. This problem can be compounded by inappropriate gain settings which 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 11MHz. In that regard, our routine clinical scans of fibroadenomas are carried out at a frequency of 8.0MHz while 8.0 or 11MHz 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 echo pattern at the higher frequencies usually give evidence that they probably are 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 research patients. Using this receiver, it has been found that when transducer frequencies of the order of 10MHz and above are combined with narrow band filtering, there is intense 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 one half centimeter in size. Additionally, tunable receiver systems may allow more precise differentiation between fibroadenomas and malignant masses (in particular, medullary carcinomas) than is now provided by standard receiver systems. 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 two of the confirmed carcinomas and three of the confirmed fibroadenomas are presented here.

Figure 7A is an image obtained by use of a 10MHz transducer and the wide band-pass (> 15MHz at 3dB) receiver system, for examination of a palpable breast mass. A small mass is imaged in Figure 7A, but because other imaged structures have a similar appearance there is uncertainty regarding its reliability. A prior clinical scan at a frequency of 8.0MHz did not detect this palpable mass. X-ray mammography indicated the presence of a lobulated, solid nodule that was suspicious for malignancy. Using the same 10MHz transducer, in combination with the tunable receiver set for a narrower band-pass (4.5MHz at 3dB), the image shown in Figure 7B was obtained. Extensive backscattering from all regions of the breast, except the 5mm mass and the muscle is now apparent. As

a result, the mass is distinctly outlined in sharp contrast to the bright surroundings. Biopsy indicated extensive sclerosing adenosis and focal changes suggestive of microglandular adenosis.

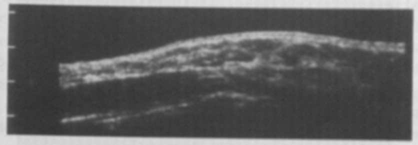

Figure 7A. Longitudinal scan image over region of palpable breast mass in breast of sixty-eight year old woman, using 10MHz transducer and a standard receiver system.(10MHz transducer pulsed to yield center frequency of 11MHz)

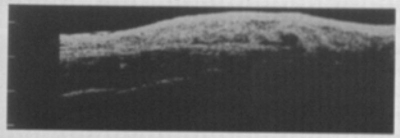

Figure 7B. Same as 7A except tunable receiver (set for narrow band-pass). Biopsy revealed sclerosing and microglandular adenosis.

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 scanner, i.e., the band-pass was only slightly narrower (13MHz at 3dB) than that used in standard clinical scans. (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 1cm 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.

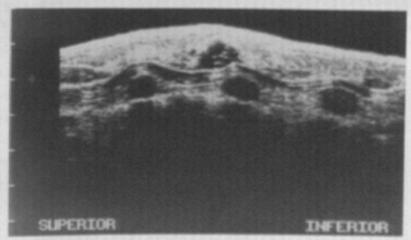

Figure 8. Longitudinal scan image of breast of forty year old woman with a biopsy proven carcinoma, using a tunable receiver controlled for a narrow band-pass and a 10MHz transducer pulsed to yield a center frequency of 11MHz. Note the high contrast between mass and surrounding tissue.

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 10MHz transducer and the tunable receiver set for a wide band-pass (> 15MHz at 3dB). 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 10MHz 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 10MHz transducer and tunable receiver were used, but the band-pass was narrowed to 10MHz for Figure 11, and to 9MHz for Figure 12. There are now clear differences between the images of these two masses, namely, the image in Figure 11 is hypoechoic and attenuating while that in Figure 12 is non-attenuating 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.

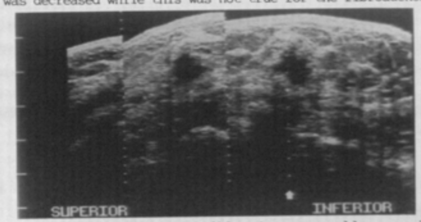

Figure 9. Bi-plane image of breast of a fifty-three year old woman with a biopsy proven medullary carcinoma, using a tunable receiver controlled for a wide band-pass and a 10MHz transducer pulsed to yield a center frequency of 11MHz.

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 10MHz transducer pulsed to yield a center frequency of 11MHz.

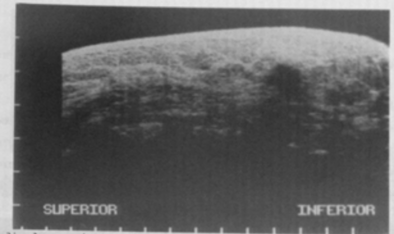

Figure 11. Longitudinal scan image of medullary carcinoma in same breast as that shown in Figure 9, using the same high frequency but controlling the tunable receiver for a narrow band-pass.

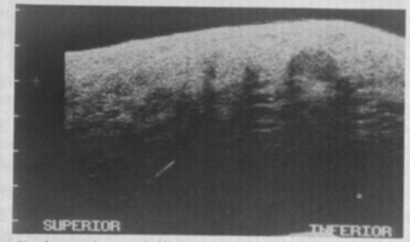

Figure 12. Longitudinal scan image of fibroadenoma in same breast as shown in Figure 10, using the same high frequency but controlling the tunable receiver for a narrow band-pass.

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 (one fibroadenoma was associated with sclerosis and fibrosis), it appears that the images of many fibroadenomas, obtained by means of a high frequency transducer and a tunable receiver set for an appropriate band-pass, 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, fibrotic or massive in size).

Normally, in our clinical scans, a high frequency (> 5MHz) transducer and a wide band-pass (> 15MHz at 3dB) receiver provides adequate information on the internal echo pattern of fibroadenomas. Occassionally, 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 7.5MHz 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 10MHz transducer and the tunable receiver set for a band-pass (12MHz at 3dB) 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.

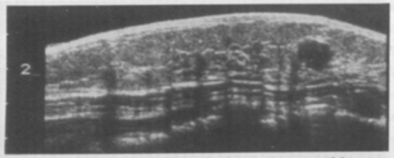

Figure 13A. Longitudinal scan image of breast of nineteen year old woman obtained with a 7.5MHz transducer using the standard clinical breast scanner. Note that despite the excellent quality of this breast image, the internal character of the mass could not be demonstrated. (Transducer pulsed to yield 8.0MHz)

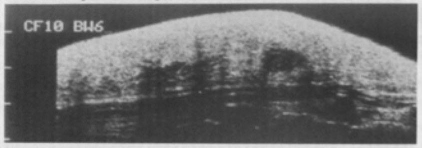

Figure 13B. Longitudinal scan image of same breast shown in Figure 13A obtained with a 10MHz transducer (pulsed to yield 11MHz) and the tunable receiver set for a narrow band-pass. (The designation BW6 is not a quantitative figure; it refers to a dial setting.) Note that the internal echo pattern is now discernable: 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 7.5MHz transducer and the standard, wide band-pass (> 15MHz at 3dB), non-tunable receiver system. The posterior ehancement, lateral shadows and homogeneous internal pattern are obvious. Figure 14B shows an image of the same breast obtained with the use of a 10MHz transducer and the tunable receiver set for a band-pass of 10MHz at 3dB. Note the sharply resolved 2mm 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 12.

Figure 14A

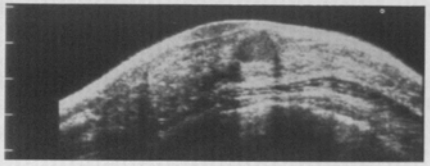

Figure 14B

Figure 14A,B. Transverse scan images of breast of a forty-five year old woman. 14A was obtained using a 7.5MHz transducer (pulsed to yield a center frequency of 8.0MHz) and a standard receiver. 14B was obtained with a 10MHz transducer (pulsed to yield 11MHz) 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 wavelength) 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 to 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 for a unit incident sound intensity, per unit volume of tissue scatters, per solid angle of incident beam) has been evaluated for various biological tissues, such as liver, heart, 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 back-scattering 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.[7-8]

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] Foster et al., found that, for in vitro examination of breast tissues at a frequency of 13MHz, the value of the backscatter coefficient of fat is significantly greater than that of ductal carcinomas.[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 7.5MHz (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] On 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 vitro" studies of the values of backscatter coefficients of breast fat, parenchyma and infiltrating ductal carcinoma, over the frequency range of 3 to 7MHz, D'Astous and Foster confirmed the Jackson et al., suggestion regarding a probable difference in the frequency dependence of the backscattering coefficient of breast fat and carcinomas.[13] D'Astous and Foster found that at low frequencies the value of the backscatter coefficient of ductal carcinoma 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 infil-trating duct carcinoma 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 tissues in images obtained at frequencies between 8 and 10MHz.

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 tumor wall scattering may be used to improve differential diagnosis.[18] Investigations 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 known information on the frequency dependence of attenuation, resolution and scattering.[1,12-14, 19] For example, although we have known from our earlier investigations that there are advantages to examination of breasts at more than one frequecny, multiple frequency examinations were not generally carried out in the clinic because of time delays associated with changing transducers.[19] 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 can readily be obtained under normal clinical conditions. For example, Figures 15A,B graphically illustrate some of the quantitative data of D'Astous and Foster on the comparative values of the back-scattering characteristics of breast fat and parenchyma over a frequency range of 3 to 7MHz, i.e., (1) that 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 2cm in size and is attenuating, its detection is not dependent on high contrast between the mass and the fatty tissue.

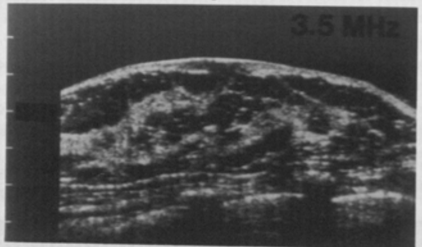

Figure 15A. Longitudinal scan image of breast of normal thirty-two year old woman obtained with a 7.5MHz transducer, pulsed to yield a center frequency of 3.5MHz and a standard wide bandwidth receiver.

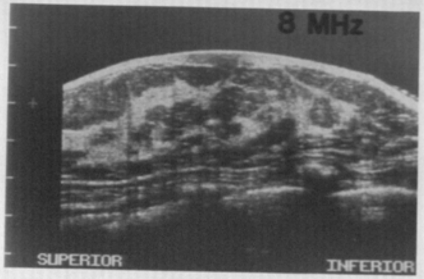

Figure 15B. Same conditions as 15A except the transducer is pulsed to yield a center frequency of 8.0MHz.

Figures 5A,B,C illustrate that some regions of a malignant mass may be hypoechoic while others are not; 5B shows the value of bi-plane scanning. A dramatic example of the advantage of multiple frequency examination is shown in Figures 6A,B,C; Figure 6B 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 F/3.75, 10MHz 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 speckle is a phenomena that is dependent on interference between reflected sound waves, it can be expected that variation of band-pass will influence this undesirable image characteristic.[20,21] Speckle and other image texture characteristics are associated with complex wave interactions which are affected by multiple system factors, including transducer characteristics.[22-27] 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 on imaging. Decreasing the low frequency components (via the band-pass) reduced the presence of large, lower frequency echoes and thus allowed use of increased gain. Additionally, since a decrease in band-pass provides an improved signal-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 confined 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 deletion (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 system, 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 fibroadenomas to differentiate them from medullary carcinomas and other malignant masses. Further, once 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 setting 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 symptomatic and non-symptomatic 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.

SUMMARY

A technique has been developed which allows more than one center frequency to be elicited from a single transducer. Clinical applications 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 masses 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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