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Ultrasound Imaging Using Diffraction Tomography in a Cylindrical Geometry

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Ultrasound imaging using diffraction tomography in a cylindrical geometry

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ABSTRACT

Tomographic images of tissue phantoms and a sample of breast tissue have been produced from an acoustic synthetic array system for frequencies near 500 kHz. The images for sound speed and attenuation show millimeter resolution and demonstrate the feasibility of obtaining high-resolution tomographic images with frequencies that can deeply penetrate tissue. The image reconstruction method is based on the Born approximation to acoustic scattering and is a simplified version of a method previously used by Andre (Andre, *et. al.*, Int. J. Imaging Systems and Technology, Vol 8, No. 1, 1997) for a circular acoustic array system. The images have comparable resolution to conventional ultrasound images at much higher frequencies (3-5 MHz) but with lower speckle noise. This shows the potential of low frequency, deeply penetrating, ultrasound for high-resolution quantitative imaging.

Keywords: diffraction, Born approximation, ultrasound tomography, quantitative imaging, tomographic reconstruction, acoustic parameters

1. INTRODUCTION

As part of the development of a new ultrasound device for quantitative imaging of acoustic parameters of tissue, the Karmanos Cancer Institute and Lawrence Livermore National Laboratory investigated the potential of low frequency ultrasound (US) for providing high-resolution images of human tissue. An immediate goal is to reduce the need for biopsy by determining whether breast masses are benign or malignant. This would reduce both trauma to the patient and health care costs. Low frequency ultrasound (~500 kHz) has advantages of greater depth of penetration and lower scattering noise over conventional US. In order to produce high-resolution images, algorithms are required that incorporate diffraction effects of the tissue. Such algorithms have the potential of resolving structures with sizes near half a wavelength (1.5 mm for 500 kHz). The feasibility of such algorithms for breast imaging was recently demonstrated by Andre, *et. al.*[1] for a ring array operating between 300 kHz and 1 MHz. The present work studied a similar imaging method in a ring geometry using two tissue phantoms that mimic breast microcalcifications and cysts, and a piece of excised breast tissue.

2. MATERIALS AND METHODS

In order to test the ability of diffraction tomography at low frequencies to image small masses in breast tissue, an acoustic scanner with interchangeable acoustic transducers was constructed at Lawrence Livermore National Laboratory. The scanner consisted of two coaxial rotational stages that could be moved independently. Transducers were mounted on two arms attached to the stages, one arm for each stage. One transducer acted as a transmitter, emitting an acoustic pulse in a broad beam oriented toward the center of rotation. The other transducer acted as a receiver, also oriented toward the center. These were moved around a circle of radius 100mm (Figure 1) with the object to be scanned placed near the center. For each transmitter position, the receiver was rotated around the circle to obtain the acoustic energy scattered from the object. The transmitter was moved around the circle in one-degree increments (360 positions). A single data set consisted of 115,200 received pulses corresponding to 360 transmit positions and 320 receiver positions for each transmit position. The number of receiver positions was less than transmit positions because the receiver could not move closer than 20 degrees on either side of the transmitter. The received pulses were Fourier transformed then sampled at several frequencies for processing into images. Figure 2 shows the transmitted pulse and its power spectrum.

Three objects were imaged with the scanner. Two objects were 40 mm diameter agar cylinders produced by Techni-Scan, Inc. One cylinder included 10 thin nylon lines arranged in five pairs at an approximate radius of 25mm. This approximated the acoustic scattering of microcalcifications in breast tissue and was called the microcalcification phantom. The other cylinder contained two long cylindrical holes filled with an alcohol and water mixture and lined with a thin rubber membrane that approximated fluid-filled cysts in breast tissue (cyst phantom). The cylinder phantoms were used to evaluate the performance of various algorithms, including the low frequency diffraction algorithms considered here. The third object was a piece of excised breast tissue contained in a plastic container. It was used for qualitative comparison with other means of imaging breast tissue.

The algorithm used to image the test objects was based on the Born approximation to the problem of acoustic scattering by an incident cylindrical wave (see Andre *et. al.*[1]). This approximation is formally valid for small, low contrast objects but can be extended to larger objects. The low contrast between tissue types in a breast makes this a reasonable approach to try. The algorithm was implemented in Matlab[2] and produced quantitative images of sound speed and attenuation for each frequency selected from the data. A background data set with no object present was used to calibrate the scanner and provides a measure of the incident acoustic field on the object. The algorithm could process each frequency of data in less than 2 minutes on a 250 MHz SGI Octane workstation.

3. RESULTS

Sound speed and attenuation mages of the microcalcification phantom are shown for two different frequencies in Figure 3. The ten nylon lines are resolved, even for the pair with the smallest separation of ~2 mm, suggesting a resolution limit of around 1 mm. Quantitatively, both the sound speed and attenuation values give reasonable values. The units of sound speed are mm/μs and the attenuation 1/mm. Some ringing around both the nylon lines and the outside perimeter of the agar cylinder is present in the reconstructions. This is a consequence of the band-limited nature of the data and could be reduced by filtering the data but at the expense of a loss of resolution. In addition there is a set of rings around the geometric center of the imaged domain that are the result of noise in the data. These artifacts may be reduced by filtering but at the expense of resolution. We have chosen not to apply filtering in order to determine the limits of resolution. In addition to the small-scale reconstruction artifacts there is a bowl-like nonuniformity in the reconstruction of the agar cylinder. There is a variation from the center of the cylinder to the outer edge that results from the limitations in the Born approximation used in the reconstruction algorithm. The effect is more noticeable for the sound speed images than the attenuation images. This effect becomes less severe with lower frequencies.

Figure 4 shows images of the cyst phantom for two frequencies. In these the most visible feature of the cavities is the rubber liner. An extension of the outer cavity can be seen where it approaches the outer edge of the agar cylinder. For this object, the sound speed image is noisy due to the low contrast between agar and water, and the cavity outlines are faint, whereas the attenuation image shows the outlines much more clearly. The attenuation in water at these frequencies is negligible, so that the attenuation in the agar stands out more clearly above the noise level.

Images of sound speed at 643 kHz and attenuation at 387 kHz are shown in Figure 5. The outer wall of the cylindrical container can be seen. The tissue rests primarily in the top half of the container with an extension along the left side. The strong feature in the center of the container is associated with the inside edge of the tissue sample. The remainder of the container is filled with fluid. The container was surrounded by a plastic bag, with a knot seen in the bottom right part of the image. This bag introduces distortion into the image, obscuring some details inside the tissue. Removal of the plastic bag improved the images of the breast tissue sample for other algorithms tested (see Leach, *et. al.*[4]). However, some thin fibrous structure can be seen in the images, especially in the attenuation image. From other images this has been identified as fibrous bands.[5] The reduction in resolution between the breast tissue sample and the previous phantoms is primarily due to the distortion of the plastic bag. However, other effects can contribute to a reduction of resolution. The larger size of the tissue (100 mm diameter for the container) introduces more error due to the inaccuracy of the Born approximation. This can be reduced by using the Rytov approximation and is part of our ongoing work. Another effect is refraction of the ultrasound out of the imaging plane since the breast tissue sample is not cylindrical. All algorithms that image in one plane will be subject to this effect, which requires data acquired outside the plane to remedy.

4. DISCUSSION

These reconstructions show that low frequency US has the potential of resolving fine scale features in breast tissue and giving quantitatively reasonable values for sound speed and attenuation. These mechanical properties can assist in identifying the tissue in any given region and determining whether a mass is malignant or benign. Artifacts such as nonuniformity in the cylinders and noise can be reduced through filtering and extensions of the Born approximation (e.g. Rytov) used to reconstruct the data in this study. A comparison with a conventional B scan US image (Figure 6) of the excised breast tissue shows improved discrimination of internal structure with the low frequency techniques. Furthermore, these low frequency reconstructions can be used as the starting point for more advanced iterative imaging techniques (e.g. Johnson and Tracy[3]). The relative simplicity and speed of the reconstruction technique could also be useful for quick looks over large areas before using more intensive imaging methods of smaller regions of interest.

5. CONCLUSIONS AND FUTURE WORK

We have shown that low frequency ultrasound using diffraction tomography can produce high-resolution quantitative images of objects with characteristics representative of human breast tissue. Thus high-resolution can be attained without necessarily going to higher frequencies. Better reconstruction algorithms that use diffraction information can improve resolution even for low frequencies. Such a capability could be used to reduce the need for biopsy to determine malignancy of breast masses. The work reported here is ongoing. Further development is being pursued in implementing an imaging algorithm based on the Rytov approximation. This would reduce the bowl-like nonuniformity in reconstructions of larger volumes and allow higher frequencies to be used, with even greater resolution. In addition, better filtering and data preprocessing would reduce noise artifacts.

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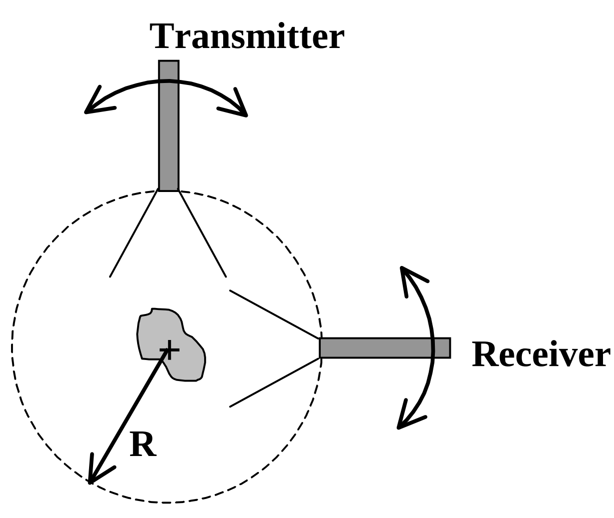

Figure 1. Scanner geometry, R = 100 mm.

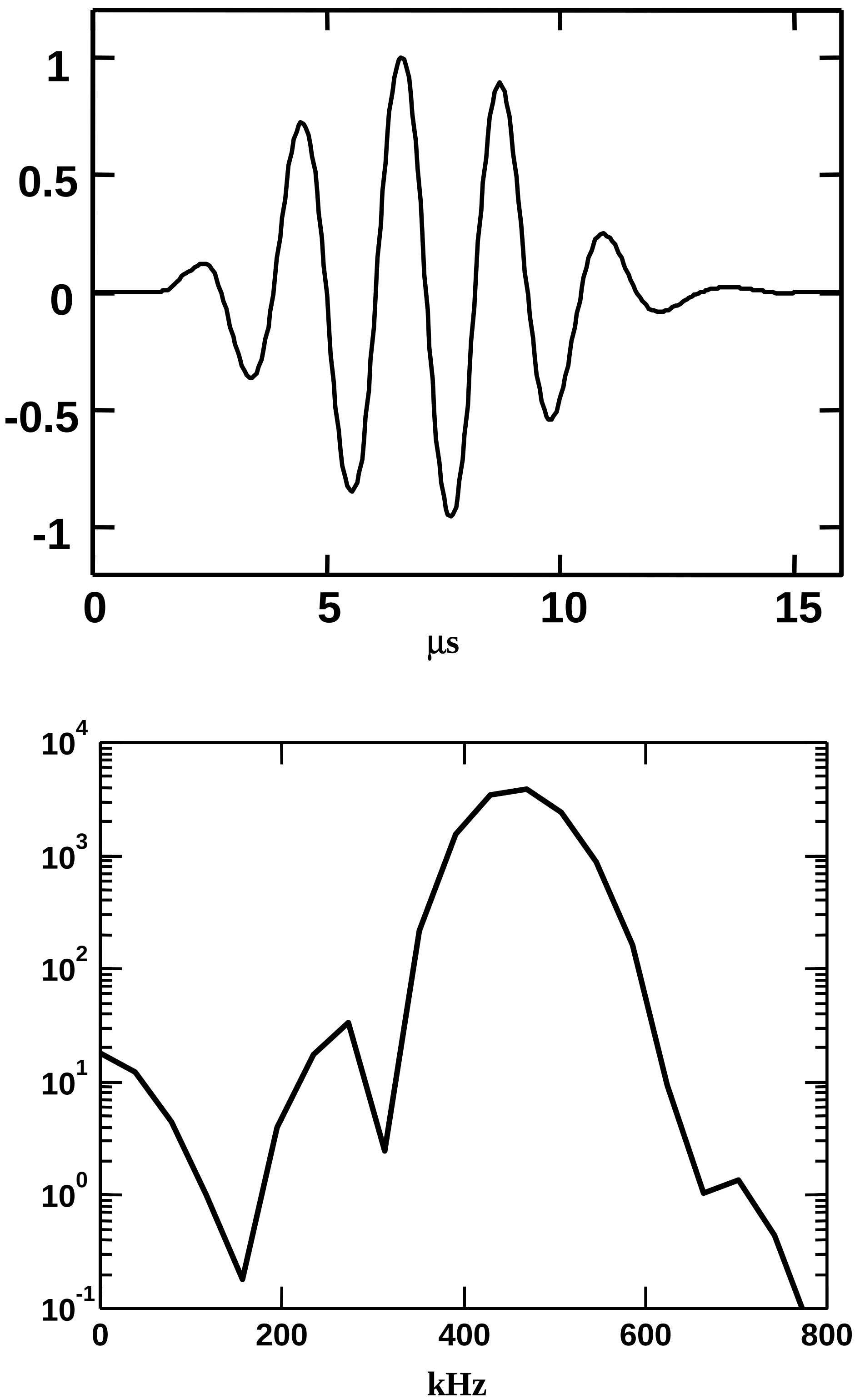

Figure 2. Transmitted acoustic pulse (top) and power spectra (bottom)

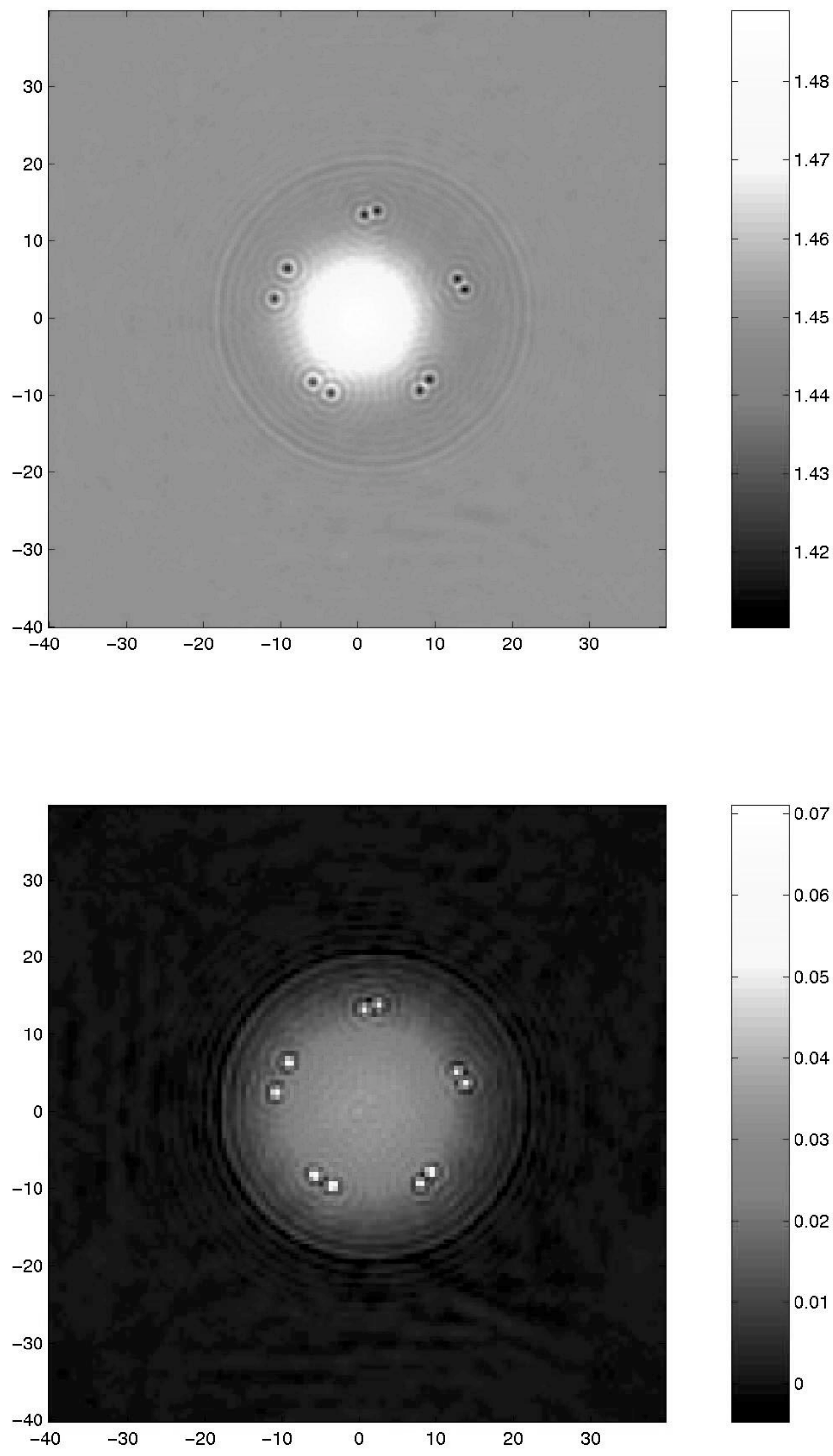

Figure 3. Sound speed (top) at 600 kHz and attenuation at 500 kHz for microcalcification phantom.

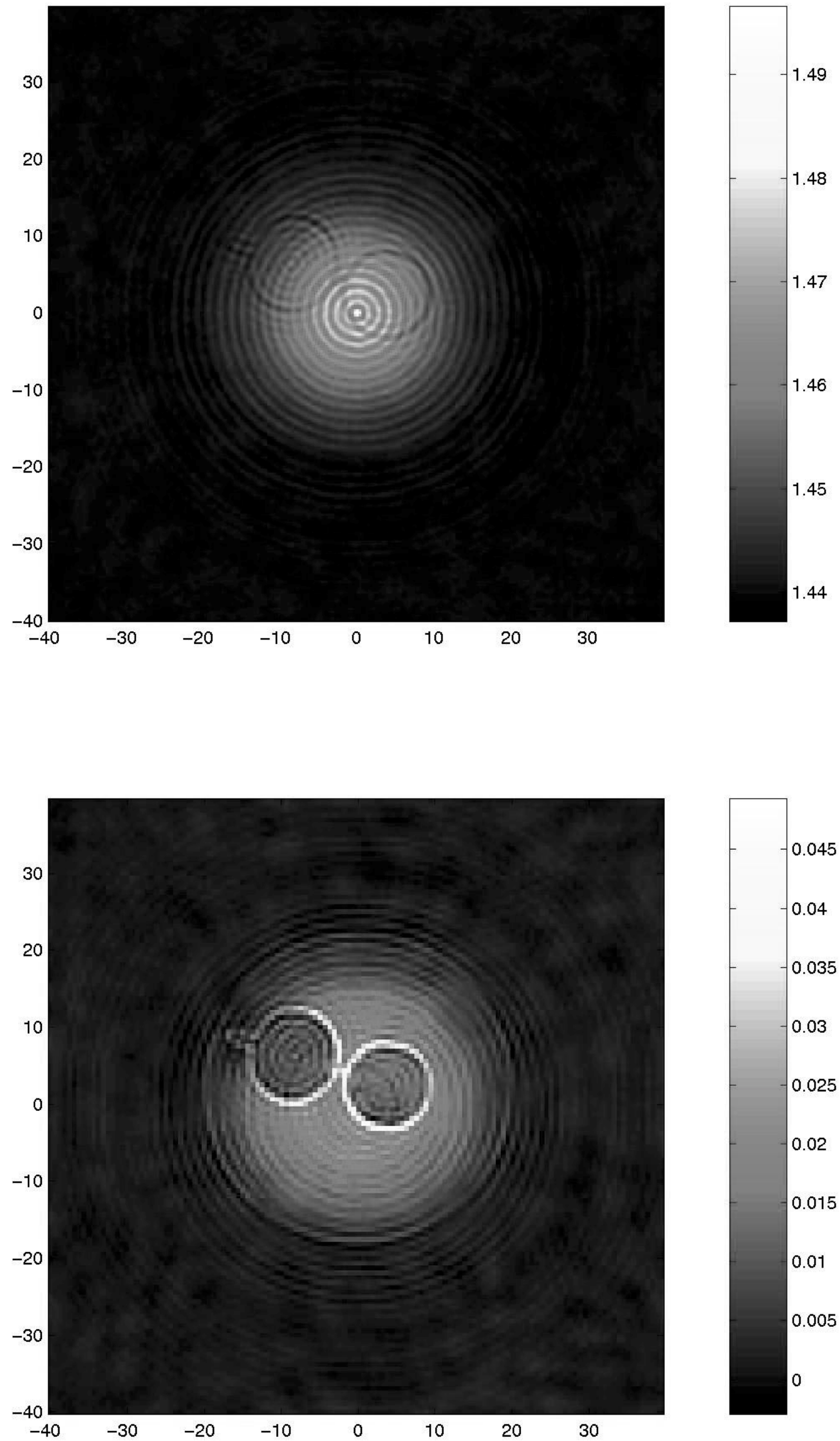

Figure 4. Sound speed (top) at 600 kHz and attenuation (bottom) at 550 kHz for cyst phantom.

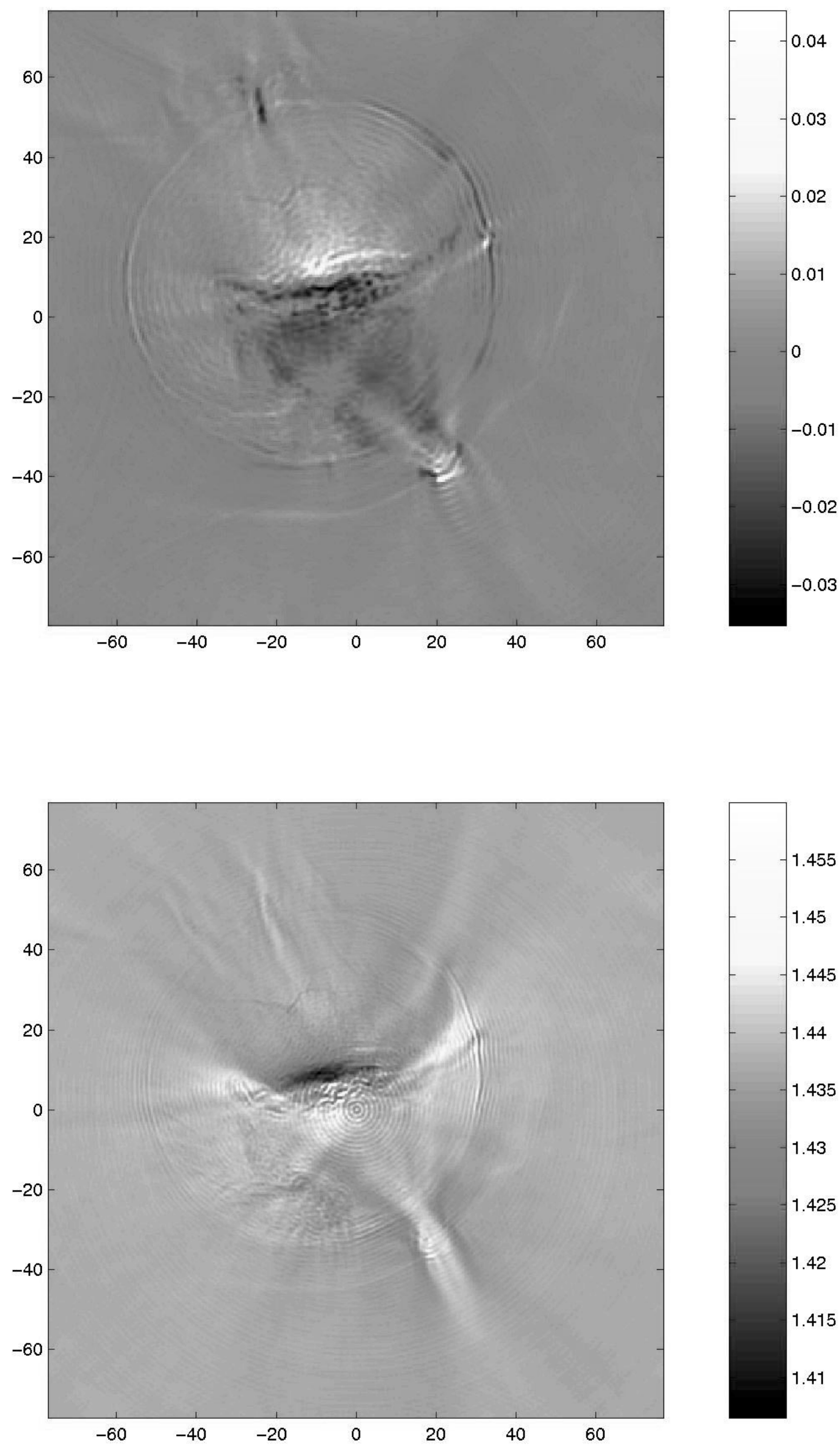

Figure 5. Attenuation (top) at 387 kHz and sound speed (bottom) at 643 kHz for breast tissue sample

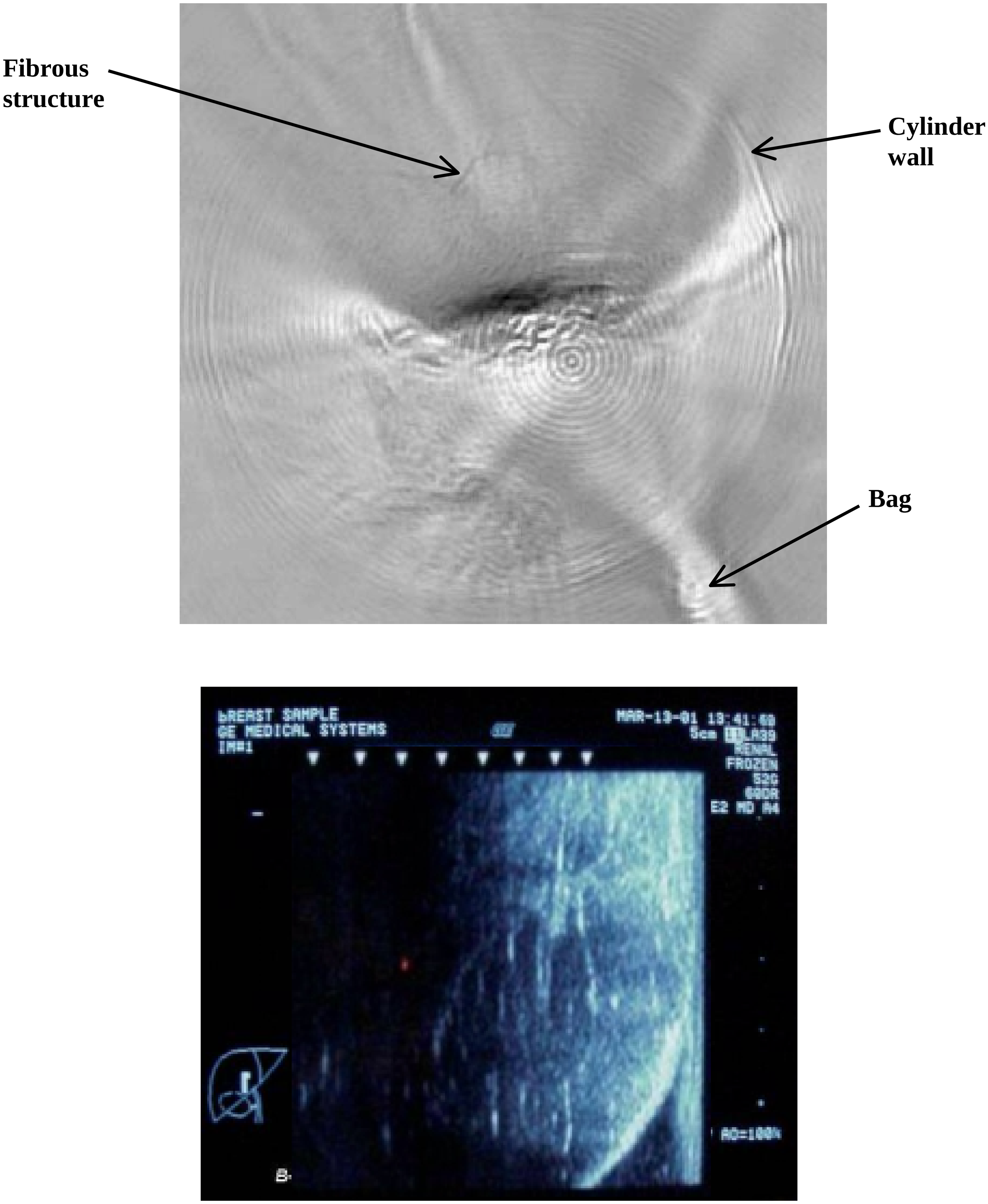

Figure 6. Sound speed image at 643 kHz (top) and B scan, 6-11 MHz, by a GE Logic 6000 (bottom) of the excised breast tissue.