3D SONOELASTOGRAPHY FOR PROSTATE TUMOR IMAGING

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ABSTRACT-Sonoelastography is a new imaging technique to detect hard tumors in soft tissue. In sonoelastography imaging low frequency (200-500 Hz) shear waves are propagated through a tissue sample while real time Doppler techniques are used to image the resulting vibration pattern on an ultrasound scanner. A sonoelastography image is therefore a mapping of the relative vibration amplitude of the tissue sample. Hard tumors are visualized as a deficit or local perturbation of the low-frequency vibration pattern in tissue.

A prostate phantom containing an isoechoic tumor was imaged using sonoelastography. The phantom was manufactured so that the phantom material mimicked both the acoustical and elastic properties of human tissue with the tumor having an elasticity 7 times that of the surrounding normal tissue. This value is in the range of reported values for hard tumors in soft tissue. Two-dimensional images of the phantom were obtained and captured using a special research package supplied with the GE scanner. Three-dimensional renderings were obtained by acquiring sequential tomographic slices and applying segmentation algorithms to delineate the tumor. Although the tumor was isoechoic on the b-scan image, it was detectable using sonoelastography. Three-dimensional renderings of the hard tissue in the phantom were made using the phantom gland surface as a reference. We conclude that the presence of hard tumors in soft surrounding tissue can be rendered in 3D using sonoelastography even when the stiff tissue is not visible when scanned using conventional ultrasound b-scan imaging.

Introduction

In vibration amplitude sonoelastography low frequency acoustic vibrations are applied to an area of tissue while being imaged by an ultrasound scanner with color flow Doppler spectral techniques. In the resulting images the areas of higher vibration are mapped to a high gray scale level while those of lower vibration are mapped to a low gray scale level. This information allows inferences about the relative elasticity of the underlying tissue because stiff areas will have smaller vibration amplitudes than areas that are less stiff. Palpation is a time-honored technique used in detecting hard tumors. When a physician applies pressure to an area of tissue containing a hard tumor, the area directly over the tumor feels harder because it requires the application of additional force to achieve the same displacement. The physician is sensing the relative elasticity of the healthy tissue versus that of the unhealthy tissue. Palpation, however, is effective only for those hard tumors that are near the surface of the organ. Because the information in sonoelastography images (sonoelastograms) allows inferences about relative elasticity, it holds the promise of being a real time imaging system capable of detecting hard tumors.

In 1988 Lerner et. al.[1] proposed a new ultrasound technique for detecting and imaging the relative stiffness of tissues, and proposed the name sonoelasticity. They used an offset-cam plunger to vibrate a sponge containing a 2 cm hard inclusion made of RTV silicone, then used the range gated Doppler function of a Toshiba commercial scanner to produce a low resolution image. Each pixel value in the image corresponded to the peak velocity measured using the range gated Doppler at that position. In 1990 Lerner, Huang and Parker [2] used an acoustic horn to externally apply low frequency (less than 1 kHz) sound waves through a tissue sample while real time Doppler techniques were used to image the resulting vibration pattern on a color flow Doppler ultrasound scanner. Phantoms containing hard tumors were imaged, as was a rabbit liver containing a 2 cm tumor. In 1995 Gao, Alam, Lerner and Parker [3] developed a theory for vibration wave propagation in inhomogeneous elastic tissue, establishing the theoretical basis for sonoelastography. The elasticity equations for an elastic medium of finite extent were formulated and solved for the vibration amplitude with and without the inclusion of a small hard tumor. The results demonstrated that a small hard tumor in an

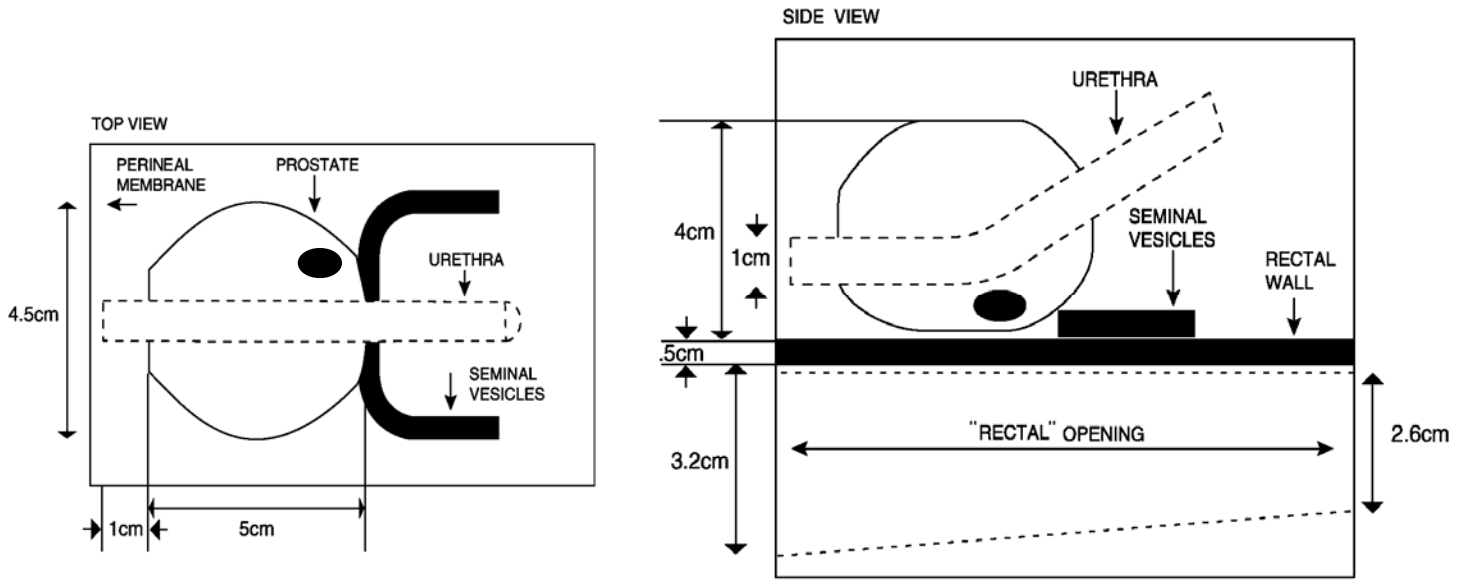

Fig 1. Top view and side view of the tissue mimicking prostate phantom used in the imaging experiments. The prostate has uniform elasticity except for the hard mass shown by the black ellipse.

otherwise homogeneous elastic medium will produce a disturbance in the vibration pattern that would not otherwise be seen if the tumor was not present.

In this paper the application of sonoelastography to the detection of hard tumors in the prostate is explored by means of an ultrasonic test object (phantom) which mimics the acoustic and elastic properties of real tissue. Two dimensional images are presented which show that a known hard lesion, not visible under conventional b-scan imaging, can be seen using sonoelastography. Three dimensional images show that the location of hard tumors can be shown relative to the surface of the organ.

Prostate Phantom

An ultrasonic tissue mimicking prostate phantom was purchased from Computer Imaging Reference Systems in Norfolk, Virginia. The phantom is life size and designed to be used as a practice tool for prostate imaging and guided biopsies. It includes the prostate gland, urethra, seminal vesicles and a rectal channel all enclosed in a clear plastic container. The phantom was manufactured so that its acoustic attenuation and its speed of sound propagation approximated that of human tissue. An ellipsoidal tumor with semi-axes of 5.5 mm, 4.5 mm, and 4.5 mm; (+/- 0.5 mm) was included in an area of the gland near the seminal vesicles. The tumor was manufactured with a measured elasticity 7 times greater than the surrounding tissue in the prostate but with acoustical properties the same as the surrounding tissue. Figure 1 shows a schematic diagram of the phantom with a small black ellipse showing the location of the tumor.

Experimental Set-Up

Fig. 2 shows the imaging set-up used for the experiments. In order to obtain an image, an external vibration was applied to the phantom while the data was acquired by the ultrasound scanning system. A 100 lbf (pounds of force) piston shaker driven by a amplified function generator applied a steady state vibration to the tissue phantom. Sinusoidal tones in the frequency range of 80 to 400 Hz were used. Imaging was done using a GE Logiq 700 ultrasound scanner. An image capture interface, called Extend, provided with the GE Logiq 700 scanner was used to create digital image files. Its capabilities include the capture of both single frame and cine-loop images which can be saved to an internal hard drive on the machine.

The resulting file contains b-scan, velocity and variance images, all spatially registered. Three dimensional images were obtained by mounting the ultrasound transducer on a motorized track which scanned the volume of interest. The track speed was synchronized to the screen frame rate allowing capture of slices at 1 mm increments in the sweep direction. After image capture, the files were transferred from the scanner's hard drive to an image processing laboratory via a network connection. Software developed in-house at the University of Rochester was used to prepare the images for display in Explorer, a commercial 3D visualization package.

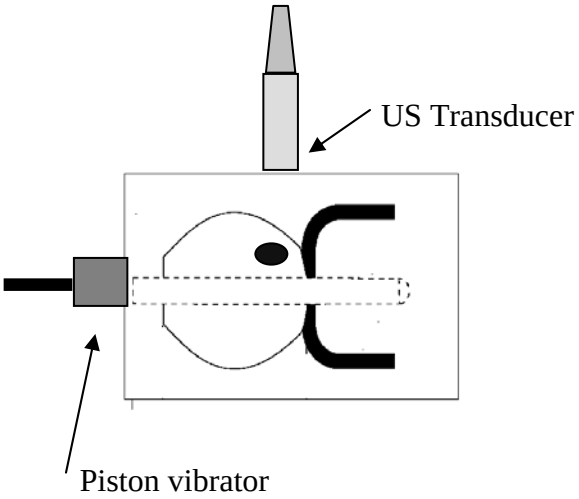

Figure 2. Position of imaging transducer and piston during the scanning process. The piston on the left was vibrated sinusoidally while held in contact with the surface of the phantom.

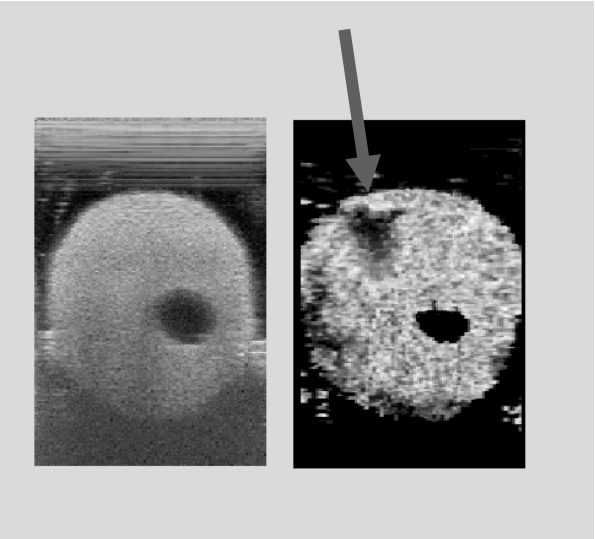

Figure 3 a) B-scan (left) of a slice of the phantom through the hard tumor. b) sonoelastogram (right) of the phantom at the same location of the hard tumor. Arrow points to location of the tumor. The area shown is 39 by 60 mm.

Images

Fig. 3 shows registered b-scan and sonoelastography images of a slice of the prostate phantom taken at 6.5 MHz while being vibrated at 296 Hz. The slice is a section through the hard ellipsoidal tumor. The b-scan image is on the left, and shows a bright profile of the gland against a darker background with the urethra opening seen as dark circular region within the gland. The hard tumor is not visible in the sonogram (b-scan image). The image on the right is the sonoelastogram, which is displayed with a 16 level gray scale. The field-of-view for both images is approximately 4 by 6 cm. Bright gray corresponds to higher vibration levels while dark gray and black corresponds to low vibration amplitude levels. The urethra is also visible as an area of low vibration along with two other regions. The arrow points to an area of dark gray which corresponds to the known location of the hard tumor inserted into the phantom at the time of its manufacture. The hard tumor has been detected by the imaging system as a disturbance in the otherwise uniform vibration pattern within the gland. The third darker region seen on the left side of the image near the edge of the gland is attributed to a modal pattern effect caused by the destructive interference from reverberations off the phantom boundaries. From a diagnostic point of view the third region represents a false positive since we have a priori knowledge that the elasticity is normal at this point in the phantom.

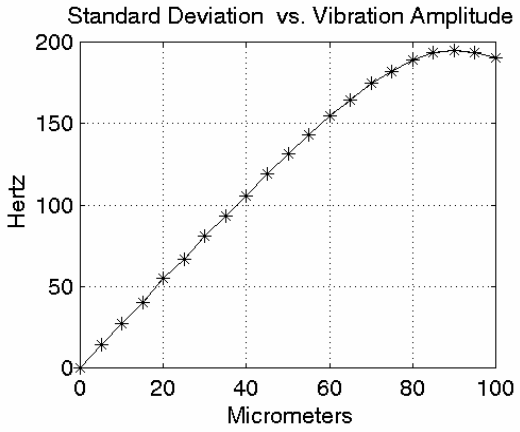

Figure 4. Plot of standard deviation versus vibration amplitude. Standard deviation is mapped to a gray scale to form a sonoelastogram. The maximum vibration level that can be imaged is determined by the sampling rate between ultrasound imaging pulses.

It is appropriate here to discuss the information content of both images. The sonogram or b-scan image maps the gradient of the acoustic impedance in the direction of the ultrasonic pulse propagation (from top to bottom in this image) to a gray scale level. At points in the image where the acoustic impedance has a large change a larger (bright) echo is returned. The speckle pattern in the image results

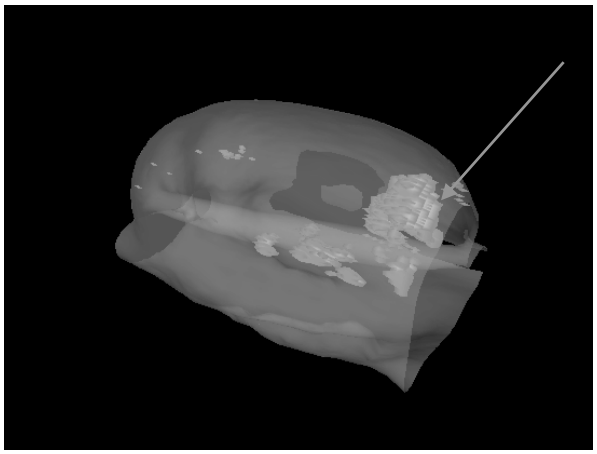

Figure 5. 3D rendering of areas of low vibration in the prostate phantom shown with the gland surface as transparent. The arrow points to the location of the tumor. The other isolated gray masses are false positives.

from the fact that there are Rayleigh scatters distributed throughout the region of interest. At locations where the impedance is constant no echoes are returned and the image is dark. The hard tumor is not visible (isoechoic) because the acoustic impedance of the phantom is uniform in that region, even though the elasticity changes abruptly there.

The sonoelastogram maps the vibration amplitude detected at each point in the image to a gray scale level. Figure 4 shows a typical curve relating vibration amplitude and the standard deviation of the power spectrum of the Doppler signal for the estimator used by the GE machine. Doppler estimators measure linear velocity by detecting the shift in the mean frequency of the return signal from a moving target [4]. When the motion is sinusoidal it has been discovered that the spread of the power spectrum (standard deviation) will vary directly with the peak vibration amplitude [5]. Standard deviation, measured in Hertz, is estimated and displayed for each pixel in the image as a gray scale level.

Figure 5 shows a 3D sonoelastography image of the tumor inside the surface of the gland. Here segmentation techniques have been used to prepare a volume rendering of the hard tumor while the b-scan was segmented to obtain a surface for the gland. The areas of low vibration in the image, including the tumor, are shown as solid gray while the gland surface is rendered as transparent gray. The urethra is visible in this 3D rendering as a tube extending from end to end through the center of the gland.

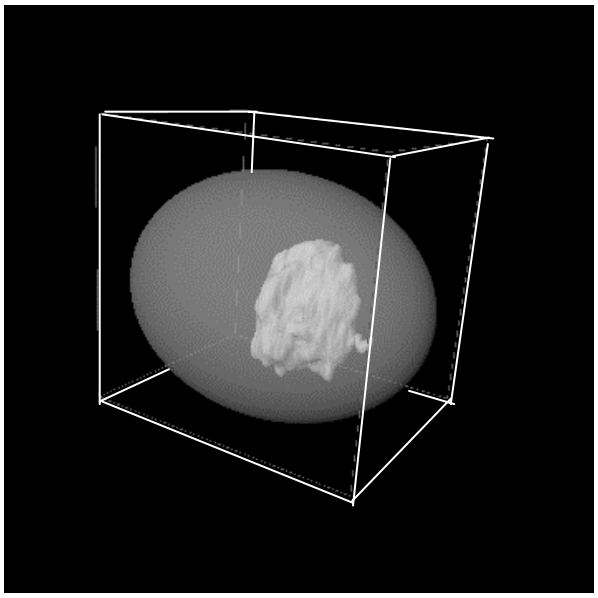

Figure 6. 3D rendering of an ex-vivo prostate. Solid light gray mass shows area of low vibration corresponding to cancerous tissue identified by pathology. Bounding box is 50 mm high, 40 mm wide and 55 mm deep (left to right in the image).

The arrow points to the known location of the hard tumor. The other solid gray masses are areas of low vibration caused by destructive interference from reverberations. It is envisioned that this kind of image will be useful to physicians in determining the location of hard tumors for planning a biopsy and other purposes.

Figure 6 shows a 3D sonoelastogram of an ex-vivo prostate taken at 6.5 MHz with an applied vibration frequency of 306 Hz. The 2D images were acquired immediately after a radical prostatectomy was performed on a patient diagnosed with prostate cancer. After the ultrasound scan the organ was taken to the pathology department where the organ was sectioned and the cancer delineated. In this 3D image the area of low vibration has been rendered as a medium gray mass and the approximate location of the surface boundary of the prostate has been represented as a transparent ellipsoid. Pathology confirmed the presence of a hard cancer in the mid-gland region where the hard mass was imaged in the sonoelastogram.

Conclusions

The feasibility of imaging an isoechoic hard region using sonoelastography has been demonstrated using a tissue mimicking phantom containing a tumor where the location and elasticity of the tumor was known. A two dimensional sonoelastogram, set to scan a slice through the phantom containing the hard tumor, showed a dark region at the known location of the tumor. Since a low gray-scale value in a region corresponds to a low vibration level we draw the inference that this region is stiffer than the surrounding tissue. When sequential 2D slices are acquired 3D image volumes can be assembled. The application of image segmentation techniques allows 3D rendering of the hard tissue detected by sonoelastography as a solid mass. 3D images were presented that display tumors within the transparently rendered surface of the prostate. We believe that such images will be useful to physicians in planning biopsy procedures and assessing the extent of the hard tumor mass within the gland.

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