Characterizing the Dynamic Properties of HIFU Lesions

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Abstract: High intensity focused ultrasound (HIFU) is a non-invasive method by which ultrasound can be used to thermally ablate tissue. One important application is the treatment of tumors. However, real-time imaging of the heating of tissue and lesion formation is a major barrier for HIFU. Our research involves employing a multi-modal approach, based on ultrasound imaging, by which the presence of a lesion can be determined and its formation observed. Three different types of properties will be mapped in the tissue: acoustical (through ultrasound backscatter and tomography), mechanical (through elastography), and optical (through acousto-optic imaging). By probing these three lesion properties we anticipate developing a robust approach to tracking HIFU lesion formation in real time. The first phases of the work have involved the development of computer models for temperature prediction in tissue and lesions and the detection and control of acoustic cavitation during lesion formation. The first lesion detection by AOI was recently achieved. The understanding and new methods anticipated from this work are intended for direct application to the emerging field of ultrasound tumor ablation.

Motivation and State of the Art

Clinical applications of HIFU therapy utilize MRI machines to image the ultrasound-induced lesions as they are being produced. However, it’s expense and space requirements inhibit the adoption of HIFU as a viable therapy for cancer. Imaging lesion formation using ultrasound would be preferable, and techniques investigated for this purpose include the use of acousto-optic imaging to obtain a robust multi-property imaging system.

Challenges

Traditional ultrasonic imaging has been unsuccessful at imaging HIFU lesions because its contrast is provided by differences in acoustic reflection (backscatter coefficient) and is affected by lesion contrast. Lesions unfortunately have backscatter coefficients close to untreated tissue.

Acousto-Optical Imaging

Acoustic waves induce fluctuations in density, and hence in optical index of refraction, absorption, and scattering. Photons that diffuse randomly walk through the ultrasound focal zone will have their velocities changed. If these photons ("tagged" photons) can be monitored, then any changes in the tissue optical properties at the focal zone can be detected. For example, if HIFU creates a lesion, the "cooled" tissue becomes more opaque, thus tending to absorb and reduce the number of any photons "tagged" in the lesion zone. The number of tagged photons detected by the detector will decrease. The figure at left depicts the optical experimental setup. The reference beam and signal beam create a photorefractive crystal (PRC) and create an interference pattern in the crystal. Through unique properties of the crystal, the local optical index of refraction changes as a function of the local optical intensity. A 3D diffraction grating is thus set up in the crystal, which deflects the reference beam into a direction parallel to the signal beam, and with the same complex wavefronts coincident at the photodetector, and constant phase difference between the two beams. When an ultrasound beam changes the phase of the photons which pass through it, the wavefront of the signal beam will change. The signal and reference beams will no longer constructively add at the photodetector, and the intensity of the output will decrease. Since it is more optically opaque, and tagged photons created there will be absorbed and not make it out of the sample into the signal beam. Thus the drop in AOI signal will be less during the time the pulse passes through the lesion creating a blip (red curve). 2D or 3D images can be constructed from individual lines taken at various positions in X and Y. To accomplish this, the sample can be moved in the X-X plane, or the acoustic source can be moved. Thus, an optical image of the interior of a diffuse medium can be made, with a resolution determined by the ultrasound field (typically of order mm).

Optical setup (left), and illustration of AOI signal and timing (right). Figures courtesy of Lei Sui.

Results to date

The first known AOI scan of a lesion in tissue was made in chicken breast. The figure at right shows a photo of a post-lesion tissue cross-section. The figure below shows an AOI scan of another lesion in this same orientation. The lesion is seen as the blue central region, measuring about 1.5mm by 10 mm. The dashed oval shows the 468 nm pressure contour of the HIFU focal region. At this altitude a standard ultrasound B-mode image of the same tissue, showing that the lesion is undetectable with this method.

Technical Approach

Our planned research involves improving ultrasonic image resolution of lesions using the following methods:

1. Acousto-optic imaging.
   Use the significant advances made in our department in the area of Acousto-Optic Imaging (AOI) to image HIFU lesions, which exhibit optical contrast. Local tissue motion, which changes during lesion formation, may also be detectable with AOI.

   Using the HIFU transducer to simultaneously create the lesion and apply an oscillatory radiation force to the lesion area, monitor local tissue motion in the lesion region. Tissue necrosis results in a marked change in stiffness, which results in a change in this tissue motion. Motion is monitored using a pulsed diagnostic transducer and “speckle tracking” correlation software.

   Using a detailed model for backscattering to include the diffraction and acoustic coupling function of the transducer, develop new processing algorithms to apply to raw data from our Analogic ultrasound imaging machine to image HIFU lesions, which exhibit optical contrast. Local tissue motion, which changes during lesion formation, may also be detectable with AOI.

Early Speckle Tracking Results: "Apparent Displacement Thermometry"

Acoustically forced tissue motion will be measured by “speckle tracking”. Ultrasound imaging A-lines like the one shown at left consist of echoes from the scattering particles in the tissue. If there are local movements in the tissue, the echoes will shift over successive time frames. Cross-correlation between segments of successive A-lines indicate how much each segment has moved.

At right is a plot of tissue motion (vertical axis), vs. time, for single A-line through the focus of HIFU heating in a tissue phantom. In this case, there is not actual motion, but the HIFU heat causes a change in acoustic velocity, which results in an “apparent” displacement. This parameter can be related a useful measure of temperature change. The heated focal zone is at a depth of about 30mm.

References:


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First Acousto-Optical Imaging Results

Experimental Setup

To photodetector

Ultrasound B-mode image of tissue. Lesion is visible.

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