3D Temperature Dependence of Ultrasonic Backscattered Energy in Images Compensated for Apparent Tissue Motion

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Abstract

Ultrasound is an attractive modality for monitoring temperature during heating of tumors to therapeutic levels. Previously, we predicted monotonic changes in ultrasonic backscattered energy (CBE) for certain sub-wavelength scatterers. Accurate measurement of CBE requires compensation for apparent motion of image features. We measured CBE in 2D in motion-compensated images of four 1-cm thick samples of bovine liver, two of turkey breast, and one of pork muscle during heating in a water bath from 37 to 50°C. Images were formed by a Terason 2000 imager with a 7 MHz linear probe focused at 4.5 cm, the center of each tissue specimen. Employing RF signals from the Terason 2000 (courtesy Teratech Corp.) permitted the use of cross-correlation as a similarity measure for automatic feature tracking with temperature. Tissue motion in 8 image regions of each specimen was tracked from 37 to 50°C in 0.5°C steps. Maximum displacement in all specimens was about 0.5 mm in both axial and lateral directions. Motion compensated image regions were demodulated and smoothed. Pixel values were squared to form the backscattered energy. We compared means of both the positive and negative changes in the BE images. CBE was monotonic. BE differed by about 4 dB at 50°C from its value at 37°C. We measured motion in 3D in one sample of turkey breast by taking 7 images at each temperature displaced by 0.6 mm in elevation. We plan to extend our 2D methods to 3D motion compensation, but because beam width in elevation was 2.5 mm, five times the maximum apparent motion in 2D, effects of apparent motion in elevation on CBE may be negligible. Relatively noise-free CBE curves from tissue volumes of less than 1 cm³ supports the use of CBE for temperature estimation.

Objectives

- Evaluate CBE for ultrasonic thermometry
  - Find the change in backscattered energy in diagnostic ultrasound images at temperatures ranging from 37 to 50oC
  - Develop and test algorithms for tracking apparent motion using the correlation of image regions at adjacent temperatures
- Evaluate CBE in 3D
  - Develop a measurement protocol for acquiring 3D datasets
  - Estimate and compensation for motion in 3D
  - Analyze motion-compensated CBE in 3D

Methods

Experimental Setup for Collecting 3D Datasets

Measurements were made with the experimental configuration depicted in Figure 1. Tissue samples were heated in an insulated tank that was filled with deionized water, which had been degassed by vacuum pumping in an appropriate vessel. Tissue was placed in the focal zone of a 7MHz linear array probe, model 10L5. Temperature in the tank was set by a heater that circulated the water in the tank. The temperature in the tissue was monitored by a thermometer, which used an indwelling needle RTD thermistor. After temperature in the tank reached equilibrium, 7 images separated by 0.6 mm were saved to disk. The temperature range covered was 37 to 50°C in 0.5°C increments.

Data Analysis in Conventional 2D Images

For a given region in lateral images (Figure 2), motion was compensated by estimating the apparent motion of the region from one temperature measurement to the next then transforming the second image by the measured displacement. The compensation procedure was applied to multiple regions within a tissue sample.

After compensation for apparent motion, the change in backscattered energy (CBE) was calculated over the range of temperatures. To find CBE compensated images were demodulated with the Hilbert transform and smoothed with a 3x3 running average filter. Values were squared to determine the backscattered energy at each pixel. The backscattered energy image at 37°C was used as the reference for the CBE at each 0.5°C step.

Measurement of Backscattered Energy in 3D

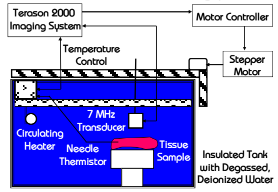

Figure 1. Configuration for automatic acquisition of 3D ultrasonic image sets from tissue at 0.5°C intervals from 37 to 50°C..

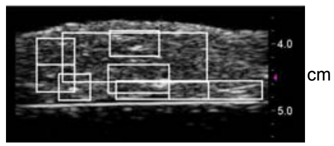

Figure 2. Terason 2000 lateral-scan image of bovine liver. Seven images separated by 0.6 mm in elevation were taken at each temperature. Focal zone of the 7 MHz transducer was at 4.5 cm (arrowhead marker). Superimposed boxes indicate regions studied.

Elevation Images from Lateral Scans

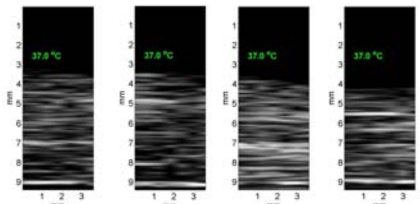

Figure 3. Elevation images in turkey breast at 37°C separated by 7.5 mm laterally.

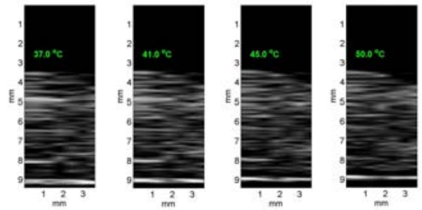

Figure 4. Elevation images in turkey breast at four temperatures from 37 to 50oC at the same lateral position (second from left above). Feature size is several times larger than in the lateral direction because the beam is not focused in elevation.

Apparent Motion in 2D

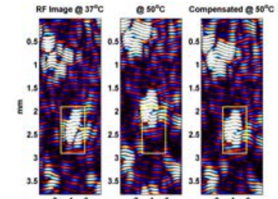

Figure 5. Radio-frequency images of bovine liver at 37°C (left) and 50°C (center & right). Features in the fixed, highlighted region appear to have moved both axially and laterally at 50°C compared to positions at 37°C. Motion compensation to correct for apparent motion of image features was applied to the image at 50°C (right).

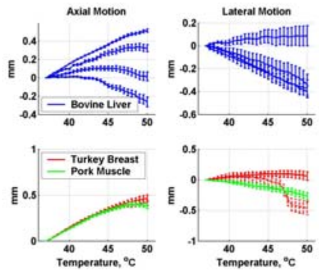

Figure 6. Apparent motion of tissue in the axial and lateral dimensions due to temperature. Each plot is the mean of motion in eight regions ± the standard error of the mean for each tissue specimen. Results from four bovine liver samples are shown in the upper panels, for two turkey breast and one pork muscle samples in the lower panels. Motion depicted in Figure 5 was quantified using cross correlation of RF signals as seen in that figure.

Change in Backscattered Energy

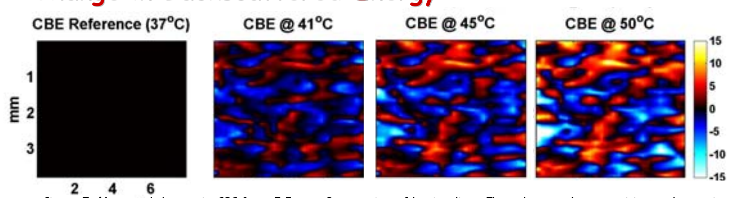

Figure 7. Measured change in CBE for a 3.5mm x 8mm region of bovine liver. The colormap shows positive and negative change as red and blue, respectively, to a maximum of 15 dB. The CBE at individual pixels appears to increase or decrease monotonically with temperature. Figure 8 below shows the results of analyzing CBE images such as these, in their entirety, for multiple regions in multiple tissue types..

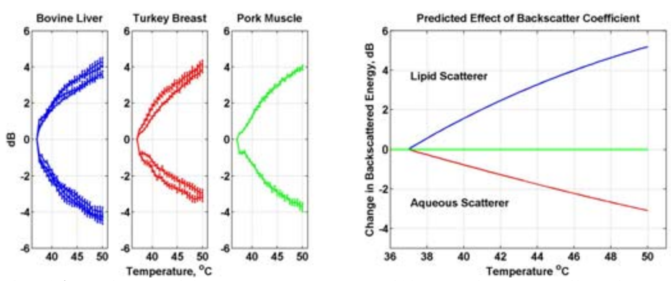

Figure 8. Means of measured CBE in positive and negative regions of BE images in four specimens of bovine liver, two of turkey breast, and one of pork muscle (left). The error bar is the standard error of the mean estimated from eight regions of interest in each of the tissue specimens shown in Figure 2. Predicted CBE for single, sub-wavelength lipid and aqueous scatterers in an aqueous medium (Straube and Arthur, Ultrasound in Med and Biol, 20, pp. 915-922, 1994.(right).

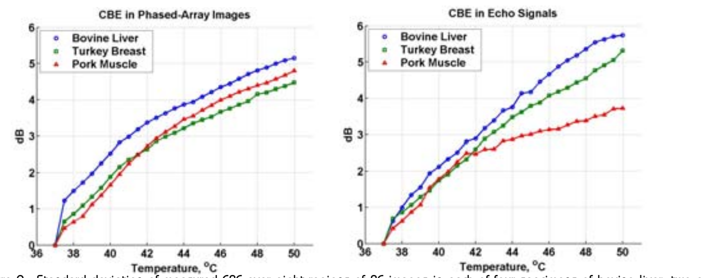

Figure 9. Standard deviation of measured CBE over eight regions of BE images in each of four specimens of bovine liver, two of turkey breast, and one of pork muscle (left). Standard deviation of measured CBE in 1D from specimens of bovine liver, turkey breast, and pork muscle reported previously (Arthur et al. Med Phys. 2003 Jun;30(6):1021-9).

Discussion and Conclusions

Analysis of ultrasound images taken at 0.5°C steps for the temperature range from 37 to 50°C showed apparent motion in both the lateral and axial direction. This motion was compensated for by using a cross correlation technique that maximized the correlation at adjacent temperatures to track regions of interest within the tissue sample. After compensation the backscattered energy relative to the baseline at 37°C was analyzed at each pixel within this region.

The analysis showed both positive and negative excursions in the relative backscattered energy similar to what we had seen previously in the 1-D case (Arthur et al. Med Phys. 2003 Jun;30(6):1021-9). The standard deviation of these positive and negative excursions tracked monotonically with temperature in the 37 to 50°C range. Although we have developed a protocol to collect and visualize 3D dataset, motion in the elevation direction has not been taken into account in these analyses.

We expect motion in elevation to have less of an effect on CBE than motion in the axial and lateral directions because the transducer we are using is not well focused in the elevation direction. The results from this study are consistent with theoretical expectations and continue to support the possibility of using CBE in ultrasound as a tool for noninvasive thermometry.

Future Directions

We plan to estimate and compensate for motion in 3D, that is, in the axial, lateral, and elevation directions simultaneously. CBE in motion-compensated images in 3D will be analyzed to determine the impact of apparent motion in elevation on measures of CBE for temperature estimation.