Washington University in St. Louis
Electrical & System Engineering

Motion Compensation for Temperature Imaging using the Change in Ultrasonic Backscattered Energy

Yuzheng Guo
Jason W. Trobaugh
R. Martin Arthur

Abstract

Background. Ultrasound is an attractive choice for noninvasive thermometry to enhance tumor treatment using hyperthermia. Our theoretical model [1] predicted and *in-vitro* experiments [2] verified that the change in backscattered ultrasonic energy (CBE) is monotonic (approximately 0.2~0.3dB/°C) with temperature in the hyperthermia range, motivating the usage of CBE for ultrasonic thermometry. One limitation in measuring temperature-dependent CBE from ultrasound images is apparent motion in the images due to change of the speed of sound and motion of the tissue. Previously, a block-matching motion-tracking method was used to compensate rigid motion but was only successful for small regions [2].

Methods. We have developed an algorithm for estimating and compensating non-rigid motion over large 2D or 3D regions. The motion field was modeled to vary linearly over the region of interest and was estimated by maximizing the cross-correlation between the reference and subsequent images using optimization functions in MATLAB®. Factors affecting performance of the algorithm were studied using simulation of images for multiple scatterers [3]. Images before and after motion were simulated by transforming scatterer locations.

Results. Our algorithm was successfully applied to images from *in-vitro* and *in-vivo* heating experiments, with significant improvement in performance over previous results based on qualitative assessment. To study the performance quantitatively, 2D images were simulated with various signal-to-noise ratio (SNR) and types and ranges of motion, including expansion and compression to study image decorrelation. CBE due to motion was different between axial and lateral directions and was about 2.5dB/0.1mm translation and 1dB per ±1% expansion axially and 4.5dB/mm and 0.35dB per ±1% laterally. Error in motion estimation decreased with SNR with minimal impact on CBE and increased with decorrelation leading to 0.1~0.2dB additional CBE. In addition to inducing estimation error and thus CBE, decorrelation itself caused erroneous CBE as much as 0.3~0.4 dB for 6% lateral compression and 1% axial compression.

Conclusions. CBE induced by motion critically limits temperature imaging and thus necessitates accurate motion estimation and compensation. Our current algorithm works effectively with motion studied in simulation and encountered in heating experiments. Future work will include incorporation of nonlinear motion field, estimation of motion in the presence of temperature-dependent CBE, reducing effects of decorrelation, and motion compensation on temperature imaging during clinical hyperthermia.

Background: Measured and Predicted Temperature Dependent CBE

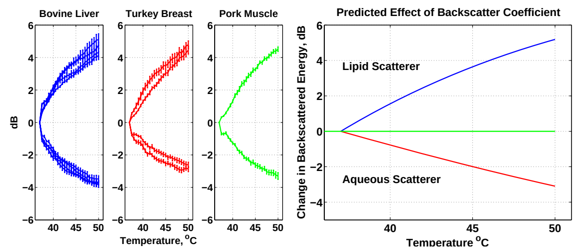

Figure 1. (Left) Positive and negative CBE from *in-vitro* experiments of bovine liver, turkey breast and pork muscle. (Right) Predicted CBE for single, sub-wavelength lipid and aqueous scatterers [1].

Motion Estimation and Compensation

Suppose $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ are the reference and the image with motion respectively, where $\mathbf{x}$ is the vector of the coordinate and $f_2(\mathbf{x}) = f_1(g(\mathbf{x}))$. The motion in the image is represented by transformation $g(\mathbf{x})$, which is composed as a vector field linearly varying between reference points (e.g. 4 corners of the image region) and estimated by maximizing the cross correlation between $f_1(\mathbf{x})$ and $f_2(g^{-1}(\mathbf{x}))$ using the optimization functions in Matlab®. Motion compensation is applied using cubic interpolation.

Estimation and Compensation of Non-rigid Motion in in-vitro Heating Experiments

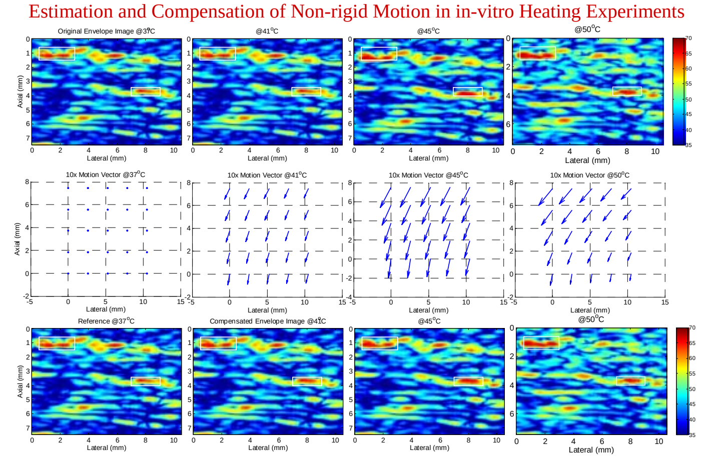

Figure 2. (Top row) Images of turkey breast at various temperatures. Apparent motion can be seen in images at 45 and 50°C. (Middle Row) Estimated motion field, which is non-rigid over the region and increases with temperature. (Bottom row) Images compensated for motion relative to the image at 37°C.

Objectives

- Development of non-rigid motion estimation and compensation algorithm.
- Study factors affecting CBE measures and motion estimation including decorrelation.

Methods

CBE Computation. Envelope images were smoothed with a 3x3 moving average filter. CBE was computed at each pixel as the ratio of pixel value at each temperatures with respect to the reference at 37°C. Means of the positive (ratio>1) and negative (ratio<1) CBE were then calculated in dB.

Simulations. Our simulations assume a linear-systems model of image formation [3]. The imaging system is represented by its point spread function. Scatterers are represented by point sources uniformly distributed in a 2D region. The resolution is approximately 0.32mm and 1.25mm for axial and lateral directions, respectively. Tissue motion is incorporated in the simulation by transforming scatterer locations, currently by scaling or displacement.

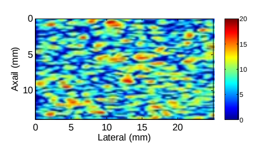

Figure 3. Typical Simulated Image [3].

CBE due to Motion

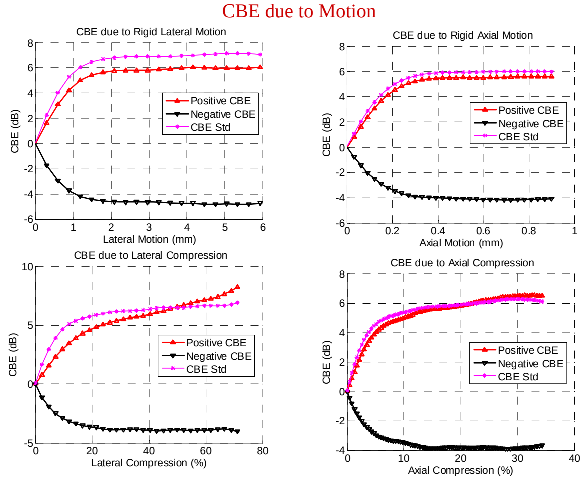

Figure 4. (Top row) Positive and negative CBE and its standard deviation due to rigid motion in both lateral and axial directions. CBE with motion approaches a limit at which images are completely decorrelated. CBE is then determined by the ratio of the variances of the two images. (Bottom row) CBE due to non-rigid motion. Positive CBE has no limit here because scatterer concentration increases with compression. Based on motion- and compression-induced CBE, accurate motion estimation and compensation will be critical for temperature imaging.

CBE due to Decorrelation

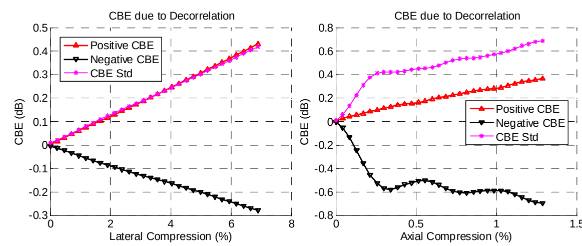

Figure 5. CBE is measured after the compression is compensated with true motion in lateral and axial direction respectively. In both cases, CBE increases with compression. This result indicates that decorrelation itself causes erroneous CBE.

Motion Estimation Error due to Decorrelation

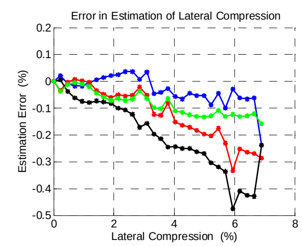

Figure 6. Error in estimation of lateral compression at the 4 reference points. The error can be as large as 0.5% and lead to 0.1~0.2dB of CBE, according to the CBE due to lateral compression in Figure 4.

Conclusions

Previous studies showed that CBE is a potential measurement for temperature imaging. From our study, it can be seen that motion induced CBE is, however, not insignificant and requires accurate motion estimation algorithm. The results from the *in-vitro* data showed that apparent motion, which was non-rigid and tended to increase with temperature, was compensated by our current algorithm. Although simulation results showed small error in motion estimation, the non-linear motion field and temperature effect have not been taken into account. Decorrelation was shown to be an important cause of estimation error and erroneous CBE. Based on results of motion-induced CBE, accurate motion estimation and compensation will be critical for temperature imaging during clinical hyperthermia.

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[1] WL Straube and RM Arthur, “Theoretical estimation of the temperature dependence of backscattered ultrasonic power for noninvasive thermometry”, Ultrasound in Med and Biol., 20:915-922, 1994.
[2] RM Arthur, JW Trobaugh, WL Straube and EG Moros, “Temperature dependence of ultrasonic backscattered energy in motion-compensated images”, IEEE Trans UFFC, 52:1644-1652, 2005.
[3] JW Trobaugh, RM Arthur, WL Straube and EG Moros, “A Simulation Model for Ultrasonic Temperature Imaging Using Change in Backscattered Energy”, Ultrasound in Med and Biol, in press, 2007.