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Motion compensation algorithm for stabilization of temporal variation in envelope statistical analysis

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1. Introduction

Non-invasive thermometry is needed for hyperthermia therapy of biological tissues. In our previous study, the temporal variation of the amplitude envelope was investigated using the Nakagami shape parameter to estimate the temperature change. The Nakagami shape parameter indicates the change in the scatterer number density caused by thermal expansion due to the temperature change, and there is a possibility that the temperature distribution can be visualized indirectly[1)].

Although we have previously suggested the possibility of evaluating the temperature distribution in *in vivo* rat tumor under hyperthermia therapy[2)], it is concerned that body motion causes misalignment of the region in the temporal analysis of the Nakagami shape parameter. This study verified the effectiveness of motion compensation algorithm by the block matching method through simulation and measurement data under different motion conditions.

2. Materials and Methods

2.1 Simulation condition

The heat conduction equation considering thermal expansion in a rigid material (cylinder of 100 mm diameter and 40 mm height, density of 1.0 g/cm^3, Young's modulus of 0.1 MPa, and Poisson's ratio of 0.48) with a linear stress-strain relationship was analyzed by the finite element method using the software (COMSOL Multiphysics) to calculate three-dimensional displacements and temperature distributions. The thermal properties of the material were as follows; linear thermal expansion coefficient of 150×10^{-6} K^{-1}; specific heat of 3000 J/kg/K; thermal conductivity of 0.6 W/m/K. The 30 W heat source was placed on the side of the cylinder, the initial temperature was set at 37 ℃.

First, the scatterers were randomly arranged in three dimensions at a scatterer number density of 20 sc/mm^3. The scatterer arrangement was successively updated by the displacement obtained in the finite element method analysis, and the radio-frequency (RF) echo signals at each time phase were numerically calculated using Field II[3)]. In addition, translational motions were applied in the lateral direction to reproduce the positional shift among temporal frames. The sound field was line-by-line imaging using a linear array probe with focused waves at a focal depth of 20 mm.

2.2 Data acquisition

Measurement data were acquired from 1% agar-1% scatterer phantom using a research ultrasound scanner (RSYS0016, Microsonic) and a 7.5 MHz linear probe (UST-5412, Fujifilm), which was the same as the simulation geometry. The sides of the phantom were covered with an electrode pad, and the phantom was heated by RF waves at 30 W from room temperature (24 ℃) to 43 ℃ using a heating machine (i-Booster, Tateyama Kagaku). A fiber-optic thermometer (m3300, Luxtron) was inserted at a depth of approximately 20 mm to measure the temperature of the phantom. Ultrasound data were collected in 0.5 ℃ increments (approximately every 2 to 3 minutes) starting at 37 ℃. The linear probe was moved by 0.1 mm pitch in the lateral direction using an automated stage.

2.3 Motion compensation algorithm

The displacement between two successive frames was estimated using the block matching (BM) method with a normalized cross-correlation function. The input data was the amplitude envelope of the beamformed RF data. The block size was 160×20 pixels (4×4 mm^2, depth × lateral directions), and search distance was 10 pixels for each direction. Each macroblock overlapped 80% in each direction. The normalized cross-correlation function was upsampled by a factor of 512 in each direction to estimate the sub-sample displacement. The 10-fold upsampled amplitude envelope by bicubic interpolation was locally compensated based on the estimated displacement in each block.

2.4 Envelope statistical analysis

The analysis window was scanned with 80% in the corrected amplitude envelope A to calculate the Nakagami shape parameter. The Nakagami distribution is defined as

$$P_{NA}(A|m,\Omega) = \frac{2m^m A^{2m-1}}{\Gamma(m)\Omega^m} e^{-\left(\frac{m}{\Omega}\right)A^2}, \qquad (1)$$

where Γ is the gamma function, m and Ω are shape and scale parameters of the Nakagami distribution. In addition, the absolute value of the change in the shape parameter, Δm [dB], was calculated to indirectly index the temperature elevation.

$$\Delta m = |10\log_{10}(m_t/m_{t=0})|. \qquad (2)$$

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The matrix of m at initial time $t = 0$ is used to normalize that at any temporal frame.

3. Results and Discussions

Figure 1 shows the estimated displacements for an arbitrary input of the displacement with or without heating and Δm change at each temperature. The displacements smaller than the pixel size between beamlines (0.2 mm pitch) could be evaluated by the interpolation function. The maximum relative error of the average estimated displacement to the input value was -17% at the input displacement of 0.01 mm. Moreover, the trend of Δm with several motions with or without heating deviated from that without motion where Δm rapidly increased near the initial temperature with the larger motion.

Figure 2 compares the calculated Δm (solid line) and displacement (dashed line) of the simulation and measurement data (mean of 3 phantoms) with or without compensation for displacement estimated by the BM method. The input of displacement in the simulation data is 0.1 mm. The motion compensation in the simulation data suppressed the rapid Δm temperature and reconstructed the same trend of Δm without motion. Although the overestimation of Δm in measurement data was also suppressed on average by the motion compensation, the compensated Δm was varied in higher temperature against the case without motion in comparison to the simulation result. The difference of fluctuation of speckle pattern caused by the change in speed of sound and shift in the slice direction would be accumulated as the mismatch of compensated amplitude envelope with larger motion from the initial frame.

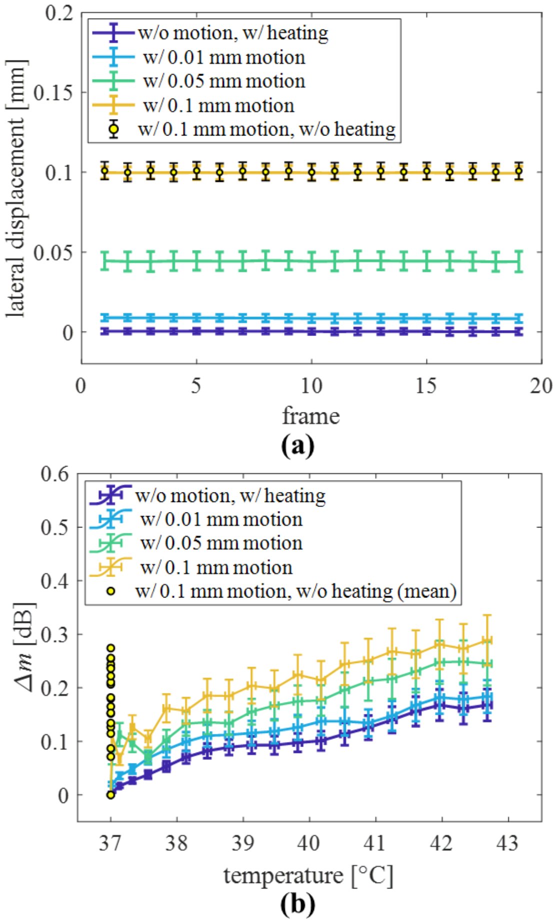

Fig. 1 Estimated displacement and Δm change in each temperature with or without heating.

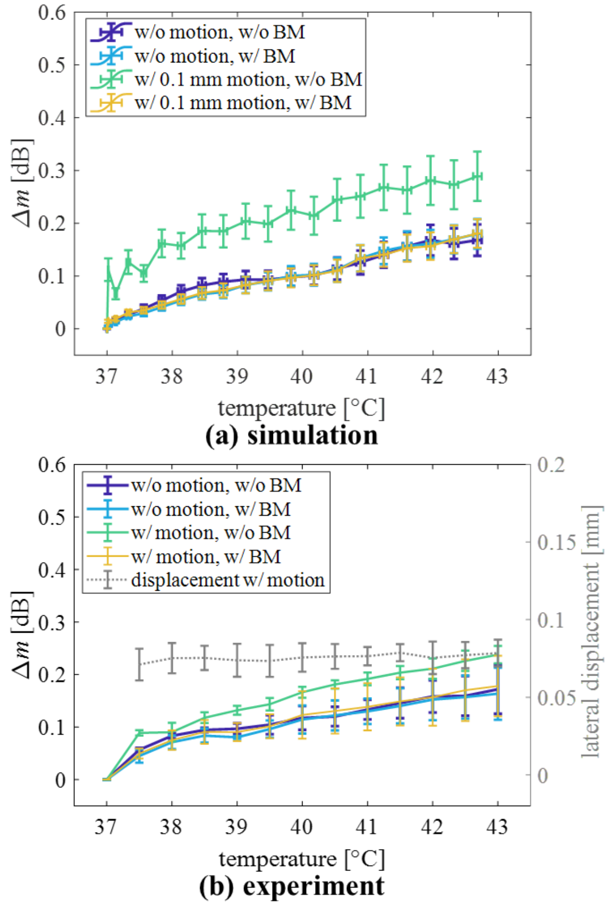

Fig. 2 Δm at each temperature in simulation and experimental (mean of 3 samples) results.

4. Conclusion

Motion compensation algorithm for a stable analysis of temporal variation of envelope statistics was examined in simulation and measurement data with temperature changes and displacement. In future work, the motion compensation algorithm will be applied to *in vivo* rat and human data to perform a robust analysis with body motion.

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References

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