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Simulation study to evaluate variable factors of Nakagami parameter due to temperature change

温度変化による仲上パラメータの変動要因のシミュレーション評価

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1. Introduction

An envelope statistical analysis method using Nakagami parameter can characterize the differences of scatterer number density and scatterer homogeneity in the biological soft tissues. Our previous studies have indicated the absolute value of the ratio change of Nakagami parameter visualized the temperature change inside tissue-mimicking phantoms, *ex-vivo*, and *in-vivo* biological soft tissues [1,2]. Although the variable factors of Nakagami parameter are considered to be caused by differences of the scatterer structure due to thermal expansion, it is necessary to provide evidence of this phenomenon. This study aims to clarify how thermal properties and scatterer structure such as scatterer number density effect the change of Nakagami parameter using the simulation approach.

2. Materials and Methods

2.1 Calculating temperature and displacement

Three-dimensional (3D) displacements and temperatures considering thermal expansion inside the cylindrical linear elastic solid (hight 20 mm; diameter 70 mm; density 1000 kg/m; Young modulus 0.1 MPa; and Poisson's ratio 0.48) were calculated using simulation software of COMSOL Multiphysics (COMSOL Inc.) based on the finite element method (FEM) as described in **Fig. 1**. Once scatterers were randomly distributed with the number density of 40 sc/mm^3 (15 sc/point spread function), their positions were sequentially updated utilizing the 3D displacements in 1 mm interval obtained from the FEM simulation. Thermal properties of this solid were variable with the thermal expansion coefficient (100 to 900×10^{-6} K^{-1}), thermal conductivity (0.1 to 1.0 W/m/K), and specific heat (2000 to 4000 J/kg/K).

The temperature on the side of the cylinder was heated up to 42°C at the initial temperature of 20 °C within the time range from 0 to 50 min. Only a plane surrounding the ultrasound probe position was free-restrained to calculate the displacement as well as all boundaries were insulated. The simulation geometry was assumed to be same as the previous experimental study of tissue-mimicking phantom [2].

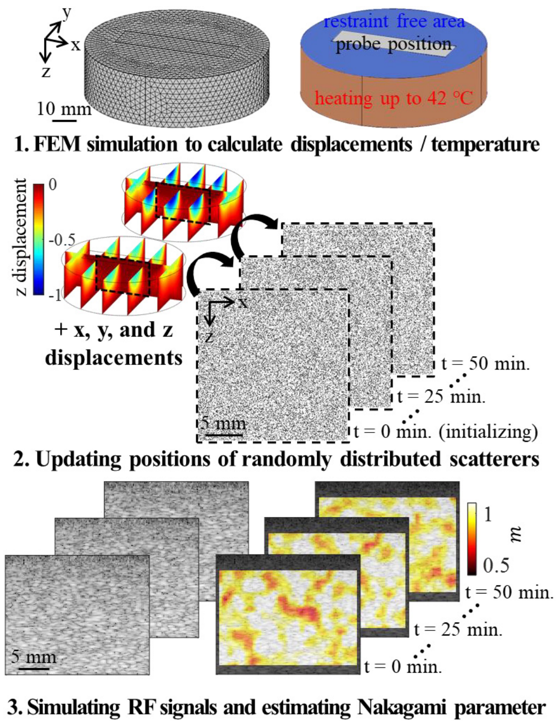

Fig. 1 Schematic diagram of simulation study

2.2 Simulating RF signals and evaluation

Radio-frequency (RF) echo signals from scatterers distribution in each time sequence were simulated using simulation software of Field II [3]. The scatterer amplitude of all scatterers was same as 1. A linear array transducer with line-by-line focused imaging was considered for transmission and reception of sound field. The center frequency of transmission was 7 MHz. Its excitation and impulse response were 2 waves of a sinusoid and were convolved it with Gaussian window with 50% fractional bandwidth at −6 dB, respectively. The sampling frequency was 31.25 MHz, and the pitch of scan lines was separated by 0.20 mm. The speed of sound was 1540 m/s.

The amplitude envelope A was calculated as the norm of the Hilbert transform of the RF signal in each scan line. Nakagami parameter m as defined in Eq. 1 was estimated using the moment method [4] of A in a local window (1.8 × 1.8 mm^2 in depth × lateral directions), and the window was shifted in two-dimension with 50% overlap.

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

where Ω is scale parameter, and Γ is the gamma function.

3. Results and Discussions

Figure 2 displays the example of spatial distributions of temperature, scatterer number density changes, and mean of the absolute logarithmic Nakagami parameter at each time was normalized with that at 0 min., i.e., $\Delta m = |10 \times \log_{10}(m_t/m_{t=0})|$. Scatterer number was locally counted in a region of 1 mm^3 at the center slice locating ultrasound probe, and it was also normalized with the initial value to indicate its absolute change. Noted that the temperature change was calculated by subtracting initial temperature. Δm randomly increases with a large scatterer number density change as well as a rise in temperature.

Figure 3 shows the relationship among temperature, scatterer number density changes, and Δm (mean and standard deviation). Although the temperature change is same in each time sequence independent of the thermal expansion coefficient, Δm is biased with increasing the thermal expansion coefficient as shown in Fig. 3(a-1). In contrast, Δm is continuously increased with increasing scatterer number density change [Fig. 3(a-2)]. As shown in Fig. 3(b-1), the slope of Δm versus temperature change is different in association with the thermal conductivity, that is, the speed of heat transfer, whereas the shift of Δm corresponds to the scatterer number density change at any thermal conductivities [Fig. 3(b-2)]. Thus, the shift of Δm indirectly associates with scatterer number density difference due to temperature change of the thermal expansion. Besides, the difference of thermal properties such as thermal expansion coefficient and thermal conductivity needs to be considered to monitor the temperature change inside specific biological tissues. Incidentally, the specific heat differences occur about 1 to 2 °C temperature change, however Δm and scatterer number density are same regardless of the specific heat differences as shown in Figs. 3(c-1) and (c-2).

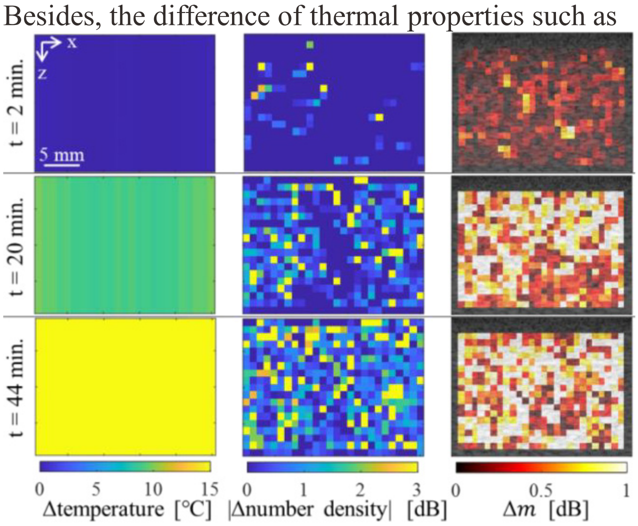

Fig. 2 Example of spatial distributions of temperature, scatterer number density changes, and Δm at thermal properties of 500×10^{-6} K^{-1}, 0.6 W/m/K, and 3000 J/kg/K.

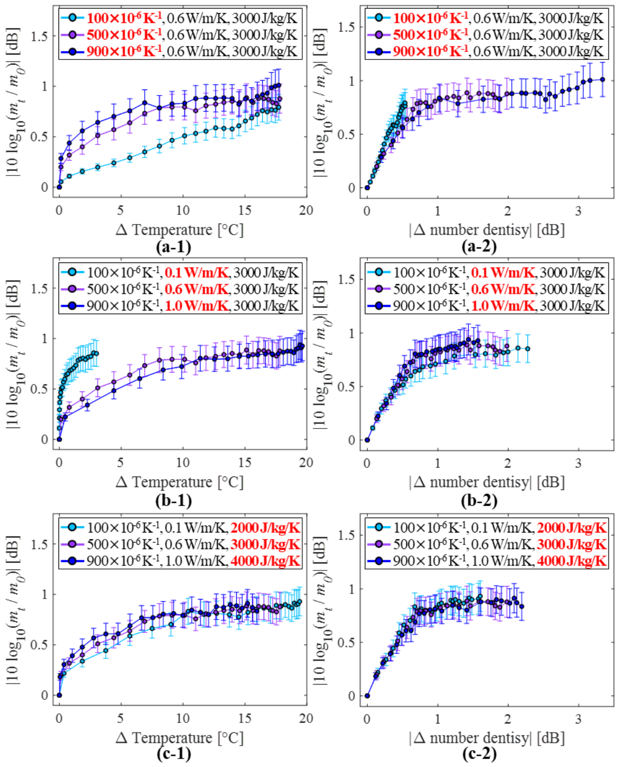

Fig. 3 Relationship among temperature, scatterer number density changes, and Δm depending on different thermal properties of thermal expansion coefficient (a), thermal conductivity (b), and heat transfer rate (c).

4. Conclusion

Simulation study verified that the changes in Nakagami parameter was caused by scatterer number density differences due to the temperature change. Furthermore, the relationship between Nakagami parameter and scatterer number density changes depended on the thermal properties such as thermal expansion coefficient and thermal conductivity. In future works, these findings of simulation study are compared to those of experimental data.

References

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