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Simulation study of ultrasonic focusing for the hip joint using 3D X-ray CT data

3D-CT データを用いた股関節近傍への超音波集束シミュレーション

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1. Introduction

Due to the increase of elderly population, fractures of proximal femora have become serious problems. This fracture causes bedridden and has a major impact on mortality. Therefore, the strength of femoral neck is an important factor. Clinical studies of Low Intensity Pulsed Ultrasound (LIPU) have reported the reduction of the healing time of bone fracture. The local ultrasound stimulation may promote active bone metabolism[1)].

In this study, for the ultrasound stimulation of hip joint with femora, installation positions of ultrasound transducers were examined. A three-dimensional wave propagation simulation using Finite Difference Time Domain (FDTD) method[2)] was performed to analyze of ultrasound wave propagation in a 3D digital human femur model.

2. Simulation of ultrasonic wave propagation

2.1. Simulation conditions

A digital model of a human proximal femur was created from the High Resolution-peripheral Quantitative CT (HR-pQCT) data of a woman (73 yrs) (permitted by ethics committee at Doshisha univ. and Nagasaki univ.). Figure 1 shows a cross section view of the model. In order to examine the focusing at the femoral neck, the proximal femur was classified into three areas. The spacial resolution of the model was 305 µm, and the time resolution was set to 41 ns considering the Counrant's stability condition[3)]. For eliminating the reflected waves from the end of the model, Higdon's second order was used as absorbing boundary conditions[4)]. Figure 2 shows the simulation model. The femur model was assumed to be surrounded by the columnar water simulating soft tissue. Assuming the bone was isotropic, we estimated elastic constants in the model. c_{11} was estimeted following the studies of Yamato et al[5)]. c_{44} were estimated using Poisson's ratio of 0.33[6)]. c_{12} was estimeted following the studies of Nakatsuji et al[7)]. The density of femur was 2000 kg/m^3.

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2.2. Virtual ultrasound radiation from the inside of hip joint

Two step simulations were performed. At first, ultrasound was transmitted from the inside of hip joint and observed at array transducers as shown in Fig. 2. This transmission point in the femur is the expected focal point in the next simulation. Here, the longitudinal wave velocity in water was 1500 m/s and the density was 1000 kg/m^3. Radiated wave from the inside of femur was a single sinusoidal wave at 100 kHz with Hann window.

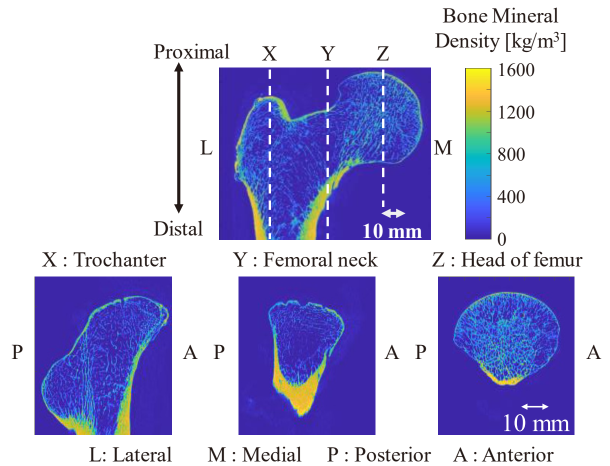

Fig. 1 The digital femur model.

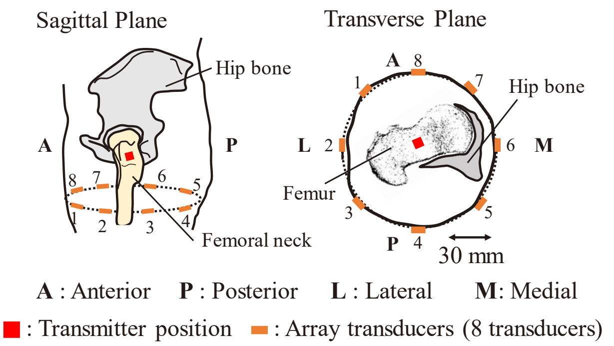

Fig. 2 Simulation conditions of the first step. Transmission from the central transducer.

2.3. Re-radiation from outside transducer

Next, re-radiating waves were emitted from the array transducer positions to focus waves at the transmission point in the femur. In order to develop a practical and simple system for future instrumentation, the re-radiated wave was one cycle of sinusoidal wave with time delay due to the arrival time of observed waves. Figure 3 shows observed waveforms at each transducer. Re-radiated waves were emitted only from the transducers at medial sites (5-8) where the amplitudes of the observed waves were large. The stress values of the femur were obtained from the simulation of re-radiated waves and discussed.

3. Results and Discussions

Figure 4 shows the average stress observed in each area (X, Y and Z) shown in Fig. 1, until 120 μs after re-radiation. From Fig. 4, it can be seen that high stress was observed at femoral neck compared to other areas.

Figure 5 (a) shows stress distributions inside the proximal femur at 120 μs after re-radiation. Figure 5 (b) shows the average stress observed in each area at 120 μs. The horizontal axis represents the distance from the proximal site. Fig. 5 (b) shows that higher stress was mostly observed in the distal part of the femur and femoral neck area. In this study, ultrasound may be focused on distal part of hip joint rather than that of proximal part because of installation positions of transducers.

These results suggest that stress may be focused on the femoral neck using simple waves radiated from transducers. In the next step, it is necessary to investigate more optimal locations of the transducer arrays on the skin surface in order to improve irradiation efficiency.

4. Summary

In this study, a three-dimentional elastic femur model was created from the in vivo HR-pQCT data. Then, focusing of the ultrasonic waves was challenged using a 3D FDTD method. Here, ultrasonic transducers were set on the virtual body surface. As a result, ultrasonic wave seemed to be focused on the femoral neck. Next step is the optimization of transducer positions.

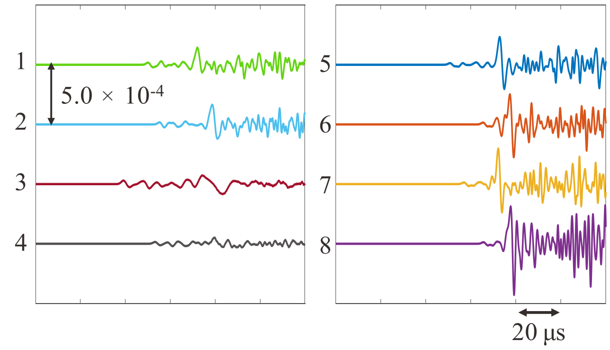

Fig. 3 Observed waveforms at each transducer.

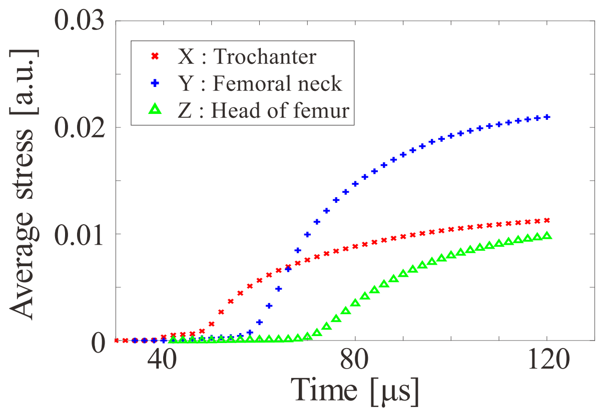

Fig. 4 Average stress observed in each area.

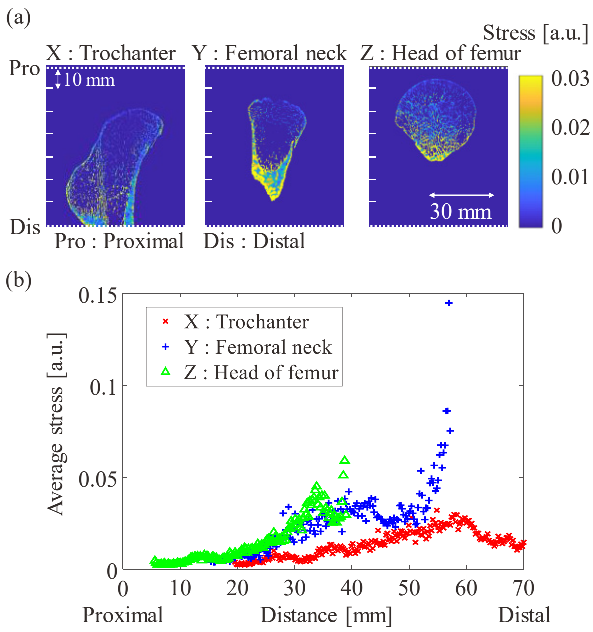

Fig. 5 (a) Stress distributions inside the bone at 120 μs after re-radiation. (b) the average stress observed in each area at 120 μs.

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