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Control of ultrasound irradiation on long bone: a simulation study

長骨中の超音波照射制御シミュレーション

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1. Introduction

Recently, clinical studies of Low Intensity Pulsed Ultrasound (LIPU) have reported the reduction of the healing time of bone fracture. However, ultrasound propagation in the human body is complex. Current LIPU system does not consider the sound field in the body. In this study, a method to converge the ultrasonic wave to the bone fracture site was investigated by the simulation of Finite Difference Time Domain (FDTD) method [1]. For, this purpose, a human radius bone model was constructed by the data of High Resolution-peripheral Quantitative CT (HR-pQCT), which was uniaxial anisotropic and heterogeneous.

2. Wave propagation simulation

2.1. Radius bone model

A 3D human radius bone model was constructed using HR-pQCT data of 66 years old female. Figure 1 shows the cross-section of the bone model. The spatial resolution of the model was 61 μm. The local bone density distributed in the range of 1500 – 2400 g/cm^3. We assumed that bone was uniaxially anisotropic and estimated the elastic constants [2]. For c_{33}, the average value of longitudinal wave velocities in the axial direction was used [3]. c_{11} was estimated using the ratio of the wave velocities in the axial and radius directions [4]. c_{44} and c_{66} was estimated assuming that Poisson's ratio was 0.33 [5], and c_{13} was estimated by wave velocity anisotropy of bone [6].

2.2. Ultrasound radiation from bone fracture site

For the wave convergence on the fracture site, we performed two simulations. At first, ultrasound was transmitted from the virtual fracture site and observed at the array transducers as shown in Fig.2. This virtual fracture site was the wave convergence target in the next simulation. Here, the bone model was immersed in water for simulating a soft tissue and the outside of water was set as vacuum. Longitudinal wave velocity and density in water were 1500 m/s and 2000 g/cm^3, respectively. The radiated wave from the virtual fracture site was a single sinusoidal wave at 1 MHz with Hann window. Each transducer was placed with tilted angle of 30 degrees (the critical angle of longitudinal wave) at 30 mm from the virtual fracture site. At each cross section, 8 transducers were placed with every 45 degrees and the radius of the array was 10 mm. The transducer size was 1×3 mm^2, following the transducers of the axial transmitting technique. For eliminating the reflected waves from the end of the model, Higdon's second-order was absorption condition was used. Figure 3 shows waveforms observed by the array transducer placed at the proximal side.

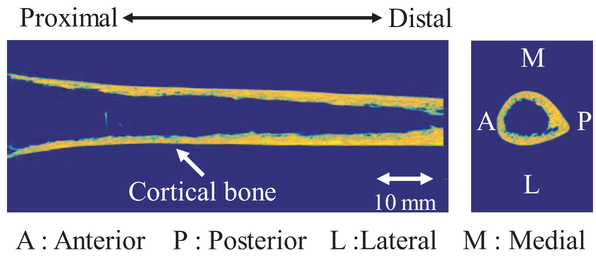

Fig. 1 3D human radius bone model created by HR-pQCT.

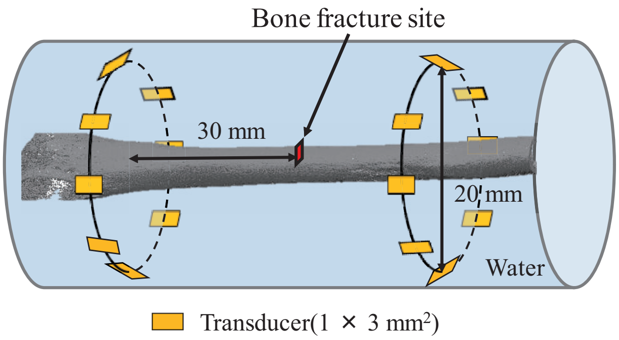

Fig.2 Simulation conditions.

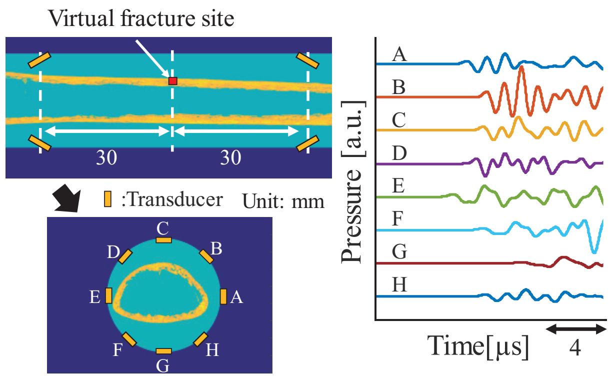

Fig.3 Observed wave forms at the array transducer placed at the proximal part of bone model.

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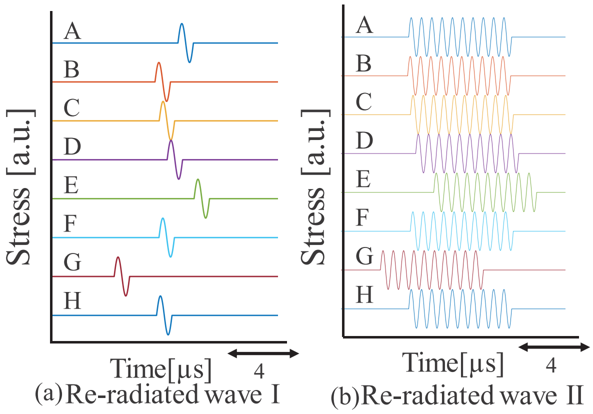

Fig.4 Re-radiated waves. (a) One sinusoidal wave. (b) 10 cycles of sinusoidal wave.

2.3. Re-radiation of ultrasound

Next, wave convergence on the fracture site was tried by re-radiating waves from array transducers. For simplicity, re-radiated waves were made from the arrival time of the first simulation. Waveforms are shown in Fig.4(a). Input signal was 1 cycle of sinusoidal wave at 1 MHz with Hann window (wave I). Furthermore, the other re-radiated waves with 10 cycles of sinusoidal wave were also used as shown in Fig.4(b) (wave II). The simulation conditions for transmitting re-radiated waves were same. The stress values at the cross section of bone fracture site were obtained from the simulation.

3. Results and discussion

Figures 5 (a) and (b) show the observed waveforms at the virtual fracture site. The sound fields at 17.6 μs (arrival time of the fast peak) are shown in Figs.6 (a) and (c). The highest stress values were observed near the virtual fracture site in both cases. Sound fields at 26.8 μs are also shown in Figs.6 (b) and (d). We can confirm that the re-radiated wave I was not well converged after the initial peak, however the re-radiated wave II converged near the virtual fracture site continuously after the initial peak. However, during wave propagation, multiple reflections and leaky waves also reached the bone fracture site and high stress values were observed at a lot of parts in the cross section of the bone fracture site. Eventually almost similar stress value was observed in most part of the radius bone model (Fig.6 (e)). The indicates that we can sonically stimulate the fracture site by the transmitter far from the site, however, more effective and simple procedure should be considered for the next step.

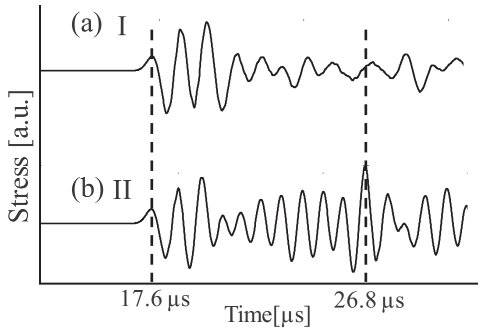

Fig.5 Observed waveforms at the bone fracture site in the cases of re-radiated wave I and II.

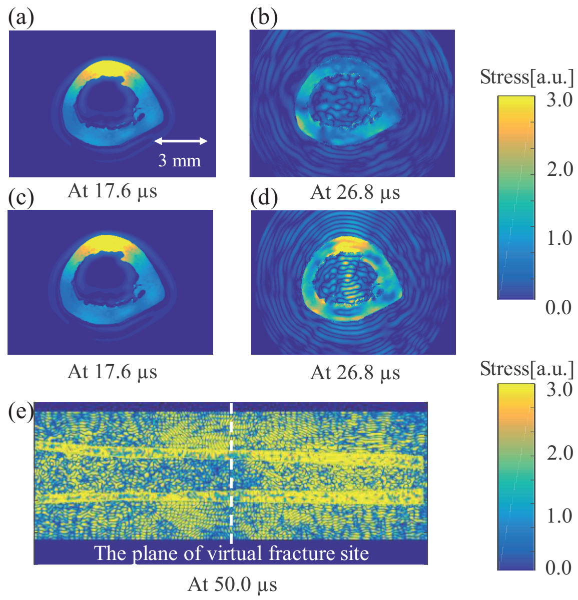

Fig.6 (a) and (b) are the sound field at 17.6 and 26.8 μs in the case of wave I (one cycle). (c) and (d) are in the case of wave II (10 cycles). (e) is the sound field at 50 μs in the case of II.

4. Conclusion

For the effective ultrasound radiation on a fracture site in bone, wave propagation simulations were performed. Ultrasound could converge or can propagate near the fracture site by the simple technique. For the future development of the LIPU, a simple and effective system may be useful for daily clinical scene.

References

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