Proceedings of Symposium on Ultrasonic Electronics, Vol. 33 (2012) pp. 501-502
13-15 November, 2012

# Long-Distance Propagation of Ultrasound in Human Body
## - Experimental and Numerical Study using 3-D Elastic Human Model
## 人体内の超音波の長距離伝搬 ― 実測と３次元弾性モデルを用いたシミュレーション

Yoshiki Nagatani (Kobe City College of Technology)
長谷芳樹 (神戸市立工業高等専門学校)

### 1. Introduction

Three-dimensional digital elastic model for acoustic simulation including whole human body was constructed by Nagatani *et al.*[1,2], however, the confirmation of the reliability of the simulation results is inadequacy because of the lack of precise comparison between experimental observations. If the reliability of an acoustic simulation system including whole body was confirmed, it will be useful for medical, welfare, and engineering applications. Therefore, a comparative study of experimental measurement and numerical study was investigated in this study focusing on the long-distance ultrasonic wave propagation mainly in inferior limb.

### 2. Experimental Measurement

Experimental measurements of ultrasonic propagation in human body were performed employing 20 male participants (20-63 years old). **Figure 1** shows the measurement system. A single pulse of ultrasound at 20 kHz was impressed to right heel (under the calcaneus) via a piezoelectric transmitter. The receiver, an acceleration sensor, was attached on the greater trochanter of right femur. The received waveform was observed by an oscilloscope.

A typical received waveform is shown in **Fig 2(a)**. Clear wave separation can be seen. This separation is considered to be come from the overlapping of multiple waves whose propagation paths are different. In order to clarify the overlapping point quantitatively, instantaneous frequency (IF) analysis shown in Fig. 2(b) was used concomitantly[3,4].

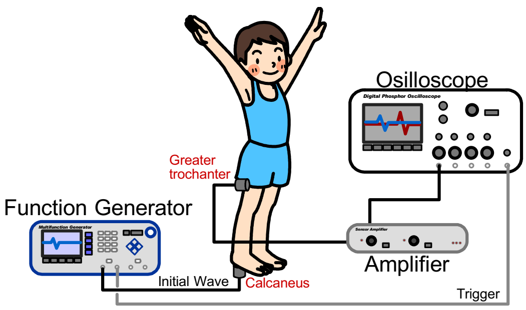


Fig.1 Measurement system.

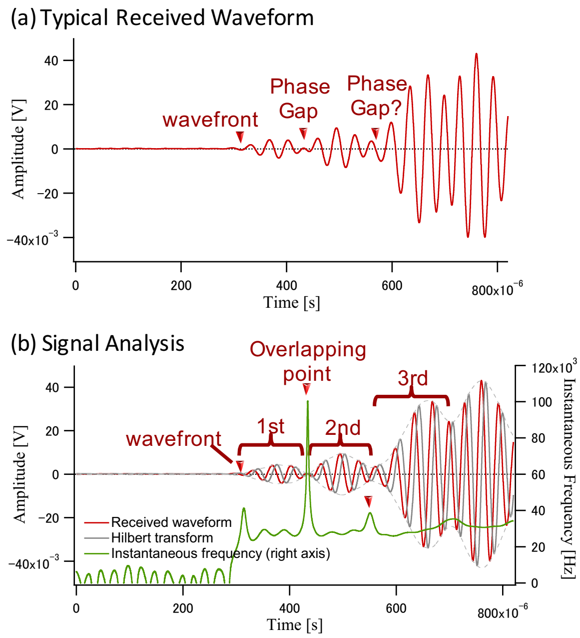


Fig.2 Typical measured waveform and waveform analysis using instantaneous frequency.

### 3. FDTD Simulation

As a three-dimensional simulation model, the male data in the "Realistic High-Resolution Whole-Body Voxel Models" constructed by Nagaoka *et al.* was used [5]. The model describes consisting tissues of normal Japanese person with the resolution of 2 mm³.

Using this model, elastic properties of the tissues are assigned to water, fat, cortical bone, bone marrow, and air. Experimentally measured values are used for the elastic coefficients of cortical bone and bone marrow[6,7]. **Figures 3** show the perspective diagram of simulation model. In addition, in order to confirm the contribution of the bone portion, a virtual model, called "Jelly Fish" model, whose bone portion were replaced by soft tissue was assumed as shown in Fig 3.

As an initial waveform, a single sinusoidal pulse at 20 kHz was virtually impressed to the right heel as shown in Fig. 3. The wave propagation was calculated by three-dimensional elastic FDTD (finite-difference time-domain) method developed by our team.

**Figures 4** show the calculated waveform. Clear wave separation can be seen. However, the amplitude of the third wave was quite huge compared to experimental measurements. This is considered to caused by the attenuation coefficients of soft tissue. In case of the “Jelly Fish” model, the primary group could not be seen. This tells us that the first wave propagates in bone portion.

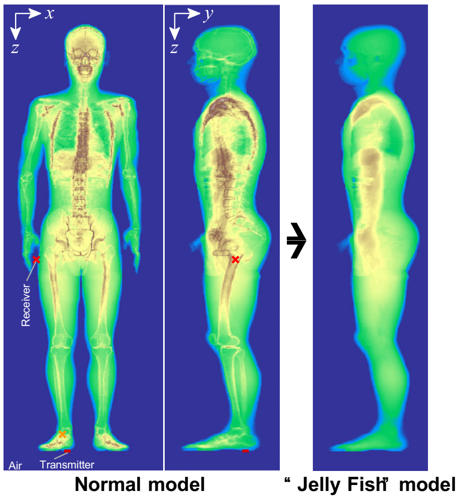


Fig.3 Perspective diagrams of the acoustic impedance of the 3-D simulation model.

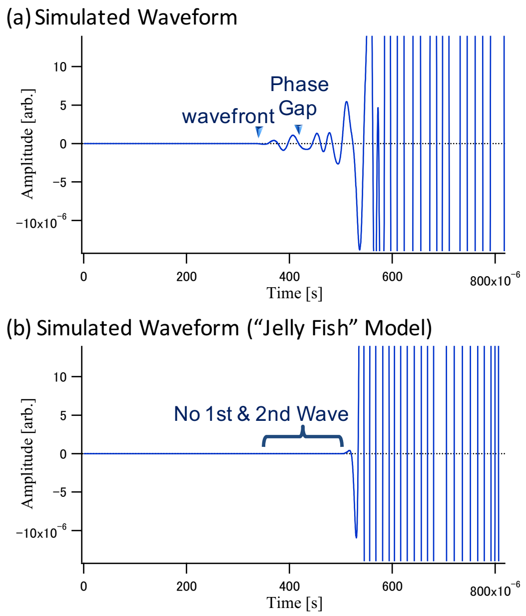


Fig.4 Simulated waveforms.

## 4. Discussions

The wave speeds of three waves derived from the wavefront (first wave) and IF (second and third wave) are shown in **Fig 5**. The speed was calculated using the arrival time and the direct distance between transmitter and receiver. The measured data shown in Fig. 5 indicate the mean values of 20 participants. As a result, the measured data and simulated data showed similar tendencies.

The speed of the first group of the observed waveform (about 2500 m/s) was much faster than that in soft tissues (about 1400-1500 m/s) or water. In consideration of these results, the first wave obviously propagates in bone portion and may reflect the bone structure of inferior limb. The effect of bone quantity or bone quality should be checked in the future work.

Since the second group also propagates faster than soft tissue, it is natural to explain that the group propagates both in bone and soft portion sequentially. On the other hand, the speed of the third wave was similar to that in soft tissues. This implies that the third wave did not propagate in bone portion. To understand the detailed behavior, the precise mechanism also should be revealed using simulation techniques in the future work.

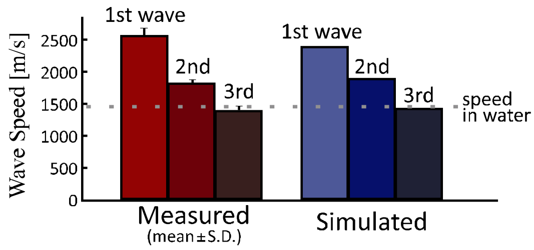


Fig.5 Measured and calculated wave speeds.

## 4. Conclusion

A comparative investigation of experimental measurement and numerical study of ultrasound propagation in human inferior limb was performed. As a result, clear wave separation caused by multi-path effect in bone and soft tissue portion could be observed. The fastest wave propagated in bone portion. This interesting behavior, that is to be investigated in the future work, may reflect the bone quality of human body.


## Acknowledgment

This study was partly supported by Research Grant by Kobe City College of Technology and Grant-in-Aid for Scientific Research (B)(24360161) by JSPS.


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