Simulation Study Correlation of Ultrasound Wave with Two Orientation of Cancellous Bone

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***Abstract*—Ultrasound technology offering a safer and inexpensive method compared to X-ray densitometry to evaluate bone quality in order to predict fracture cause by osteoporosis disease. Yet, dual X-ray absorptiometry still become choice due to its accuracy and reliability to predict fracture risk compared to quantitative ultrasound (QUS). Moreover, QUS method also isn't fully exploiting interactions between ultrasound wave and bone structure orientation. Hence, this paper is focused on investigation of fast and slow wave propagation in cancellous bone by manipulating vertical (y) and horizontal (x) direction of bone structure orientation. Using Finite Difference Time Domain simulation software, 50 Volt peak-to-peak of the Sine Gaussian wave is transmitted through cancellous bone model as well as setting up other parameter. The result shows that, at the y-direction, first and second wave which have similar behavior with fast and slow wave was observed in time domain at the earlier of wave arrival. The results also have a good agreement with other research where fast and slow wave can be clearly observed in time domain depending on cancellous bone orientation. Besides, future study will focus on analysis of fast and slow wave in overall backscattered wave using Pulse Echo measurement technique.**

***Index Terms*—Cancellous Bone; Fast and Slow Wave; FDTD; QUS.**

I. INTRODUCTION

Ultrasound is a cyclic sound pressure with frequencies greater than 20 kHz, the limit of human hearing [1, 2]. For bone densitometry application, the frequency range of the ultrasound wave is usually around 0.2 to 2 MHz, which is lower than the frequencies used for conventional ultrasound imaging due to bone highly attenuated nature [3]. As an introduction to bone, bone can be characterized into cortical (compact) and cancellous (also known as trabecular or spongy) bone [4]. Osteoporosis disease is famously known worldwide as metabolic bone disease [5] which affects bone quality and increases fracture risk among elderly people especially postmenopausal women. Osteoporosis causes cortical bone thinning and cancellous bone perforation [6] as well as diminishing of the overall bone strength and weakened capacity to resist fracturing [7].

Hence, the primary method for diagnosing osteoporosis and associated fracture risk relies on bone densitometry to measure bone mass [8]. The density of the bone corresponds to bone mass density (BMD) which can be measured with dual X-ray absorptiometry (DXA) to predict fracture [4]. DXA is the standard diagnostic method for osteoporosis assessment which is considered as the 'gold' standard to BMD at the hip, spine, and forearm [8, 9]. Nevertheless, DXA are not widely available due to its high expense, inconvenience, and the reluctance among patients concerning X-ray exposure, mainly in young adults and children [8]. Due to the problem, a safe and inexpensive method of Quantitative Ultrasound (QUS) was introduced [10]. Based on two parameters which are attenuation and velocity, ultrasound wave can provide information regarding of bone structure [3]. Still, QUS has not fully exploited the potential of ultrasound wave because the wave measured is only overall waves and cancellous bone is proven support two modes ultrasound wave that might provide more accurate information regarding of bone microstructure [11].

Thus, the main motivation of this paper is to conduct a Finite Difference Time Domain (FDTD) simulation of ultrasound wave propagation through cancellous bone to observe the existence of fast and slow wave. The simulation also conducted to observe the propagation fast and slow wave toward two differences (vertical and horizontal) direction of wave propagation in cancellous bone.

II. QUANTITATIVE ULTRASOUND

The concept of QUS is transmitting of ultrasound wave through bone to measure density, elasticity and structure of the bone. Both velocity and attenuation of the ultrasound propagation wave are affected by the medium. Therefore, bone tissue either soft or hard tissue is characterized in terms of ultrasonic velocity and attenuation [8]. The main contributions of attenuation of bone are absorbing and scattering due to its internal material [12-14]. Moreover, there are several techniques to measure ultrasound wave correlation on bone. However, only through-transmission technique has been used to research fast and slow wave thoroughly in experiments and simulations.

A. Through-transmission

Through-transmission (TT) technique is the earliest technique used to measure the quality of the heel bone. The basic concept of TT measurement technique is with pair of ultrasound transducer which acts as a transmitter and the other one acting as a receiver which is placed facing with each other [3, 10, 15]. The transmitter emit ultrasound wave which passes through the bone specimen and received at the receiver. Conventional QUS method analyzes attenuation using this technique, namely Broadband Ultrasound Attenuation (BUA) which basically compared between attenuation of receiving a wave through the bone specimen and through water only. Another analysis can be used by using this technique is speed of sound (SOS) and expressed in (m/s). SOS measurement is capable to estimate density and elasticity of the bone [15, 16].

III. Fast and Slow Wave

Ultrasound waves propagate through cancellous bone has been observed to support two modes of ultrasound wave. This phenomenon has been predicted by Biot's theory which adopting the theory of geophysical testing of porous rock [17]. The Biot's theory predicts that two longitudinal waves, is able to propagate through a fluid saturated porous elastic solid [11, 18]. The fast wave is characterized as in-phase and slow wave is out-phase wave between fluid and solid [19]. Parameter of fast and slow wave is able to provide the speed and amplitude that have correlated with bone parameters [20-26].

Hence, recovering the ultrasound properties of the individual fast and slow wave, as an alternative of the overall waves, may lead to improvement of bone quality assessment [17]. Several considerations must be done to ensure clear observation of fast and slow wave especially in time domain. The first consideration is to use a very short pulse wave [11]. The second consideration is depending on the direction of wave propagation relative to the anatomical orientation of cancellous bone. Fast and slow wave have been observed in time domain at the direction parallel to cancellous bone main trabecular alignment [11].

IV. Material and Methods

Brief explanation of the simulation is based on the FDTD environment to simulate the propagation of ultrasound wave through cancellous bone model. FDTD based simulation also has become an option for several researchers to investigate correlation between ultrasound and bone [27, 28]. Furthermore, the transmitting technique using is TT. The received waveform is observed in order to determine the existence of fast and slow wave

Table 1
Material Properties

Simulation material	Density	Velocity
Bone	1.85 g/cm^3	Bulk: 2900 m/s, Shear: 1300 m/s
Water	1 g/cm^3	1497 m/s

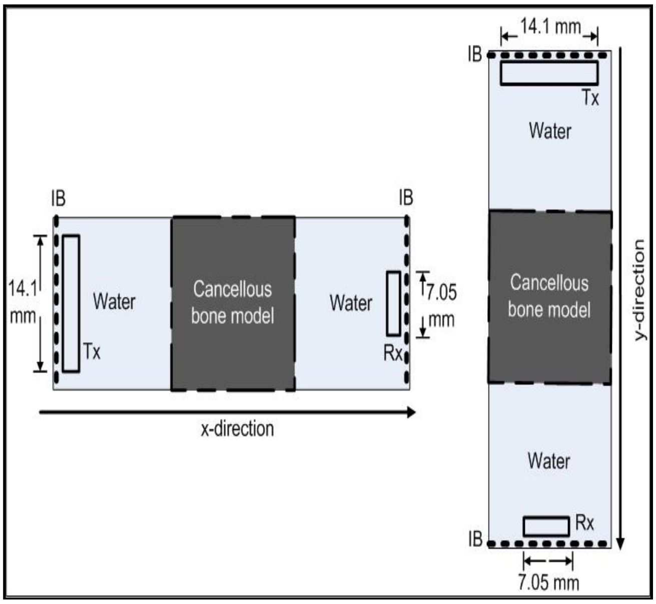

Figure 1: Simulation diagram

There are two propagation directions for this simulation which is an x-direction and y-direction. The result is centered on an observation on the differences in terms of amplitude of fast and slow waves.

A. Simulation software

The simulation software used is Wave3000 (Wave3000 CyberLogic®, Inc., New York, NY) which is a 3D FDTD simulation environment. This software is created mainly for ultrasound wave propagation FDTD investigation. In addition, this software is easy to use and complete with necessary requirement to run ultrasound wave simulations such as to create source pulse, transmitter, receiver, boundary condition and others. Moreover the software is also equipped with the designated bones template (calcaneal site) that has been characterized by its properties (Table 1) which based on real bone properties.

B. Simulation set-up

Based on TT technique, the pulse wave generator is set to 50 Voltage peak-to-peaks (Vpp) with Sine Gaussian waveform as shown in Figure 3. The ultrasound frequency is set to 1 MHz which is common frequency value for bone related measurement [3, 29].The ultrasonic transmitter (Tx) is set to be planar type with the diameter of 14.1mm. For the receiver (Rx) part, the diameter is set to 7.05mm. The distance between Tx to cancellous bone and cancellous bone to Rx is similar. However, the distance between the Tx – cancellous bone – Rx was not specified for this simulation since the purpose is to observe the existence fast and slow wave.

Standard boundary condition for x-direction ultrasonic wave propagation simulation was set for z-plane and y-plane. For x-direction, at the x-plane, infinite boundary (IB) condition was set to eliminate the effect of reflection in that direction and act as wave absorber. The use of standard boundary conditions is to eliminate reflections in vertical displacements and only allow reflection on horizontal displacements. Furthermore, standard boundary condition for y-direction ultrasonic wave propagation simulation was set for z-plane and x-plane. At y-plane, IB condition was also set.

The cancellous bone model is a template model provided by the Wave3000 for study purposes as shown in Figure 2. The dimension of the cancellous bone model is 1 × 0.8 × 0.3 mm^3. The bone marrow's material properties were set similar to water. The medium between Tx – cancellous bone – Rx is also water as shown in Figure 1.

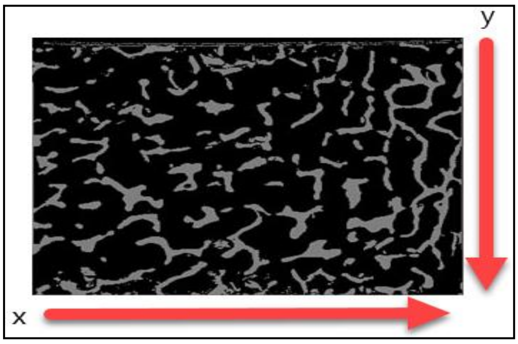

Figure 2: Bone model template diagram. The gray color corresponds to bone and black color is corresponds to bone marrow (water).

V. RESULT AND DISCUSSION

All waveforms from simulation software Wave3000 was saved in text document and the discrete value saved was plotted back using Matlab software (Mathworks Inc., USA). Figure 3 shows the output waveform from the transmitter which is propagating through water only. The Vpp is 48 Volt, which is not changing much compared to Vpp that has been set earlier. This is due to water is a good medium for ultrasound wave to propagate with less attenuate and can travel farther.

Figure 4 and Figure 5 shows a received waveform propagate to the x-direction and y-direction of the cancellous bone captured by the receiver, respectively. Note that the time of arrival of ultrasound wave between x-direction and y-direction is different due to the differences in propagation distance. Both waveforms arrived at the receiver started with small in amplitude because the source of the first arriving wave is directly through cancellous bone. The later wave (x-direction after 2.15 µs and y-direction after 2.3 µs) is assumed arrived from reflected wave between solid parts of cancellous bone.

Moreover, referring to Figure 5, at the beginning of ultrasound wave arrival at the receiver for y-direction, it can be observed there are two modes longitudinal waves which is similar in shape to the of transmitting pulse. However, different happened to the x-direction, where at the beginning of wave arrival, the receiver did not show clearly any sign of two modes longitudinal waves in time domain. The result is supported with Figure 6 which shows x-direction enlarged received waveform.

Figure 7 shows two waves, first and second wave which for this case is correspond to fast and slow wave. The first wave maximum amplitude is very small in about 1 µV. The resolution for the receiver to capture is low, thus causing the shape of fast wave distorted. For the second wave, the maximum amplitude is about 90 µV and the shape of the wave is much clear compared to first wave. Other laboratories also reporting that fast wave is too small due to its attenuation nature [6, 26]. In addition, the phenomenon might be occurs due to low density specimen [26]. Hence, it is normal to receive fast wave in small amplitude. Further, despite fast and slow wave is proved to propagate through cancellous bone, the cancellous bone orientation also playing an important role in order to observe those waves separated in time domain [11, 30-35].

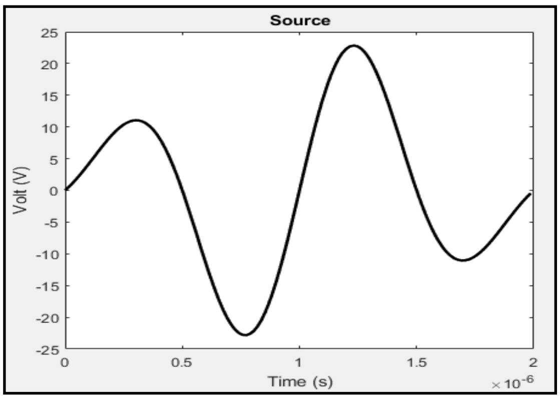

Figure 3: Sine Gaussian Wave

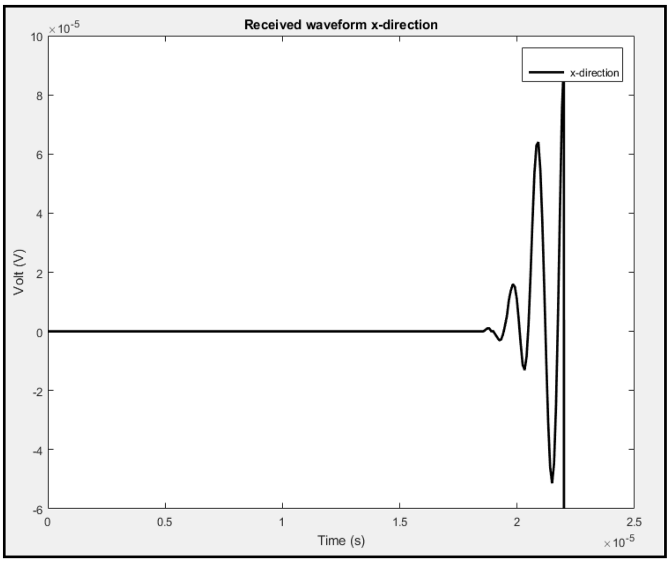

Figure 4: Received waveform for x-direction

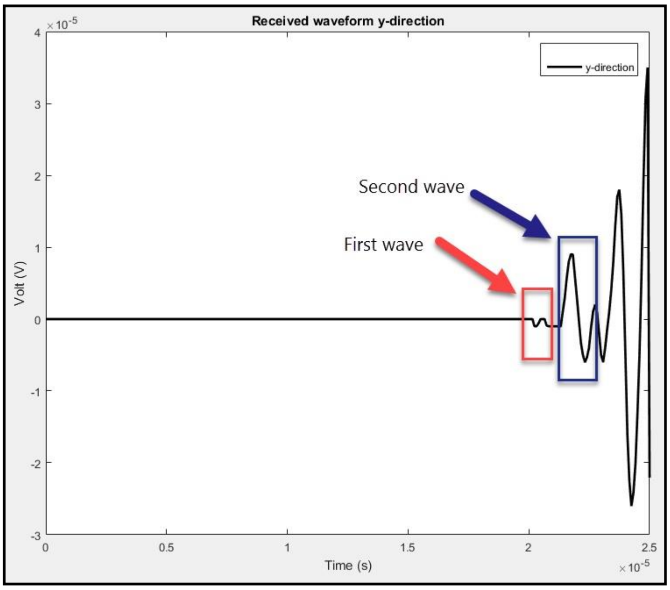

Figure 5: Received waveform for y-direction

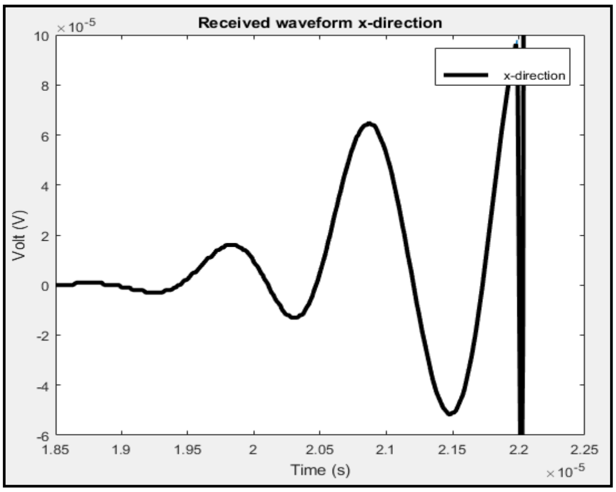

Figure 6: The received waveform for x-direction (enlarged)

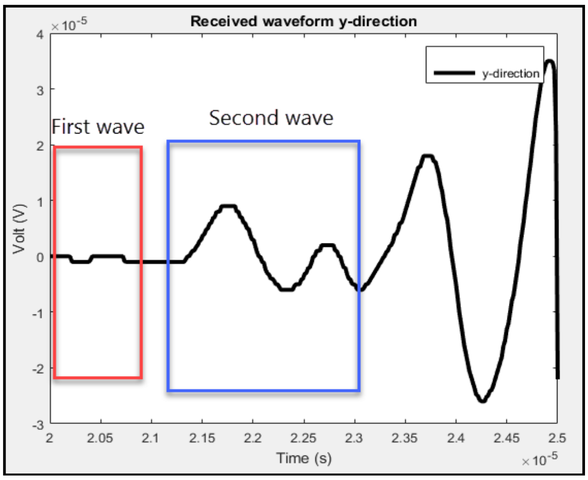

Figure 7: Received waveform for y-direction (enlarged)

Besides, the main trabecular elements in the propagation direction and trabecular structure are closely associated to both the fast and slow wave propagation [36, 37]. In the case of x-direction, the fast and slow wave might be overlapped with each other and showing no clear separation of fast and slow wave [35]. This can happen because of the lack of longer solid trabecular [11, 30]. By referring Figure 2, longer solid trabecular can be observed in the y-direction. This orientation is important to ensure fast and slow wave arrives at the receiver separated in time domain. The y-direction orientation can be assumed similar to the bone orientation parallel to trabecular alignment [11, 30-35].

VI. Conclusion

Using FDTD based commercial software Wave3000 to investigate propagation of fast and slow wave in cancellous bone shows a good agreement with other researchers. The simulation is conducted towards providing cancellous bone model by the software indicate that, in y-direction, the first and second wave which shows similar behavior of fast and slow wave can be observed separately in time domain despite the first wave amplitude was distorted due to receiver resolution. These results show that, bone orientation plays an important role in separation of fast and slow wave in time domain.

However, this study is starting line for further investigation of fast and slow wave using other measurement technique, namely pulse-echo (PE) technique. The recent simulation study shows that, fast and slow wave can be observed in overall backscattered wave at certain cancellous bone depth. PE technique has several advantages compared to the TT technique, for instance, can be measured at crucial bone sites such as spine which cannot be measured by TT technique.

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