CORRELATION REFLECTED FAST AND SLOW WAVES WITH VARIOUS CANCELLOUS BONE MODELS USING PULSE-ECHO ULTRASOUND TECHNIQUE

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Attenuation and velocity of an ultrasound wave parameter can be analyzed to estimate the quality of the bone. However, the bone quality evaluation using ultrasound is still not comparable with X-ray densitometry. Considering the parameters of the fast and slow waves perhaps develop the measurement accuracy of the ultrasound. Currently, fast and slow waves measured using through transmission (TT) technique. Nonetheless, this technique applied two transducers, which limited to certain parts of the skeletal structure. Based on pulse-echo (PE) technique which is much easier to use due to single transducer uses and analyse fast and slow waves might be able to solve the problems. Therefore, the objective of this study is to conduct simulation and experiment of the PE technique to study the correlation between fast and slow waves with various porosities and thicknesses of two-dimentional cancellous models and bone phantom (polyurethane (PU) foam) and comparing the result obtained to the result of the TT technique and previous works. The ultrasound wave measurement was done based on TT and PE technique for both simulation and experiment. The measurement also was repeated for every porosity and thickness. The "incident" and "reflected" waves then separated using bandlimited deconvolution method by estimating the time threshold between transfer function of the fast and slow waves. Then, the parameters for mix, fast and slow waves were calculated, plotted against porosity for several thicknesses and compared in terms of their correlation coefficient. There are two types of bone models orientation (parallel and perpendicular) and two types of materials in the simulation (bone and PU – to compare with experiment). The result showed some of the fast and slow waves were in good agreement with previous work in terms of the behaviour of the wave parameters against porosity for every thickness. Moreover, the bone orientations (simulation), frequency spectral content and domination of the wave can influence the behaviour of the fast and slow waves. The thickness factor influences the parameters of fast and slow waves. Nonetheless, the reaction varied depending on the porosity level. Based on the phase velocity parameters, the separation of the fast and slow waves are easier for the thicker samples for PU materials (simulation and experiment) but the same for bone materials. The overall correlation coefficient of the amplitude and signal loss parameters for the reflected wave was slightly lower compared to incident wave due to suffering additional propagation loss. Nevertheless, for the attenuation parameters, most incident and reflected fast and slow waves shows a consistent trends and good correlation coefficient for simulation and experiment (Bone – $R^2_{\beta I/Rfast} = 0.52/0.50_{\text{average}}$ and $R^2_{\beta Islow} = 0.67_{\text{average}}$) (PU – $R^2_{\beta I/Rfast} = 0.86/0.61_{\text{max}}$) (Experiment – $R^2_{\beta Ifast} = 0.88_{\text{max}}$ and $R^2_{\beta Rfast} = 0.58_{\text{average}}$, $R^2_{\beta Islow} = 0.65_{\text{max}}$ and $R^2_{\beta Rslow} = 0.70_{\text{average}}$). This indicates that, the reflected fast and slow wave showed similar behaviour as the incident fast and slow wave and feasible to be applied in PE measurement technique. The result from simulation (PU materials) was also in good agreement with the experiment. The overall result shows, considering reflected fast and slow waves especially the attenuation parameter to estimate bone quality, might be able to improve the measurement accuracy for PE technique.

ABSTRAK

Pelemahan dan halaju parameter gelombang ultrabunyi boleh dianalisis untuk menganggar kualiti tulang. Walau bagaimanapun, penilaian kualiti tulang menggunakan ultrabunyi masih tidak setanding dengan densitometri sinar-X. Memandangkan parameter gelombang cepat dan lambat mungkin meningkatkan ketepatan pengukuran ultrabunyi. Pada masa ini, gelombang cepat dan lambat diukur menggunakan teknik penembusan transmisi (TT). Namun, teknik ini menggunakan dua transduser yang terhad untuk sebahagian struktur rangka. Berdasarkan teknik gema nadi (PE) yang lebih mudah digunakan kerana menggunakan transduser tunggal dan analisis gelombang cepat dan lambat mungkin dapat menyelesaikan masalah ini. Oleh itu, objektif kajian ini adalah untuk menjalankan simulasi dan eksperimen menggunakan teknik PE untuk menyiasat korelasi antara gelombang cepat dan lambat dengan pelbagai porositi dan ketebalan model kanselus dua – dimensi dan tulang fantom (busa poliuretana (PU)) dan membandingkan hasil yang diperolehi dengan hasil daripada teknik TT dan hasil kerja sebelumnya. Pengukuran gelombang ultrabunyi dilaksanakan berdasarkan teknik TT dan PE untuk kedua-dua simulasi dan eksperimen. Pengukuran juga diulang untuk setiap keliangan dan ketebalan. Gelombang "tuju" dan "pantulan" telah dipisahkan menggunakan kaedah penyahkonvolusi jalur terhad dengan menganggarkan ambang masa antara fungsi pemindahan gelombang cepat dan lambat. Kemudian, parameter untuk gelombang campuran, cepat dan lambat dikira, diplot terhadap keliangan untuk beberapa ketebalan dan dibandingkan dari segi pekali korelasi mereka. Terdapat dua jenis orientasi model tulang (selari dan serenjang) dan dua jenis bahan dalam simulasi (tulang dan PU – untuk dibandingkan dengan eksperimen). Keputusan menunjukkan bahawa, sesetengah gelombang cepat dan lambat selari dengan kerja sebelum ini dari segi kelakuan parameter gelombang terhadap keliangan untuk setiap ketebalan. Selain itu, orientasi tulang (simulasi), kandungan spektral frekuensi dan penguasaan gelombang dapat mempengaruhi tingkah laku gelombang cepat dan lambat. Faktor ketebalan mempengaruhi parameter gelombang cepat dan lambat. Namun, tindak balas adalah berbeza-beza bergantung kepada tahap keliangan. Berdasarkan parameter halaju fasa, pemisahan gelombang cepat dan lambat adalah lebih mudah bagi sampel yang tebal untuk bahan PU (simulasi dan eksperimen) tetapi sama untuk bahan tulang. Pekali korelasi keseluruhan parameter amplitud dan kehilangan isyarat untuk gelombang pantulan sedikit rendah berbanding gelombang tuju kerana mengalami kehilangan perambatan tambahan. Walaupun begitu, bagi parameter pelemahan, kebanyakan gelombang tuju dan pantulan cepat dan lambat menunjukkan trend yang konsisten dan pekali korelasi yang baik untuk simulasi dan eksperimen. (Tulang – $R^2_{\beta I/Rfast}$ = $0.52/0.50_{average}$ and $R^2_{\beta Islow}$ = $0.67_{average}$) (PU – $R^2_{\beta I/Rfast}$ = $0.86/0.61_{max}$) (Eksperimen – $R^2_{\beta Ifast}$ = 0.88_{max} and $R^2_{\beta Rfast}$ = $0.58_{average}$, $R^2_{\beta Islow}$ = 0.65_{max} and $R^2_{\beta Rslow}$ = $0.70_{average}$). Ini menunjukan, gelombang pantulan cepat dan lambat menunjukan kelakuan yang sama dengan gelombang tuju cepat dan lambat dan boleh diaplikasikan kepada teknik pengukuran PE. Hasil daripada simulasi (bahan PU) juga adalah selari dengan eksperimen. Hasil keseluruhan menunjukan, mengambil kira gelombang pantulan cepat dan lambat terutamanya parameter pelemahan untuk menganggarkan kualiti tulang mungkin dapat meningkatkan ketepatan pengukuran untuk teknik PE.

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LIST OF ABBREVIATIONS

TT	-	Through Transmission
PE	-	Pulse-echo
UTM	-	Universiti Teknologi Malaysia
QUS	-	Quantitative Ultrasound
KK	-	Kramers-Kronig
SL	-	Signal Loss
BUA	-	Broadband Ultrasound Attenuation
SOS	-	Speed of Sound
AIB	-	Apparent Integrated Backscattered
IRC	-	Integrated Reflection Coefficient
BUB	-	Broadband Ultrasound Backscattered
BMD	-	Bone Mass Density
QCT	-	Quantitative Computed Tomography
DXA	-	Dual X-Ray Bone Densitometry
SAGE	-	Space Alternating Generalized Expectation Maximization
MLSP + CF	-	Modified Least Squares Prony + Curve Fitting
FDI	-	Frequency Domain Interferometry
FDTD	-	Finite Difference Time Domain
BV/TV	-	Bone Volume Fraction
WHO	-	World Health Organization
2-D	-	2-Dimensional
3-D	-	3-Dimensional
AT	-	Axial Transmission
TOF	-	Time of Flight
FDUA	-	Frequency Dependent Ultrasound Attenuation
AVF	-	Aluminium Volume Fraction
BSC	-	Backscattered Coefficient
PU	-	Polyurethane
SI	-	Separation Index

TASB	-	Time Slope Of Apparent Backscatter
MIIR	-	Medical Imaging, Instrumentation and Robotic
EFIT	-	Elastodynamic Finite Integration Technique
FFT	-	Fast Fourier Transform
DA	-	Degree of Anisotropy
TX	-	Transmitter
RX	-	Receiver
FEM	-	Finite Element Method
USB	-	Universal Serial Bus
MOS	-	Malaysian Osteoporosis Society
PCF	-	Pound per cubic foot

LIST OF SYMBOLS

f	-	Frequency
D,d	-	Thickness
C	-	Phase velocity
β	-	Slope of attenuation
A	-	Amplitude
V	-	Voltage
dB	-	Decibel
s	-	Second
V_{pp}	-	Voltage peak-to-peak
Hz	-	Hertz
cm	-	Centimeter
g/cc	-	Gram per cubic centimetre
µ	-	Micro
π	-	Pi
ω	-	Angular frequency
‖	-	Parallel
⊥	-	Perpendicular
Cl	-	Longitudinal Velocity
Cs	-	Shear Velocity
σf	-	Bandwidth
I	-	Incident
R	-	Reflected
fast	-	Fast wave
slow	-	Slow wave
mix	-	Mix wave/Original wave/Unseparated wave

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Ultrasound systems are widely used and they can be found in many applications such as in engineering, medicine [1], biology, and other areas [2]. Generally, the ultrasound is a cyclic sound pressure with frequencies greater than 20 kHz, the limit of human hearing [3]. In medical diagnostic, ultrasound frequency used was ranging from 1 to 20 MHz [3]. However, for bone densitometry application, the frequency range for the ultrasound wave is usually around 0.2 to 2 MHz which is lower than the frequency used for conventional ultrasound imaging due to bone highly attenuated nature [4]. There are several modalities of the ultrasound medical application such as A-mode, B-mode, M-mode and Doppler imaging where each modality has it's own specific uses [5]. Ultrasound technology was introduced for bone related purposes taking place since 1950 where the ultrasound application was used to monitor fracture healing at the tibia (shin bone) [6]. Ultrasound wave also can be used to determine the geometrical outcome of double co-planar edge cracks on the stress intensity factor in the human femur bone. The results of these findings can be used to suggest appropriate implants to minimize the effects of stress at the bone, thereby speeding up the time taken by the bone to recover from the fracture [7].

Based on the attenuation and velocity, ultrasound parameters were analyzed to assess the quality of bone [8]. The velocity of ultrasound corresponds to density and elasticity of the bone whereas attenuation corresponds to the structure of the bone [8]. From the clinical aspect, the ultrasound possesses invaluable interest due to widely available, low cost, non-ionizing radiation, portable, short examination time, and capability of real-time image display compared to other modalities such as X-ray based bone densitometry [4]. There are three types of ultrasound measurement techniques, such as through transmission technique (TT), axial transmission (AT) technique and pulse-echo technique (PE). The TT measurement technique was one of the earliest and most common techniques to estimate bone quality. This is due to the technique being easy to implement and analyze since the propagation of wave was straightforward, where one transducer transmitted the wave that passed through the samples and received to the other transducer that act as receivers [4]. Meanwhile, the AT measurement technique usually used to investigate long or cortical bones and the ultrasound probe commonly used was scanner type, where there have several transmitters and receivers in the single probe [4, 9, 10]. For the PE measurement technique, only one transducer used and acted as both transmitter and receiver [4].

Osteoporosis disease is generally characterized by a systemic impairment of bone mass, strength, and microarchitecture, which increases the propensity of fragility fractures. Osteoporosis was also known as a silent disease because the disease is often detected when the fracture has occurred [8, 11]. The cause for the diseases to occur was usually due to low Vitamin D intake (important for bone health), lack of calcium and food fortification consumed [11]. Additionally, there is also lack of sun exposure because of the tendency to remain indoors during the day due to the hot and humid climate as well as the increase in urban living. This problem was happen globally including in Malaysia [11]. Thus, bone quality checks regularly can be one method of disease prevention for osteoporosis before its get worse.

Current measurement techniques available are based on X-ray and ultrasound. However, both techniques have pros and cons in measuring the quality of the bone. For the X-ray based densitometry, Dual X-Ray Absorptiometry (DXA) and Quantitative Computed Tomography (QCT) can estimate bone quality and predict bone fracture more precisely [12]. Even so, both techniques mentioned above involve ionization of radiation wherein could be harmful to the patient's body if it is exposed many times [8]. Moreover, most of the equipment is non-portable and requires a high cost to operate and for maintenance purposes. Because of that, another alternative method is introduced namely Quantitative Ultrasound (QUS). QUS method is much safer, cheaper, and portable. However, DXA is still an option for most hospitals to evaluate bone despite QUS measurement has been proven to predict hip fractures and all osteoporotic fractures with similar relative risk as other central X-ray based bone density [13]. This is due to QUS only analyzing overall ultrasound waves which cannot provide enough information regarding bone microstructural [13, 14]. Hence, researchers still find the best solution to improve the accuracy of bone density estimation based on ultrasound technology.

The combination of solid and fluid (pore part) of the cancellous bone was found to be supporting two types of wave that corresponds to each solid and fluid in the porous structure of the bone [15]. The two types of wave are known as the fast wave and slow waves. The previous study shows the microstructure and other properties of the cancellous bone correlate more with the fast and slow waves [16-22] and by analyzing ultrasound the fast and slow waves might able to improve the bone quality estimation based on ultrasound. Even so, the observation of fast and slow wave in time domain is affected by the degree of anisotropy of the cancellous bone and these waves can overlapped with each other [15]. Bandlimited deconvolution is created as one of the methods to separate fast and slow waves [23, 24]. This method successfully separates fast and slow waves at least in the TT measurement technique. The discovery of fast and slow wave might useful to increase the precision of bone health using ultrasound.

1.2 Motivation of the Study

The increased the number of old people also one of the reasons to find a new solution regarding bone quality estimation. At the local level, the population of elderly in Malaysia have increased proportionally to the technology advancement and health standard [25]. In 2050, the Malaysian population aged over 50 years projected to increase by 163% in the next 4 decades, rising from 5.3 million in 2013 to 13.9 million [25]. Life expectancy will also rise from 74 years to 81 years and approximately one-third of the total population are those aged over 50 years by 2050 [25].

Large-scale epidemiological fracture studies need to be funded and conducted as there is still a lack of data on fractures due to osteoporosis in Malaysia and hip fracture incidence data in the year of 1996 and 1997 are the most reliable at the moment [25]. New data collection on hip fractures has been conducted by the Malaysian Osteoporosis Society (MOS) for the year of 2012 and will compare it with data in the year of 1996 and 1997. As many as 90 per 100,000 individuals per year suffered hip fracture in the year of 1996 to 1997 that occurred to those over the age of 50. From this report [26], the increase in the elderly population might contributed to the increase in such cases.

In terms of ethnic breakdown, the highest cases of hip fractures occur in the population of Chinese women about 44.8% of the overall case against the Malay and Indian women [25]. The total cost of hospital treatment for hip fracture patients in 1997 is estimated at 6.8 million USD (RM 22 million) and of that amount, the cost of rehabilitation or treatment in a nursing home is not included [25]. The number and cost of hip fractures are expected to increase in line with the increasing population of the elderly [27]. Hence, action is required to tackle the projected burden of osteoporosis as indicates the rising of the elderly population.

1.3 Problem Statement

Emerging of the ultrasound fast and slow waves propagate through cancellous bone shows a very good agreement with bone microstructural, thereby, increasing precision of bone estimation based on QUS. Only Through-transmission (TT) measurement technique successfully applies the concept of two modes ultrasound waves at the wrist for the current two modes ultrasound wave machine [13, 14]. Still, the TT measurement technique is limited to certain parts of the skeletal area whereas fracture risk caused by Osteoporosis disease often occurs not only at the wrist but also occurs at the hip and spine which can increase mortality rate [13, 14].

However, another measurement technique namely Pulse-echo (PE) technique is proposed to solve these problems as the technique only uses one transducer and is capable of measuring at the vital skeletal site. Yet, the accuracy of PE technique is still not powerful compared to TT technique because of the complex behaviour of reflected and backscattered wave relation with inhomogeneity of cancellous bone. Because of that, Hosokowa *et al*. [16, 28-30] demonstrated Finite Difference Time Domain (FDTD) simulation to show that fast and slow waves can be reflected and backscattered too, hence, considering fast and slow wave might improve the PE technique for bone quality estimation. Thus, the PE measurement technique that applies the concept of two modes ultrasound wave is proposed to evaluate bone density with high precision and not limited to certain skeletal sites such as the spine.

Therefore, this research will look into the research of ultrasound PE measurement technique utilizing both simulation and experiment to examine the correlation of fast and slow waves parameters with various porosities of bone models and phantoms. The consistency of the trends and performance of the correlation coefficient for various thicknesses of the bone models and phantoms will also be observed. The recorded reflected wave (original wave or mix wave) will be processed by using the bandlimited deconvolution method in order to decompose into the individual reflected fast and slow waves. Then, the result of the correlation coefficient between the ultrasound parameters of the mix, fast and slow waves will be compared. Previously, there are no attempts by other researchers to decompose the reflected waves obtained from PE technique into individual reflected fast and slow waves using the bandlimited deconvolution method. Hence, the overall result of PE technique will be compared to the TT technique since this technique has been done many times to analyze fast and slow waves.

1.4 Hypothesis

The hypotheses of the study are as follows:

1. When porosity of the cancellous bone increases, slow wave amplitude increase, while fast wave amplitude decreases.

2. Attenuation of the fast wave is directly proportional, while attenuation of slow wave is inversely proportional to the increases of cancellous bone porosity.

3. Reflected fast and slow wave parameters were found to correlate more with the bone microstructure of the bone models compared to the reflected mix wave.

1.5 Research Questions

The research questions of the study are as follows:

1. Is the reflected fast and slow waves obtained from PE measurement technique can be decomposed from mix wave using the bandlimited deconvolution method just like the incident fast and slow wave obtained from TT measurement technique?

2. Is the behaviour of incident fast and slow wave parameters using TT measurement technique is the same as the reflected fast and slow wave parameters using PE measurement technique?

3. What are the ultrasound wave parameters that related most to changes in porosity of the cancellous bone structure?

1.6 Objective (s) of the Study

This study embarks on the following objectives:

1. To prove that the reflected fast and slow waves obtained from pulse-echo technique can be decomposed from mix wave using a bandlimited deconvolution method for both simulation and experiment.

2. To formulate the correlation of the reflected fast and slow wave's parameters with various porosity level and thicknesses of the cancellous bone models

3. To compare the behaviour and performance of parameters of the fast and slow waves for both PE and TT measurement technique in simulation which is based on the Elastodynamic Finite Integration Technique (EFIT) and experiment, where both are based on QUS measurement method.

1.7 Scope of the Study

The scopes of the study are divided according to the objectives described in section 1.6. They are as follows:

1. To prove that the reflected fast and slow waves obtained from pulse-echo technique can be decomposed from mix wave using a bandlimited deconvolution method for both simulation and experiment.

   (a) The bandlimited deconvolution method will be used to distinguish overlapping incidents and reflected fast and slow waves.

   (b) Two types of materials will be involved in the simulation, which are bone and PU materials in order to compare with the experiment that uses bone phantom (PU foam).

2. To formulate the correlation of the reflected fast and slow wave's parameters with various porosity level and thicknesses of the cancellous bone models.

   (a) The ultrasound parameters will be computed to the incident and reflected unseparated wave (mix), fast and slow waves.

(b) The parameters computation will be done to several thicknesess of bone models/phantom.

3. To compare the behaviour and performance of parameters of the fast and slow waves for both PE and TT measurement technique in simulation which is based on the Elastodynamic Finite Integration Technique (EFIT) and experiment, where both are based on QUS measurement method.

   (a) The ultrasound parameters will be plotted against porosity for several thicknesess and compare in term of their correlation coefficient for both simulation and experiment.

   (b) The comparison will be done between unseparated (mix), fast and slow waves for TT and PE measurement technique in order to determine which wave has a higher correlation with porosity and is consistent for every thickness.

1.8 Significance of the Study

The significances of the study are as follows:

1. The separation and estimation of reflected fast and slow wave can provide an additional option to improve the current PE measurement technique by considering the two modes wave in their measurement to estimate bone quality.

2. The finding of the study can be useful to other researchers as an example to investigate the correlation of the parameters of reflected fast and slow waves using bandlimited deconvolution method, since there are no attempts previously made to obtain and analyze the reflected fast and slow waves in real experiments.

3. Despite the bone phantom was not a real human bone, but, the microstructure of the PU foam made by Sawbones® have biomechanical properties similar to the real human bone and this PU foam was used as a standard material for testing orthopaedic devices and instruments.

4. This study is relevant in bone estimation based on ultrasound wave research, especially for understanding the behaviour of both incidents and reflected fast and slow waves towards various porosities and thicknesses of the porous structure.

1.9 Thesis Outline

The thesis outline consists of an introduction, literature review, proposed method, methodology, result and discussion as well as the conclusion.

Chapter 1. Introduction

This chapter comprised the background, motivation, problem statement, hypothesis, research question, objective and scope as well as the significance of the study.

Chapter 2. Literature review and theoretical background

The literature review cover the information and theory related to the study such as the structure of human cancellous bone, related disease as well as bone losses. Moreover, this chapter also studies the current method to estimate bone quality such as X-ray based measurement. In addition, the current method to estimate bone quality based on ultrasound is also studied. Last but not least, regarding the application of fast and slow wave for the bone quality estimation, as well as previous works, also be studied.

Chapter 3. Proposed method – fast and slow wave

In this chapter, the study was focused on the theory of the fast and slow wave that applied in the mathematical model of the propagation of ultrasound through the porous structure. Moreover, the proposed method that was implemented based on the mathematical models also presented, including the overall picture of the method of the study that were conducted.

Chapter 4. Methodology

The methodology chapter discuss the process of the study, especially in terms of data collection and analysis. The measurement technique of both TT and PE as well as the information about the simulation and experiment was also shown and discussed such as the simulation software, bone models (simulation), bone phantom (experiment), experimental setup, a method to separate fast and slow waves and ultrasound paramater calculation.

Chapter 5. Result and discussion

This chapter discuss the result obtained from the simulation and experiment for both incidents and reflected waves. The results also cover the two types of material, such as bone and PU material. The simulation results based on PU material were compared with the results of the experiments, which also use PU foam. The parameters were calculated and then plotted against porosity for every thickness in order to study the correlation between them. Then, the result was compared between the TT and PE measurement technique for mix and two modes wave to determine which one of these waves are correlated more with various porosities and thicknesses. Last but not least, the result obtained were be verified with previous works.

Chapter 6. Conclusion

The conclusion chapter cover the finding of the overall study, limitation and recommendation as well as the future improvement that can be done in order to pursue the research to the next level.

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