Measurement of Bone Density Parameters using Ultrasound and Hardware Development on bone Density Measurement

Kunal Khosla, Apurva Naik

Abstract: ***Ultrasound waves due to their inherent small wave-length can be used in diagnosis or evaluation of tissue. Ultrasound simulations can be useful to investigate and analyze different properties at different sites especially when there is no volumetric data available. In the proposed paper, simulation of ultrasound in a 2-D bone model and hardware implementation has been presented. Due to complex structures of bone, a simple linear model consisting of both cortical and cancellous bone has been proposed. In the simulation, a broadband emitter with center frequency of 1 Megahertz is used along with an array of receivers to capture the signal. An attempt has been made to calculate bone density parameters in-vivo for human feet, and finally display the computed parameters onto a LCD using Arduino Uno Board. An algorithm involving fourier transforms was used to calculate Broadband Ultrasound Attenuation (BUA) and Speed of Sound (SoS) in Matrix Laboratory (MATLAB).***

Keywords: ***Broadband ultrasound attenuation, speed of sound, simsonic, matrix laboratory, osteoporosis, osteopenia, quantitative ultrasound.***

I. INTRODUCTION

Use of ultrasound frequencies has the diagnostic capabilities of tissue monitoring, because it can penetrate the bulk, due to its small wavelength. Its diagnostic capabilities include Non- Destructive testing (NDT), tissue healing and foetal health monitoring. There are many commercial devices available in the market which can be used to measure T-Score and Z- Score, like the Mini Omni Portable bone density device by Beamed which applies the probe onto the tibia and wrist and the Sonost-2000 by osteosys which is heel densitometer. Dual Energy X-Ray Absorptiometry (DEXA) scan which is considered a gold standard in bone density measurement, mea- sures bone density at various sites, including the hip, vertebrae etc. Quantitative Computed tomography (QCT) utilizes X-rays at various angles to take measurements and produce images which are finally stitched together to give you a final image. It is used in assessment of risk of fractures.

Biot's theory derives the equations of wave propagation in porous media. The idea of Biot's theory was that the outcome of an incident sound wave onto a porous solid was a fast, slow wave along with a shear wave [3], [4]. Some success has been achieved in modelling sound waves in cancellous bone using different forms of biot's theory. Except frequencies greater than 1 *MHz*, biot's theory should be applicable as the wavelengths of the order of 1.5 *mm* at 1 *M Hz* are larger than the pore size in bones [5, p. 3286].

A. Bone Models and their material constants

The densities [1, p. 195] and elastic constants [1, p. 195] can be used as inputs for building nominal bone models [1, p. 195]. The constants for cortical bone used here were homogenized (average properties of hard tissue and pores [1,p. 194]) and transversely anisotropic. The values of density and elastic constants C_{11}, C_{22}, C_{12} and C_{66} for cortical has been taken from [1, p. 195]. Osteoporotic bones were simulated by reducing the thickness of the cortical bone and changing the densities and elastic constants of the trabecular bone [1,p. 218]. The cortical bone was considered to be perfectly linear in shape, disregarding any curvature which can be responsible for change in *BUA* values. For cancellous bone, the data has been taken from [2, p. 667]. 1.6 g/cm^3 and 1.85 g/cm^3, are assumed to be densities of an osteoporotic and normal subject respectively. Elastic constants C_{22}, C_{66} and C_{12} were derived from C_{11} and C_{44} using Lame parameters μ, λ and equations 1 and 2. The data for density is inconsistent as cortical and cancellous bone density cannot be same because cortical bone is more dense, however the density for osteoporotic subjects is lower than normal, which has been included in these models and one can observe the changes in attenuation values.

$$C_{11} = C_{22} = \lambda + 2\mu \qquad (1)$$

$$C_{44} = \mu \qquad (2)$$

For example, the 2-D plate bone model for an osteoporotic subject has been shown in "Fig. 1".

B. Simulation Components

To study the nature of bone, a 2-D plate model with cortical and cancellous bone both were drawn. This model can be used to assess the mechanical properties for osteoporotic or normal conditions at different bone sites. In this Simulation,

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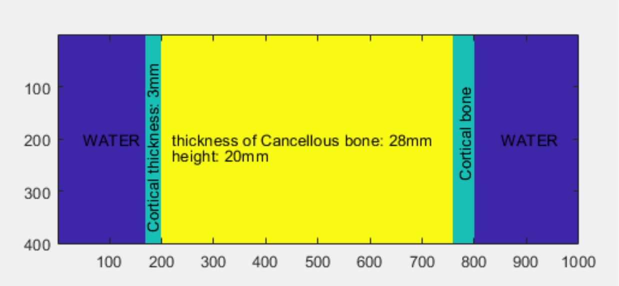


Fig. 1. 2-D Bone plate model

simsonic uses elastic constants and densities as parameters for laying the foundation of nominal bone model. To study the bone density parameters, of cortical and cancellous bones, a 2-D plate model with the dimensions of the calcaneus, if not there exact anatomy had been drawn. In the workstation, separate directories have been assigned for simulation for sample and reference signals. A broadband emitter with centre frequency of 1 *M Hz* is used along with an array of receivers to capture the signal. The calculation of broadband ultrasound attenuation uses the slope of attenuation versus frequency in the range 200 *KHz* to 600 *KHz*. *BUA* is a measure of frequency dependence of the attenuation of ultrasound measured in decibels/megahertz (*dB/M Hz*) and *SoS* is the speed of ultrasound in the sample expressed in meters/second (*m/s*). Attenuation, velocity can be found out by computing the fourier transform as per formulas in [6, p. 158,159] which are 3, 4, 5 and 6. Equation 3 was multiplied by 20 to convert the value into decibles.

$$BUA(f) = \frac{A_r(f)}{A(f)} \tag{3}$$

$$Phi(f) = arctan\frac{A(f)}{A_r(f)} \tag{4}$$

$$v(f) = \frac{1}{\frac{1}{v_0} - \frac{Phi(f)}{2\pi fl}} \tag{5}$$

$$UBV(f_c) = v(f) \tag{6}$$

where A_r is the amplitude spectrum of specimen in water, A is amplitude spectrum with water alone. $V(f)$ is the phase velocity, v_o is velocity of sound in water, f/f_c is the fre- quency/centre frequency,$U\,BV$ is the ultrasound bone velocity and l is the length of the specimen. Stiffness index can be calculated with the help of 7 used in the Achilles system.

$$SI = 0.67 * BUA + 0.28 * SOS - 420 \tag{7}$$

where *SoS*, *BUA* are the speed of sound and broadband ultrasound attenuation respectively. The plot of frequency dependent attenuation was obtained as in “Fig. 2” for a normal subject and in figure “Fig. 3” for osteoporotic subject. The slope of the linear portion (*BUA*) was obtained in the range 500 *KHz* to 700 *KHz* .

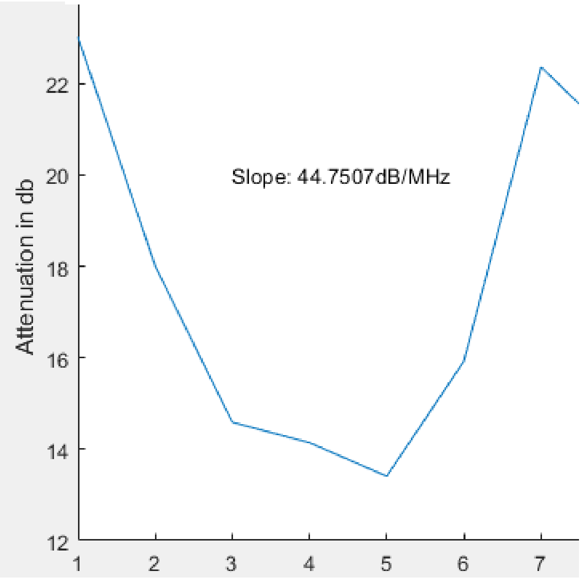


Fig. 2. Broadband Ultrasound Attenuation in a normal bone sample

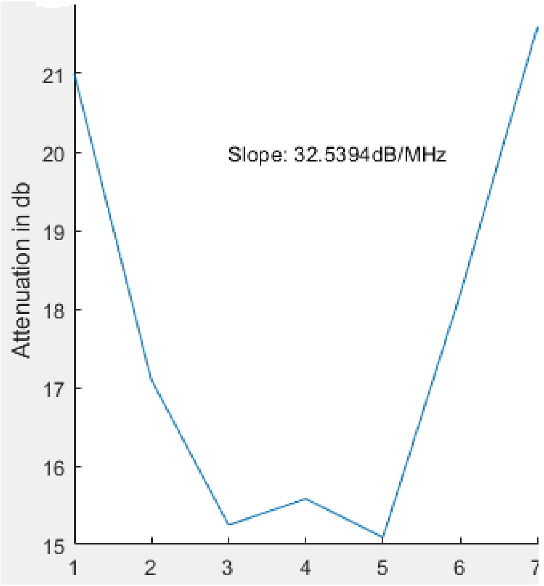


Fig. 3. Broadband Ultrasound Attenuation in an osteoporotic bone sample

C. Methods

The method used here is through mode of transmission and other methods like guided waves or axial transmission can also be used to assess bone condition. In the latter approach the emitter and receiver are on the same side of the specimen.

Bone acts as a waveguide in this mode where the wave travels across the surface to finally reach the receiver.

The tibia, wrist (arm) etc. are popular sites for measurement of bone density using axial transmission while the calcaneus is considered an ideal position for measurement using a pulse through technique. The length of the cortical part in the model of calcaneus was taken to be 1.5 *mm* close to the value of 1.4 *mm* in [7]. The length for cancellous part in normal subjects was considered to be 30 *mm* and 28 *mm* for osteoporotic subjects. Velocity was calculated with the help of 5 and 6.

II. HARDWARE DEVELOPMENT

The hardware setup in "Fig. 4" has a MHF-400 pulser receiver by Roop Telsonic,

Fig. 4. Hardware setup for Non-Destructive Evaluation in through transmission mode, Courtesy: Cummins College of Engineering Pune

Tektronix TBS 1062 Digital Storage Oscilloscope and a pair of 1 *MHz* broadband transducers. A Negative going trigger pulse was used for excitation of the transducer. Water was used as a reference medium in the water bath here. The data obtained showed significant attenuation when the subject's heel was placed in vitro between the transducers. The values of *BUA* and *SoS* were noted. Data may have some errors due to calibration, motion artefacts and non-contact with sensors. To develop the analysis technique, Experimental data of in-vivo measurements of a trabecular bone sample provided by Dr. C.M. Langton was taken. A Fast Fourier Transform (FFT) window of length 512 and sampling frequency of 50 *M Hz* was used in the algorithm. To calculate *BUA* and *SoS* the methods in section I-C were followed. But this time, we focused on the linear portion between 200 *KHz* to 600 *KHz* along with a digitization frequency of 100 *MHz*.

A Liquid Crystal Display (LCD) interface with Arduino Uno board to display values of Bone Mineral Density (BMD) in gm/cm^3 was achieved. The values obtained in algorithm were serially transmitted at a baud rate of 9600 to display BMD. The formula [8, p. 89], to compute BMD is used here, arduino package was installed in the MATLAB workstation to establish a connection between arduino and Personal Computer (PC). The setup for the same is shown in "Fig. 5".

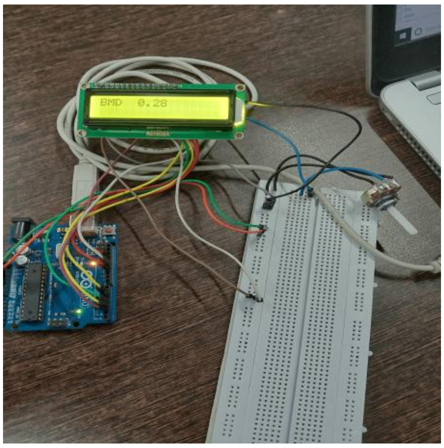
III. OBSERVATIONS

The computed results of simulation for normal and osteoporotic subjects are shown in "table I". Along with this data, results from in vivo measurements of the human feet are shown. As it can be seen, decrease in density leads to decrease in attenuation because of loss of bone due to disease. However, there was no significant change in speed of the subjects, although osteoporotic subjects showed a very minor increase. These values will be far from close to real data, because the parameters defined were used in nominal bone models and no porosity was considered for cancellous bone which plays a significant role in change in *BUA*. Nonetheless, the decrease in *BUA* values is of significance. It can be useful to study the role, effects of cancellous and cortical bone in measurement of *BUA* and *SoS*. Another interesting observation was the difference in values obtained from in-vitro and in-vivo measurements and the role soft tissue and other artefacts could play in these measurements.

IV. RESULTS

The *SoS* and *BUA* values were computed via simulation using the software SimSonic [9] with a 1 *MHz* Gaussian pulse and fractional bandwidth of 0.55 at 3 *db* and time duration of 3 *us.*

Fig. 5. LCD and Hardware setup for display of results



V. CONCLUSION

The *SOS* and *BUA* values using the techniques mentioned were calculated. Difference in *BUA* values were obtained for osteoporosis and normal samples in simulation. Moreover, variation in *BUA* values in the experimental setup with soft tissue and without soft tissue was noted. The 2D linear bone model served as a useful way of assessment of parameters during simulation in through mode. The *BUA* and *SoS* were close to the values reported in literature. Hence, ultrasound can be useful in estimation of bone density.

TABLE I
BUA AND *SoS* FOR NORMAL AND OSTEOPOROTIC BONE IN DIFFERENT SCENARIOS

Category	**Bone Type**	**BUA in dB/MHz**	**SOS in m/s**
Simulation	Trabecular (normal)	44.7	1504.064
Simulation	Trabecular(Osteoporosis)	35.2	1505.04
Experimental	Human Heel (in vitro)	29.69	1501.72

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