The Feasibility of Using High Amplitude Pulsed Ultrasound for Combined Hard Tissue and Soft Tissues Imaging

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Abstract: - The limitation of ultrasound imaging is its difficulty in penetrating hard tissue such as bone due to large difference between the acoustic impedance of the bone and soft tissues, and in addition bones have a high attenuation rate. Hence, the outer surface of bony structure can be visualized and not soft tissues or lesions lying behind or within bone. The purpose of this study is to investigate the possibility of high amplitude pulse ultrasound to penetrate the combined hard tissue and soft tissues. Quantitative calculation and experiment set-up have been done on the human lower leg which is used as a sample. The result shows that the high amplitude pulse ultrasound is capable to penetrate the human lower leg. After giving 1 MHz of frequency and 200 V of pulse amplitude, signal of amount ~89 mV was detected at the edge of leg while ~50 μs time of flight was required. The result agrees with calculation in modeling (85.16 mV and 56.76 μs). This research will be a fundamental basis for future combined hard tissue and soft tissues imaging using high amplitude pulse ultrasound.

Key-Words: - Pulsed ultrasound, High power, Attenuation, Bone, Hard tissue imaging

1 Introduction

Ultrasound has several inherent advantages such as widely available, low costs, non ionizing radiation, portable, short examination time and capability of real time image display as compared to other modalities such as X-ray, CT, MRI, bone scan, PET and SPECT [1]. For these reasons at present, ultrasound imaging is second only to X-rays in its frequency of use and range of application in clinical medicine [2]. However, the existing ultrasound modality has a limitation in the imaging of high density tissue such as bone [3]. It is because of large difference between acoustic impedance of bone and soft tissues, also bones have a high absorption rate. Due to the inability of ultrasound waves to penetrate bone, the outer surface of bony structure can be visualized and on the other hand, soft tissues or lesions lying behind or within bone cannot be imaged and will be seen as an anechoic region [4].

At present, to our knowledge no research has been done using high amplitude pulse ultrasound for combined hard tissue and soft tissue imaging which the human lower leg is used as a sample.

In order to enable the use of high amplitude ultrasound for the human lower leg, a mathematical and experimental investigation is pursued. Our quantitative calculation through a one dimensional modelling proved that the high amplitude pulse ultrasound can penetrate the human lower leg. It means that high amplitude pulse ultrasound has possibility to do the imaging of combined hard tissue and soft tissue.

The research will investigate the high power ultrasound wave propagation in human lower leg through quantitative analysis. To verify the calculation results, an experimental set-up using a short pulse high amplitude ultrasound to drive the ultrasound transducer has been done. It is further expected to obtain the optimum values of power used by bone imaging without producing any adverse biological effects. This research will be a fundamental basis for future bone imaging using high power ultrasound.

2 Ultrasound Attenuation Principle

The physics of ultrasound and the ultrasound wave propagation equations in human tissues, muscle and bone are described in forth.

Consider an infinitely small amplitude plane ultrasound wave propagating in a perfectly elastic isotropic medium such as tissue. It is also consider that the medium is linear and lossless to the propagation of an ultrasound wave. The second-order differential equation of the ultrasound wave propagation for a one dimensional (1-D) which describes the time change of pressure in terms of its change with distance is as below [5],

$$\frac{\partial^2 \Delta P}{\partial t^2} = c^2 \frac{\partial^2 \Delta P}{\partial x^2} \tag{1}$$

where ΔP is the change in local pressure or the particle displacement amplitude in the tissue, x is the position in space along the direction of propagation, t is the time and c is the propagation speed. As the ultrasound propagates further, part of the wave will be reflected back when it hits tissue boundary and another part will be further transmitted and attenuated inside the tissue.

Total attenuation of an acoustic wave includes energy loss (absorption) and tissue scattering. For most soft tissues, scattering is negligible and attenuation and absorption coefficients are approximately equal. At a frequency of 1 MHz, bone has the highest true absorption of the body tissues, more than 20 times higher than any soft tissue [6].

As ultrasound passes through a medium it is exponentially attenuated according to the equation,

$$A = A_0 e^{-\alpha x} \tag{2}$$

where A is the amplitude of the sound wave, i.e. pressure, A_0 is the initial amplitude of the sound wave, α is the amplitude attenuation coefficient and x is the distance travelled by the sound wave. The amplitude attenuation coefficient is normally expressed in dB cm^{-1} and is defined as follows [7]:

$$\begin{aligned} \alpha(dB cm^{-1}) &= -\left(\frac{1}{x}\right).20.\log_{10}\frac{A}{A_0} \\ &= 8.686\alpha(cm^{-1}) \end{aligned} \tag{3}$$

Typical values of the attenuation coefficient for some materials are given in Table 1.

Table 1. Acoustic Properties of Biological Tissues and Relevant Materials

Material	**Speed (m/s) at 20 to 25°C**	**Acoustic Impedance (MRayl)**	**Attenuation Coeffcient (np/cm at 1 MHz)**
Air	343	0.0004	1.38
Water	1480	1.48	0.00025
Fat	1450	1.38	0.06
Myocardium	1550	1.62	0.35
Blood	1550	1.61	0.02
Liver	1570	1.65	0.11
Skull bone	3360	6.00	1.30
Aluminum	6420	17.00	0.0021

On the other hand, the relative importance of absorption and scattering to attenuation of ultrasound in biological tissues is a matter that is continuously debated. Investigations to date have shown that scattering contributes little to attenuation—at most, a few percentage points—in most soft tissues [8]. Therefore, it is safe to say that absorption is the dominant mechanism for ultrasonic attenuation in biological tissues.

2.1 Acoustic Impedance and Transmission-Reflection

Formula of acoustic impedance is important for determining transmission-reflection phenomena.

The reflection and transmission of ultrasound energy at a boundary between two different tissues occurs because of the differences in the acoustic impedances of the two tissues. Each tissue has its own acoustic impedance (Z), which is equal to the density (ρ) of the tissue multiplied by the speed of sound (c) that is given by $Z = \rho c$. The SI units for acoustic impedance (Z) is kg/(m^2sec) or rayls, the density (ρ) in kg/m^3 and the speed of sound (c) in m/sec. The reflection coefficient and transmission coefficient describe the fraction of sound intensity incident on an interface that are reflected and transmitted. The bigger the difference, the more completely the ultrasound is reflected, and the less is transmitted into the second tissue. If we assume that the boundary is plane and large compared to the wavelength and the ultrasound is perpendicular to the interface, the reflection pressure amplitude coefficient, Rp, is defined as the ratio of reflected pressure, Pr, and incident pressure, Pi, as [9],

$$R_p = \frac{P_t}{P_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{4}$$

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where Z_1 and Z_2 are the characteristic impedances of the tissue 1 and tissue 2. Similarly the transmission pressure amplitude coefficient, Tp, is defined as the ratio of transmitted pressure, Pt, and incident pressure, Pi, as,

$$\frac{P_t}{P_i} = T_p = \frac{2Z_2}{Z_1 + Z_2} \tag{5}$$

Overall energy conservation requires that

$$\left(\frac{Z_1}{Z_2}\right) T^2 + R^2 = 1 \tag{6}$$

When penetration to deeper structures is important, lower frequency ultrasound transducers must be used, because of the strong dependence of attenuation with frequency.

2.2 Acoustic Pressure and Time of Flight

Electric voltage can be coupled into acoustic pressure value with the help of electromechanical coefficient. In the meanwhile, ultrasound time of flight is defined.

Time of flight is the elapsed time from transmission of an ultrasound pulse to the detection of a received pulse in either a pulse-echo or a transmission system. If the sound speed is known, the thickness of an object can be found from the time difference between the front surface echo and the back surface echo.

If the production of ultrasound waves is based on the 'through-transmission' principle, time of flight is the time for a pulse to travel from the transducer to the reflector (interface). In the other words, it is the time for ultrasound energy to travel from the boundary of the tissue to the other boundary of the same tissue and directly related to the depth of the interface as [10],

$$t = \frac{D}{c} \tag{7}$$

3 Device and Method

In order to prove that high power ultrasound wave with applied short period amplitude voltage up to 1000 V can penetrate the high density tissue and produce a readable output voltage by receiver unit, an analysis and experiment will be done. Besides it will investigate the suitable waveform to get the optimum power transmitted through the high density tissue.

In this research, the high voltage pulsed wave will be applied to ultrasonic transducer which will act as transmitter. The high power ultrasound wave will propagate through the human lower leg specimen. Once the ultrasound wave penetrates the specimen, it will be detected by another ultrasonic transducer which will act as receiver. The parameters to be considered for the high power ultrasound wave to penetrate the specimen are pulse duration, pulse amplitude, pulse repetition frequency (PRF), pulse duty cycle, frequency of transducer, and depth of ultrasound wave.

Quantitative analysis of high power ultrasound wave propagation based on acoustic impedance and attenuation in human lower leg model would be proposed. The ultrasound wave transmitted into the lower leg which consists of skin, muscle and bone will be distributed and reflected. Performance testing in real environment implementation in vitro would then be conducted.

4 Ultrasound Attenuation through Human Lower Leg

The received voltage pulses deliver two kinds of information: first their amplitudes are proportional to the acoustic impedance mismatch at the position of reflection and second, the position itself can be calculated exactly from the delay time between pulse transmission and reception, provided the sound wave velocity is known [11]. The cross section of human lower leg is illustrated as following Fig.1.

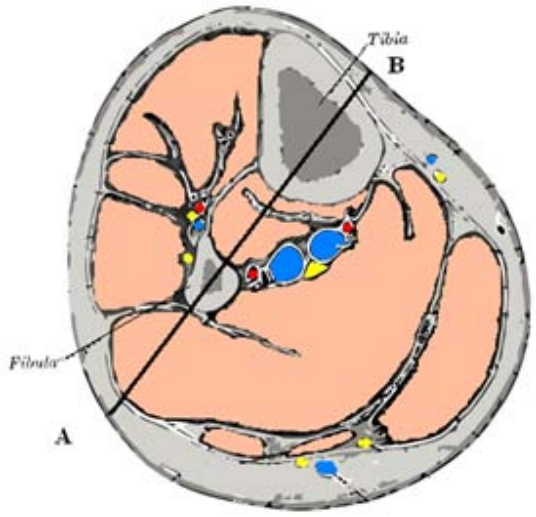

Fig.1 Human Lower Leg Cross Section

The production of ultrasound waves is based on the 'through-transmission' principle. Ultrasonic energy (ultrasound beam) propagates through the medium in a straight single line. In this case, AB path was chosen due to maximum bone obstacle on its way. Hence, the received signal can be assumed to come from the target situated on the beam axis. This is a simplest medical ultrasound scan produces a one-dimensional map of the positions of boundaries, along the direction of the transmitted beam. This is called the amplitude mode scan or A-mode scan. A-mode (A-line or 1-D imaging), or amplitude mode horizontal axis represents distance or depth. As complement, the vertical axis represents the amplitude.

Time of flight (TOF) is directly related to the depth of reflecting interface in a straight line from the transducer probe. The incidence of the ultrasound wave between two medium is perpendicular to the surface (normal incidence), so that the transmission is optimal.

Ultrasound beam is transmitted through a uniform homogeneous medium. The acoustic properties of medium such as velocity of propagation are uniform. The medium boundaries are relatively large compared to the wavelength, plain, smooth and the reflections are specular. There are no multiple reflections between medium.

The transducer consists of a single element circular disc. The ultrasonic wave initially propagates in a cylindrical beam and the diameter of the beam being equal to the diameter of the transducer. Ultrasonic beam is not focusing (unfocused beam) and very narrow so that all echoes originating from its central axis. Wave propagations are either the plane wave or the spherical wave.

These assumptions are important for the developing of optimal ultrasound imaging systems. Thus, details in Fig.2 (see appendix) are obtained.

4.1 Acoustic Pressure Penetration

Figure 3 shows the calculation of acoustic intensity penetration through human leg model.

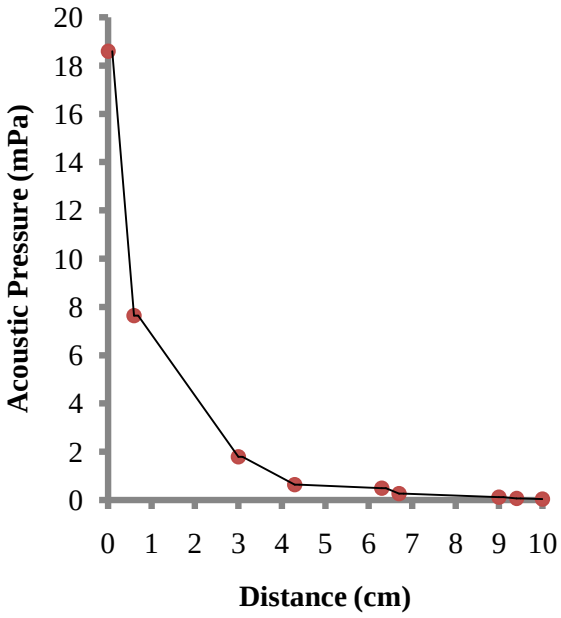

Fig.3 Graph of Acoustic Pressure Penetration

Based on trend in Fig.5, the rough correlation of acoustic pressure in lower leg related to distance penetration can be derived as in (8).

$$P = 11.75e^{-0.55x} \tag{8}$$

P is acoustic pressure (mPa) and x is distance (cm). It gives $R^2 = 0.776$.

4.2 Attenuation Profile

The attenuation profile for each region of leg is shown in Fig.4.

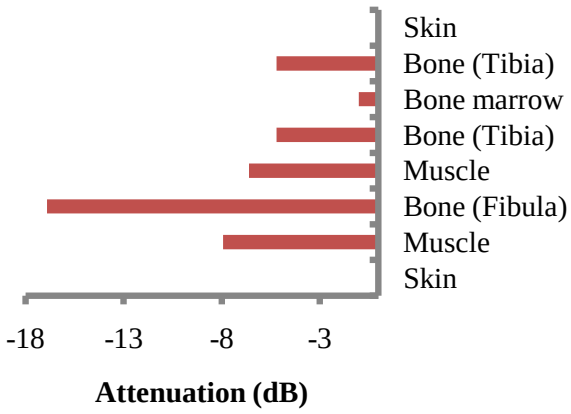

Fig.4 Chart of Attenuation Profile

Fibula bone introduces the highest attenuation. On the contrary, absorption caused by muscle is

much intense than of tibia. Logically, skin has minimum attenuation followed with bone marrow.

4.3 Time of Flight

Total time required for the wave to be transmitted can be deducted from the following Fig.5.

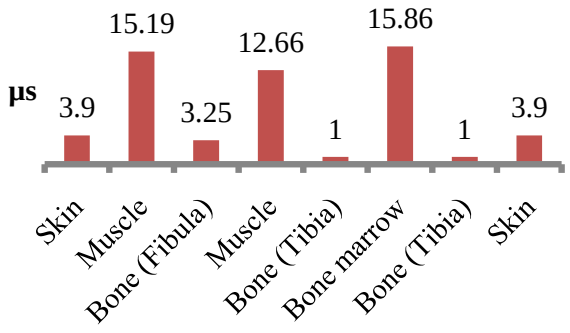

Fig.5 Time of Flight for Each Region (in µs)

Significant delay occurs through bone marrow and muscle. Less influential consume of time is given by skin, fibula, and tibia respectively.

5 In Vitro Experiment

The experiment was done with set-up as in Fig.6 (see appendix). Pulse generator 4001 was triggering the high power FS-100. Olympus contact transducer gave 1 MHz signal in transmit-through mode. Waveforms (input-output) were observed by digital oscilloscope DSO-2280. On PC, captured graph is caught in Fig.7.

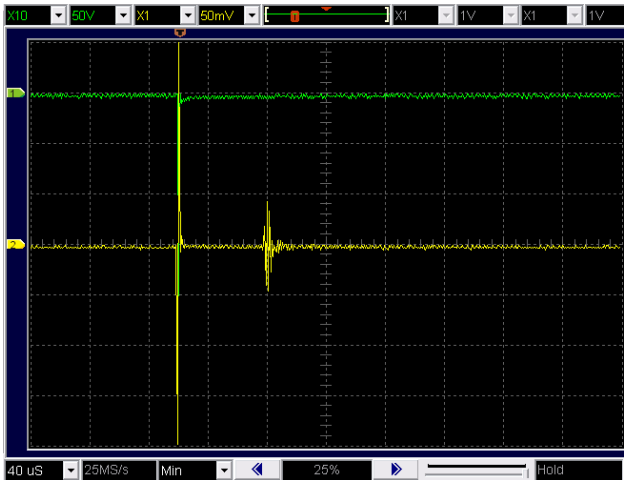

Fig.9 Ultrasound Signal at Edges of Position A-B

Path AB (see Fig.1) was decided. A 200 V pulse signal was transmitted via transducer and still adequately imposed an 89 mV on receiver side. There was about 50 µs gap between transmitted and received signal.

6 Conclusion

This study has proven that large amplitude pulsed ultrasound is able to pass through the bone. The feasibility of high power ultrasound for hard tissue imaging has been investigated. Quantitative analysis level and consequently in vitro experiment applied to human lower leg model is resulting in acceptable acoustic energy distribution.

7 Discussion for Future Work

From our simple calculation, it is expected that the high power ultrasound can penetrate the hard tissue. However, it may cause an undesired thermal effect. High-intensity focused ultrasound (HIFU) up to I_{SPTA} = 10 kW/cm^2 can damage the tissue through heating mechanism [28]. IEC (International Electro-technical Commission) has stated that the allowed maximum temperature of surface ultrasound transducer for external and internal used on tissue is 43°C. This is also depends on the ultrasound exposure time [29]. Hence, energy distribution and thermal distribution using Finite Difference Time Domain (FDTD) algorithm, Finite Difference Time Domain (PML) equation and Penne's Bio-Heat-Transfer-Equation (BHTE) could be further analyzed.

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	A							B
Ultrasonic Transmitter	Skin	Muscle	Bone (Fibula)	Muscle	Bone (Tibia)	Bone marrow	Bone (Tibia)	Skin	**Ultrasonic Receiver**
PZT, 1 MHz Size = 20 mm^2 Z = 33 MRayls Kt = 0.5									**PZT**, 1 MHz Size = 20 mm^2 Z = 33 MRayls Kt = 0.5
Distance	0.6 cm	2.4 cm	1.3 cm	2 cm	0.4 cm	2.3 cm	0.4 cm	0.6 cm	
	6 points 1 6	24 points 7 30	13 points 31 43	20 points 44 63	4 points 64 67	23 points 68 90	4 points 91 94	6 points 95 100	
c (m/s)	1540	1580	4000	1580	4000	1450	4000	1540	
Z (Rayls) ((kg/m^{2}s) × 10^6)	1.61	1.70	7.84	1.70	7.84	1.34	7.84	1.61	
α (dB/cm)	0.06	3.3	13	3.3	13	0.434	13	0.06	
Reflection / Transmission R	T R	T R	T R	T R	T R	T R	T R	T R	T
	(2.719%)	(102.72%)	**(-64.36%)**	(35.64%)	**(-70.81%)**	(29.19%)	**(-65.93%)**	(34.07%)	
(-90.7%)	(9.3%)	(64.36%)	(164.36%)	(64.36%)	(164.36%)	(70.81%)	(170.81%)	(90.7%)	(190.7%)
Attenuation	-0.036 dB	-7.92 dB	-16.9 dB	-6.6 dB	-5.2 dB	-1 dB	-5.2 dB	-0.036 dB	
	(99.59%)	(40.18%)	(14.29%)	(46.77%)	(54.95%)	(89.13 %)	(54.95 %)	(99.59%)	
Input Voltage, Vi = 400 V									**Output Voltage, Vo = 85.16 mV**
200	18.6	7.64	12.56	298.39m	490.43m	78.66m	119.75m	22.42m	42.58m
Pressure	18.52	19.02	1.79	0.638	269.49m	70.11m	65.8m	22.33m	
TOF (μs)	3.9	15.19	3.25	12.66	1.0	15.86	1.0	3.9	**TOF = 56.76 μs**

Fig.2 Calculation of Ultrasound Attenuation through Human Lower Leg

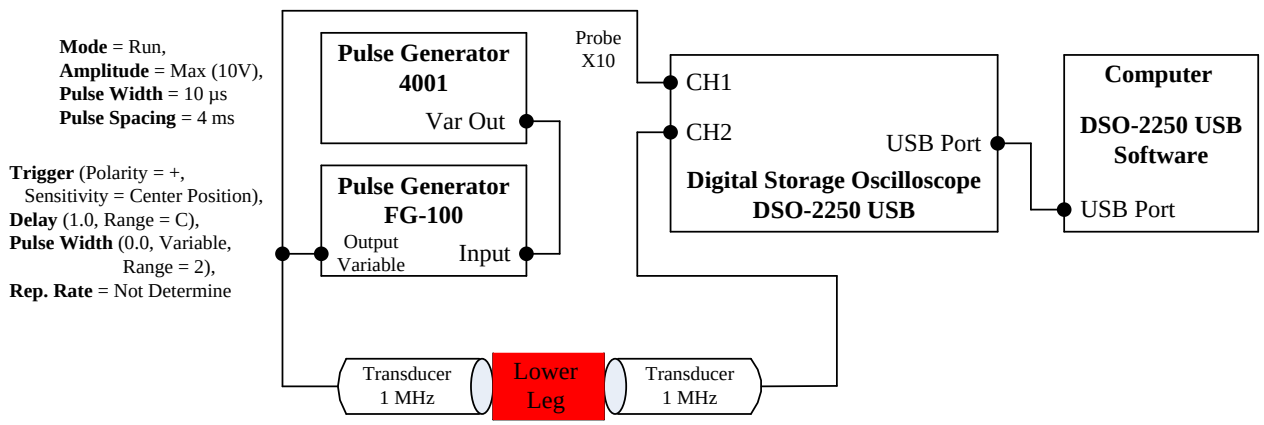

Fig.6 In Vitro Experiment Device Set-Up