Frequency Independence of Ultrasound Transit Time Spectroscopy

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Abstract — **Recent studies have shown that ultrasound transit time spectroscopy (UTTS) is an alternative method to describe ultrasound wave propagation through complex samples as an array of parallel sonic rays. This technique has the potential to characterize bone properties including volume fraction and may be implemented in clinical systems to predict osteoporotic fracture risk. In contrast to broadband ultrasound attenuation, which is highly frequency dependent, we hypothesise that UTTS is frequency independent. This study measured 1 MHz and 5 MHz broadband ultrasound signals through a set of acrylic step-wedge samples. Digital deconvolution of the signals through water and each sample was applied to derive a transit time spectrum. The resulting spectra at both 1 MHz and 5 MHz were compared to the predicted transit time values. Linear regression analysis yields agreement (R^2) of 99.23% and 99.74% at 1 Mhz and 5 MHz respectively indicating frequency independence of transit time spectra.**

Keywords— **Deconvolution, Ultrasound, Transit Time Spectrum, Solid Volume Fraction**

I. Introduction

Osteoporosis is the systematic loss of bone leading to increased porosity, fragility and fracture risk. The disease is a significant public health burden affecting more than 200 million people worldwide. Although quantitative ultrasound (QUS) assessment of osteoporosis, in particular the measurement of broadband ultrasound attenuation (BUA), offers non-ionizing, portable, and reliable prediction of fracture risk, its widespread utilisation suffers from both a limited understanding of ultrasound wave propagation through cancellous bone and an inability to elucidate the density and structure of a cancellous bone sample.

Previous studies have shown that an ultrasound wave propagating through a complex medium such as cancellous bone may be approximated by an array of parallel sonic rays, the transit time of each determined by the proportions of bone and marrow [1], [2]. We hypothesise that the resulting transit time spectrum (TTS) has the potential to reliably estimate the solid volume fraction of a bone sample, and hence, offers for the first time using ultrasound, the application of World Health Organisation definitions of osteopenia and osteoporosis. The aim of this study was to demonstrate that the TTS is independent of ultrasound frequency.

II. Materials and Methods

A. Experimental Ultrasound Measurements

The ultrasound experiments were performed in transmission mode utilising pairs of 1 MHz and 5 MHz broadband ultrasound transducers, all 0.75" in diameter, single element, and unfocused. The transducers were immersed in water, coaxially aligned with a fixed separation of 20.4 mm. The transmitter and receiver are connected to a high frequency pulser-receiver (Panametrics, PR5800, Austin, TX, USA). The measured ultrasound signals were acquired with 100 MHz sampling frequency by a 14-bit digitiser card and saved for further analysis. A sketch of the experimental set-up is shown in figure 1.

A range of ten different acrylic step-wedge samples, as shown in figure 2, was used. The samples have cylindrical shape with 20.4 mm height and of equal diameter to the transducer surface, varying in thickness normal to the direction of ultrasound propagation. The different number of steps results in a range of transit time inhomogeneities. Acrylic and water serve as surrogates for bone and marrow respectively with a speed of sound of v_a=2635.3 m/s for acrylic and v_w=1486.1 m/s for water respectively, measured experimentally at 21.3 °C water temperature.

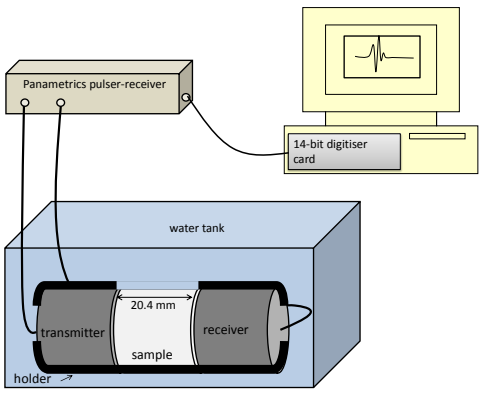

Fig. 1: Experimental set-up.

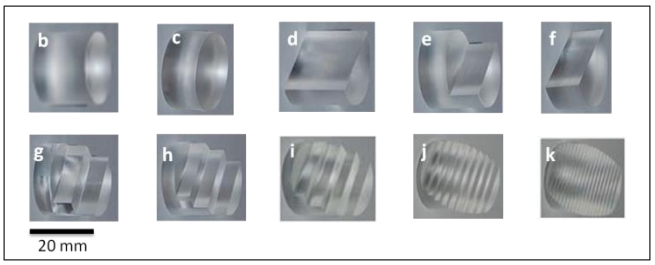

Fig. 2: Photographs of the different acrylic models. Model 'a' corresponding to 'marrow' is substituted by water and serves as a reference and is not shown in this figure.

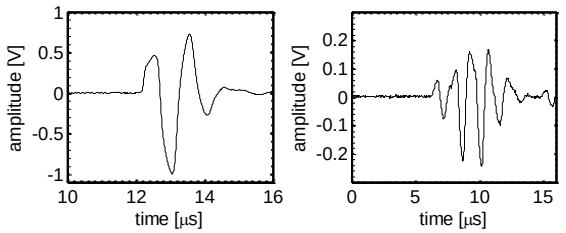

Fig. 3: *left:* 1 MHz ultrasound signal through water (input signal), *right:* 1 MHz ultrasound signal through model 'h' with 4 steps. Note the enlarged time scale for the signal through water.

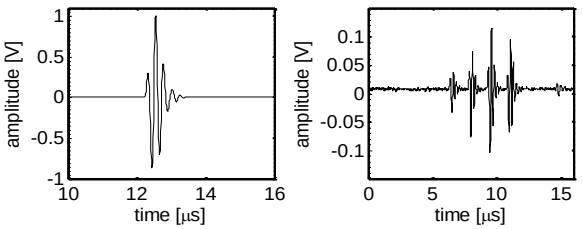

Fig. 4: *left:* 5 MHz ultrasound signal through water (input signal), *right:* 5 MHz signal through model 'h' with 4 steps. Note the enlarged time scale for the signal through water.

B. Derivation of Transit Time Spectrum via Deconvolution

The transit time spectra (TTS) for each sample were derived via digital deconvolution of the measured ultrasound signals. Noting that the output signal may be described by the convolution of the sample-specific TTS and the input signal, an inverse solution for the TTS may be derived using the numerical active-set deconvolution method [2]. The 1 and 5 MHz ultrasound signals through water served as the input signal, while the measured ultrasound signal through the samples were used as the output signals for the computational deconvolution of two signals. The resulting TTS were then compared to predicted TTS values based on the sonic ray concept [3].

C. Sonic Ray Concept

Previous studies [1], [3] have shown that ultrasonic wave propagation may be described by an array of parallel sonic rays. Each ray has a unique transit time defined by the amount of material the ray is travelling through. The transit time spectrum ranges from t_{min} (transit time only through solid) to t_{max} (transit time only through liquid). The output signal measured by a phase sensitive transducer is then the superposition of all sonic rays.

III. Results and Discussion

Figure 3 and 4 displays the measured 1 MHz and 5 MHz ultrasound signals solely through water (left hand side) and an example of measured ultrasound signals through a step-wedge sample, in this case model 'h' with four steps (right hand side). The experimentally derived transit time spectra (TTS) are shown in figure 5-8 along side with corresponding predicted transit time values.

It is observed that albeit the input and output signals are different for 1 MHz and 5 MHz, showing phase interference in the 1 MHz but no signal overlap in the 5 MHz output signal, the resulting transit time spectra exhibit similar properties; for example four distinct peaks corresponding to the individual steps of model 'h'.

The black bars correspond to the experimentally derived TTS and the white bars to the predicted TTS respectively. Note that the time axis is negative with a maximum value of 0 μs = t_{max}, indicating the transit time solely through water as demonstrated for model 'a'. Consequently, all sonic rays encountering a solid portion will have shorter, i.e. negative transit times. The y-axis indicates the proportion P(t) of sonic rays with a specific transit time. The proportions within the predicted TTS were calculated by the relative sonificated area and the relative attenuation of each individual sonic ray for each step-wedge. Noting the attenuation of acrylic to be 25.3 Np/m at 1 MHz and 78.3 Np/m at 5 MHz, the proportion within the 5 MHz TTS is lower than the proportion within the 1 MHz TTS. The low amplitude peaks in the experimentally derived transit time spectra, particularly in the 1 MHz TTS (figure 5 and figure 6) are due to noise and may be avoided by applying a threshold. An interesting observation is that these deconvolution artifacts are highly suppressed in 5 MHz TTS, which is likely due to the fact that the 5 MHz output signals have less phase interference.

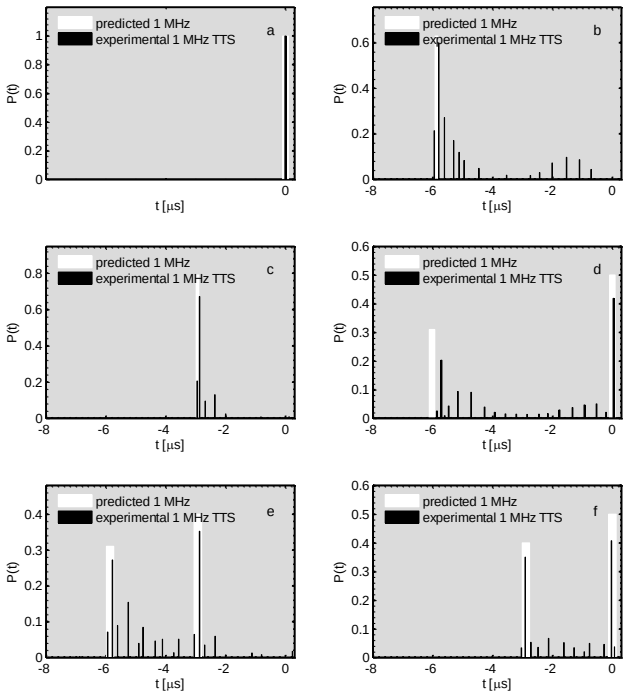

Fig. 5: Comparison of the experimental via deconvolution derived TTS with the predicted TTS for models ‘a’-‘f’ for 1 MHz.

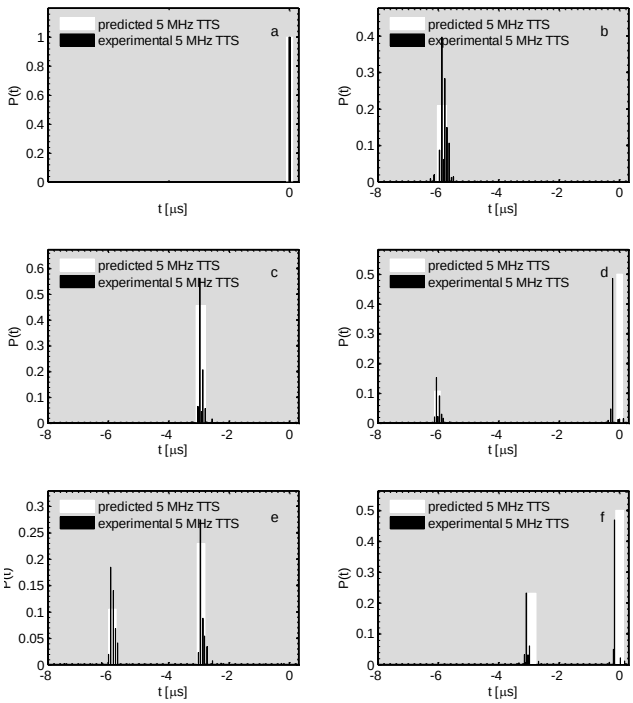

Fig. 7: Comparison of the experimental via deconvolution derived TTS with the predicted TTS for models ‘a’-‘f’ for 5 MHz.

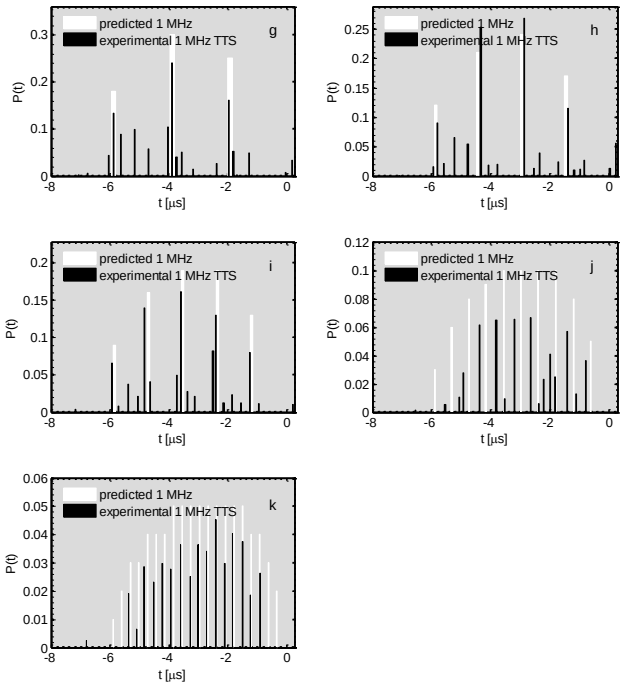

Fig. 6: Comparison of the experimental via deconvolution derived TTS with the predicted TTS for models ‘g’-‘k’ for 1 MHz.

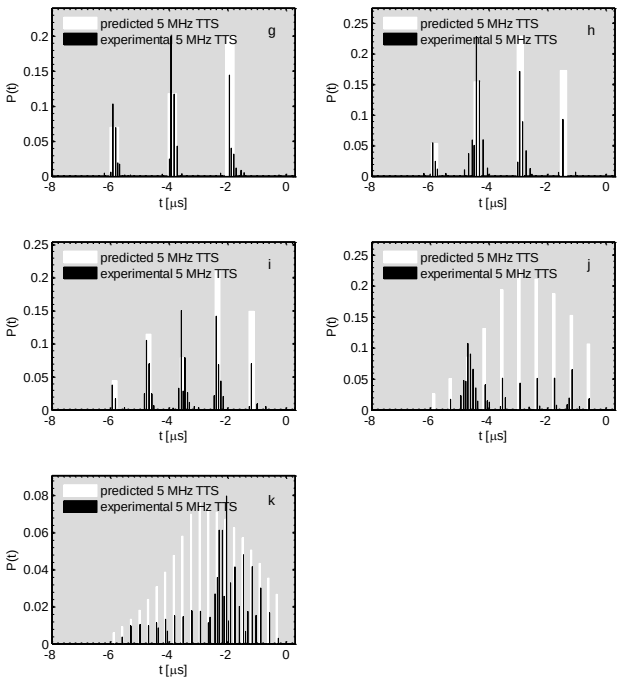

Fig. 8: Comparison of the experimental via deconvolution derived TTS with the predicted TTS for models ‘g’-‘k’ for 5 MHz.

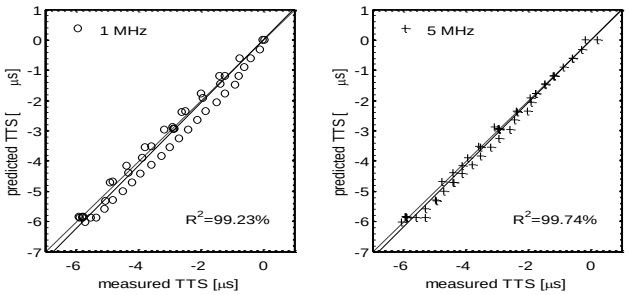

Fig. 9: Comparison of predicted TTS values (based on the parallel sonic ray model) with the experimentally derived TTS values of 1 MHz (left, circles) and 5 MHz (right, stars). The dashed line represents the line of equality, the solid line the linear regression fit.

Table 1 Linear regression analysis results

	1 MHz	5 MHz
Fit type	Linear model $f(x)=p_1 \cdot x + p_2$	Linear model $f(x)=p_1 \cdot x + p_2$
Coefficients with 95% confidence bounds	p_1=1.039 [1.027, 1.051]	p_1 = 1.028 [1.021, 1.035]
	p_2 = -1.301e-08 [-3.394e-08, 7.917e-09]	p_2= -3.209e-09 [-1.532e-08, 8.9e-09]
SSE	4.483e-12	1.495e-12
RMSE	1.434e-07	8.282e-08
R-square	**0.9923**	**0.9974**

SSE: sum of squares due to error, RMSE: root mean squared error

Figure 9 shows the comparison of experimentally derived and predicted transit time values at both 1 MHz and 5 MHz. A linear regression fit yields agreements (R^2) of 99.23% (1 MHz) and 99.74% (5 MHz). The results of the linear regression analysis are listed in table 1. Frequency independence of the transit time values is given for p_1=1 and p_2=0. From our analysis with p_1 close to 1 and p_2 close to 0, we can conclude that the transit time values for 1 MHz and 5 MHz have a high agreement of more than 99% with the predicted values and hence are frequency independent.

IV. Conclusions

We have shown that ultrasound transit time spectroscopy is frequency independent. It is further envisaged that it may quantify bone morphology thereby providing both reliable estimation of WHO criteria and improved prediction of osteoporotic fracture risk.

References

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