Simultaneous assessment of bone thickness and velocity for ultrasonic computed tomography using transmission-echo method

Rui Zheng, Philippe Lasaygues

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Simultaneous Assessment of Bone Thickness and Velocity for Ultrasonic Computed Tomography Using Transmission-Echo Method

Rui Zheng
Dept. of surgery
University of Alberta
Edmonton, AB, Canada
rui.zheng@ualberta.ca

Philippe Lasaygues
Laboratory of Mechanics and Acoustics
Aix-Marseille University UPR CNRS 7051
Marseille, France
Lasaygues@lma.cnrs-mrs.fr

***Abstract*—The robustness and accuracy of the transmission-echo (TE) method is investigated on simultaneous thickness and velocity estimation of double-layered thin bone samples. Twenty-two pairs of bovine cortical samples were assembled and measured by two pairs of immersion transducers with nominal frequencies of 1MHz and 2.25MHz. For each measurement, the TOF of six pulses contained by one transmission and two echo signals were detected and then used for the calculation. The mean relative errors of effective samples for 1MHz and 2.25MHz transducers are 4.87% and 7.13% on cortical thickness estimation, and 4.65% and 5.88% on velocity assessment, respectively. The method shows more stability on velocity measurement. For both thickness and velocity measurement, the experiments in low frequency provide more accurate estimations than high frequency. It is demonstrated that the TE method shows a potential to simultaneously estimate the cortical thickness and ultrasonic wave velocity for the mimic model of long bones.**

Keywords— transmission-echo method; bone thickness; bone velocity; initial modeling;ultrasonic imaging.

I. INTRODUCTION

Ultrasonic computed tomography (UCT) based on inversion scattering theory has been developed and *in vitro* applied to the measurement of long bone samples such as cross-sectional imaging of children femurs and cortical thickness estimation based on the reconstructed inner structures [1][2]. It is of great importance to establish more accurate and precise initial models before the inversion procedure, for the acoustical impedance contrast level between the hard tissue (bone) and the background (soft tissues *in vivo* or water in vitro) is very high for long bone structures [3]. Therefore the ultrasonic wave velocity and thickness of cortex are demanded to be predetermined for each single object and then used for the initial modeling.

Conventionally on velocity and thickness estimation, one parameter can be only calculated when the other is given, for example, the ultrasonic wave velocity can be computed by dividing the sample thickness by the measured time of flight (TOF). Many techniques have been implemented to measure speed of sound (SOS) and broadband ultrasound attenuation (BUA) specially adapted to bone tissue study [4][5][6]. Different from the conventional methods with only the main pulses used for analysis, the improved methods analyze and apply the multiple pulses in transmission or reflection signals to the parameter estimation in order that the thickness and velocity can be simultaneously assessed. This improved estimation method has been utilized to investigate the SOS and thickness of porous composites at the same time [7][8]. Recently Loosvelt and Lasaygues [9] applied the multiple-pulse method to the bone study using low frequency transducers. The wavelet-based processing (WBP) method was developed to identify the desired multiple transmission or reflection pulses from main pulses in the case of overlapped signals. The results demonstrate a mean estimated error ranged from 1% to 3.5% and are comparable to those reference values from the physical measurements. Moreover, the WBP method in transmission and echo modes was applied to the thin bone sample assessment, whose thickness is approximate or smaller than the ultrasound wavelength used in ultrasonic imaging, and the results match well with the mechanical measurement and other ultrasonic methods using high-frequency transducers. [10][11].

II. METHODS AND EXPERIMENTS

A. Transmission-echo method

Fig. 1 illustrates the six pulses to be applied in the transmission-echo (TE) method, which are the echoes from left transmitter t_{L1} and t_{L2}, echoes from right transmitter t_{R1} and t_{R2}, and transmission pulses t_1 and t_2. Together with the arrival time of reference signal t_0 and the reference velocity V_0, the ultrasonic wave velocity of object sample material, V_e and the thickness of two layers, e_1 and e_2 can be calculated using the equations indicated as below:

$$V_e = \frac{V_0(2t_0 - t_{L1} - t_{R1} - t_2 + t_1)}{3t_1 - t_{L1} - t_{R1} - t_2} \tag{1}$$

$$e_1 = \frac{V_e(t_{L2} - t_{L1})}{2} \qquad e_2 = \frac{V_e(t_{R2} - t_{R1})}{2} \tag{2}$$

The most important step for TE method is the TOF determination for different pulses, especially for the multiple reflection or transmission pulses. Therefore the WBP method originated from the Meyer-Jaffard algorithm are introduced to improve the accuracy and robustness of TOF measurements. The wavelet decomposition method applies orthonormal properties on the dyadic grid, which will result in the coefficients on particular scale and correspondingly lead to the locations of TOF [9].

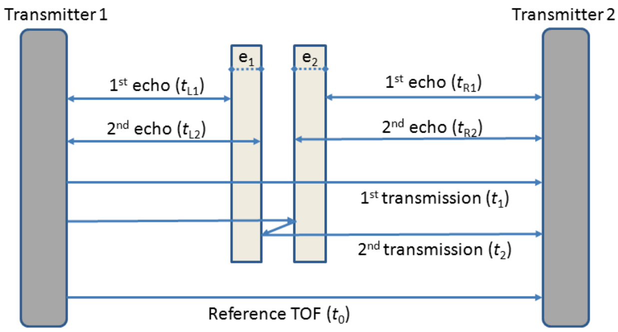

Fig. 1. The schematic of transmission-echo (TE) method in UCT.

B. Samples and experimental setup

Sixteen bovine cortex thin plates whose thickness is ranged from 0.93 to 2.32 mm were paired to compose 22 double-layer bone model samples for the measurement. The samples are divided into two categories according to different orientations of bone matrix: radial direction or transverse direction i.e. perpendicular to the radial direction. Only the samples from the same matrix orientation category can be paired in order to keep the consistency of bone properties, e.g. the acoustic velocities. The paired samples were aligned with their surfaces parallel to each other and then attached at both edges by reusable adhesive putty with 1-2 cm distance aparted.

The thickness of samples was physically measured by caliper and the velocities have been estimated during the previous work [11]. These results are proposed as the reference values and compared with the results from TE method. It is to be noticed that the average velocity of each pair of samples was calculated and used as the reference since TE method is only able to estimate one value of velocity for both samples in the pair. In the latter manuscript, the measured thickness from caliper and TE method will be correspondingly denoted as "caliper" and "TE", and the velocities from the previous echo experiments and TE method will be denoted as "WBP" and "TE", respectively.

Two pairs of immersion transducers with different nominal frequencies were applied to the measurements. The 1MHz transducers (Imasonic® 1718A) were dedicated to a preliminary study of the TE method in the exceptionally small scale of thickness (0.3~0.7 wavelength which is ~3.4 mm in bone tissue). The focus transducers with the nominal frequency 2.25MHz (Imasonic® 1719A) were then used for the accuracy and precision assessment of TE method. In this case, the sample thickness is range in 0.6 to 1.5 times of the wavelengths (~1.5 mm in bone tissue).

Fig. 2 shows the experimental setup for the TE method. The sample was firstly fixed in a specially designed aluminum frame and then placed at the focal spots of the pair of transducers (~90mm for the 1MHz and ~150mm for the 2.25MHz). The reference signals were collected without the frame in between before the sample measurement. In the case of 2.25MHz focus transducers, the samples were placed vertical to water level as shown in the figure so that the diverged ultrasound fan-beam can penetrate samples in the center position and cover contact areas as large as possible. The bone surfaces were parallel to the transducer surface to reduce energy loss due to the incident angles. The waveform generator (TTI® TGA1241) was employed to produce the target source wavelet for the TE method.

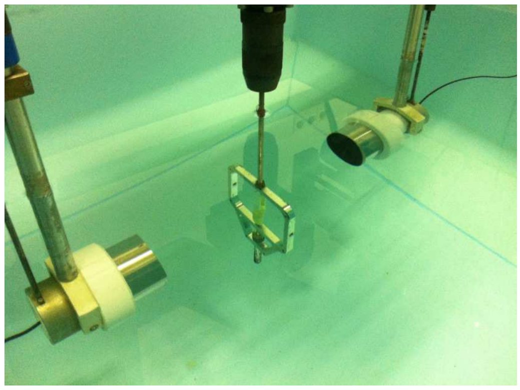

Fig. 2. The experimental device for the TE method.

III. RESULTS AND DISSCUSSIONS

A. Preliminary results with low frequency transducer

Since the ultrasound wavelength in bone tissue at the nominal frequency of 1MHz is about 3.4mm which is more than twice thickness of some samples, only nine pairs of thicker samples were applied for this preliminary study. Table 1 summarizes the measurement results for the nine pairs of double-layer thin bone samples using 1MHz transducers. Among all measurements, three groups (1, 6 and 9) with the least thickness (<0.4 wavelength) are failed for the estimation, two groups (3 and 7) with the most thickness (>0.6 wavelength) provide the best estimation, and other groups (2, 4, 5 and 8) are only successful on the velocity estimation.

For cortical thickness estimation, since the ultrasonic wavelength is about 3.4mm, thus theoretically the thickness larger than half wavelength (~1.7mm) can be measured. As shown in Table 1, the relative errors referring to caliper of 6 measurements with sample thickness larger than 1.7mm are ranged from 3.74% to 7.69%, while other samples present very unpredictable results, some errors are more than 100%, and 4 measurements are completely failed to obtain the thickness.

The mean error of the 6 "proper" measurements, whose sample thickness is larger than half wavelength, is 4.87%.

For acoustic velocity estimation, the TE method shows better performance, most samples can be measured, the relative errors (referring to the results measured by WBP echo method and single sample [11]) are ranged from 0.02% to 11.07%, and the mean error is as low as 4.65%. Furthermore the velocity estimation is less influenced by sample thickness, the relative errors are more consistent in the different thickness range, and the measurements are failed only in the extreme condition of very thin samples (<0.4 wavelength).

TABLE 1. The measured thickness and velocity for nine pairs of double-layer thin bone samples using 1MHz transducers.

Sample Pairs	**Left thickness**			**Right thickness**			**Velocity**		
	Caliper (mm)	***TE (mm)***	***Error (%)***	***Caliper (mm)***	***TE (mm)***	***Error (%)***	***WBP (m/s)***	***TE (m/s)***	***Error (%)***
1	1.06	-	-	0.98	1.65	68.37	3361	-	-
2	1.33	3.19	139.85	1.29	2.95	128.68	3489	3665	5.05
3	2.32	2.18	6.03	1.82	1.96	7.69	3404	3206	5.82
4	1.64	1.91	16.46	2.14	2.22	3.74	3390	3383	0.20
5	1.51	3.6	138.41	1.24	3.09	149.19	3527	3917	11.07
6	0.98	-	-	1.06	1.73	63.21	3361	-	-
7	1.82	1.96	7.69	2.32	2.2	5.17	3404	3209	5.72
8	2.14	2.22	3.74	1.64	3.53	115.24	3390	3391	0.02
9	1.24	-	-	1.51	-	-	3527	-	-

B. Methodology evaluation with high frequency

1) Thickness measurement

Among 22 pairs of samples, there are still 4 measurements failed for the thickness assessment due to irregular shapes, inhomogeneous physical properties and improper location of samples; the relative errors of failed measurements are as high as 36% to 63%. These data points are exclusive from the latter analysis.

Fig. 3 illustrates the relative errors of all other 40 successful measurements in the ascending order of sample thickness. Of all measurements, the errors are ranged from 0% to 22.58%. The relative errors are apparently decreased with the increase of sample thickness. Table 2 lists the statistical results of thickness measurements in three different ranges: smaller than 1mm (~0.7 wavelength), 1-1.6mm (0.7-1 wavelength) and larger than 1.6mm (>1 wavelength). It is depicted that the group with larger thickness shows much smaller average errors (4.29% and 5.88%) than the small thickness group (12.16%), especially in the condition that the thickness is smaller than 1mm (~0.7 wavelength), the errors can be up to 22%. The reason for this discrepancy can be contributed to uncertainty of TOF estimation for Eq. (2) due to serious interference between the two echoes from inner and outer surfaces in the case of thin samples.

The overall mean error of 2.25MHz frequency measurements is 7.13%, which is slightly higher than the results from 1MHz frequency measurements 4.87%. The lower attenuation due to lower nominal frequency of transducers can result in the more penetration of ultrasound waves, and moreover the larger amplitudes of signals and higher signal-to-noise ratio (SNR). Therefore the lower frequency provides the better performance for thickness measurements.

Lastly the correlation coefficient between caliper measurements and TE method is 0.9628. This result indicates the notable consistency between physical measurement and ultrasonic method.

2) Velocity estimation

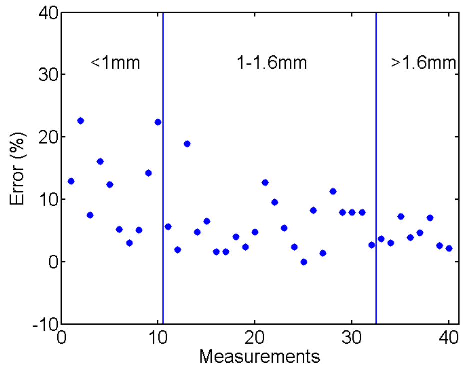

Fig. 3. The relative errors of sample thickness referring to caliper measurement for all 40 successful measurements using the TE method at nominal frequency of 2.25MHz in the ascending order of sample thickness.

TABLE 1. The thickness measurements in different ranges.

Thickness Range	**No. of Measurements**	**Average Relative Error**
< 1.0 cm	10	12.16%
1.0-1.6 cm	22	5.88%
> 1.6 cm	8	4.29%
Overall	40	7.13%

Fig. 4 shows the calculated relative errors of estimated velocity using TE method referring to the WBP method in the ascending order of combined sample thickness which is sum of the thickness of measured pair of samples. The combined sample thickness is ranged from 1.91mm to 4.14mm, and the errors are ranged from 0.04% to 12.20%. There are no apparent influences of various sample thicknesses on velocity estimation. It is different from the case of thickness measurement, in which the accuracy of estimation is greatly improved with the increase of sample thickness. It can be derived that the independency of velocity measurement from cortical thickness in WBP method results in more stable estimation of velocities in TE method [11].

However, a small trend of increasing errors is appeared with the increased combined thickness. Table 3 summarizes the calculated average relative errors for four groups of different combined thickness ranges. It is depicted that the groups with larger thickness shows a slightly higher average errors, except the fourth group including only one sample pair which could be an exceptional case during the measurement. In addition, the overall relative error of all 22 samples pairs measured by 2.25MHz transducers is 5.88%, which is also slightly larger than the average error of 4.65% from 1MHz transducers. Both cases indicate that the estimation accuracy will be affected by attenuation of bone tissues. In the cases of larger combined thickness and higher nominal frequency of transducers, the relative errors of estimated velocities are increased, for the higher attenuation introduces more noises and scattering interferences to the signals moreover leads to a lower SNR.

The mean velocities estimated by the WBP and TE method are 3378 m/s and 3280 m/s for the samples with radial bone matrix direction, 3456 m/s and 3389 m/s for transverse matrix direction respectively. These results are approximate to each other. The smaller magnitudes in the TE method possibly result from the long term preservation and exposure to low temperature between the TE and WBP experiments. However, the TE method demonstrates much larger variation than the WBP method; the standard deviations (STD) of TE method are 220 m/s and 263 m/s for radial and transverse groups, which are much higher than the STDs of WBP method (20 m/s and 56 m/s) for the same bone samples. The variation of velocity measurement may arise from the more complex structures of the models used by TE method. Firstly, the double bone layers produce longer propagation path and more energy loss of ultrasound waves. Secondly, the refraction and reflection during the propagation can generate more scattering and diffraction influences on signals and then arise the uncertainty of TOF detection, especially for the main and multiple transmission pulses t_1 and t_2. Despite of large variation, the estimated velocities from TE method show similar properties as the WBP method. For example, the velocities of the radial direction group are both smaller than the transverse direction group, and the STDs of transverse group are both larger than the radial direction group. It is indicated that the TE method is a consistent and robust approach for the velocity estimation even under the condition of more complex structures.

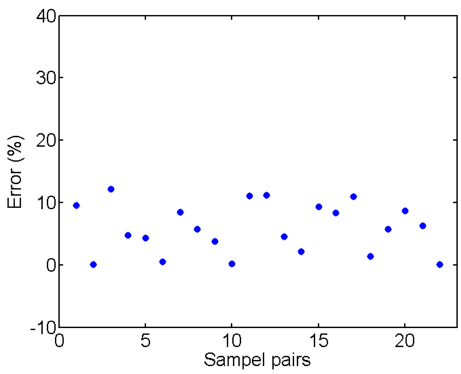

Fig. 4. The relative errors of ultrasonic wave velocities referring to the WBP echo method for all 22 pairs of samples using the TE method at nominal frequency of 2.25MHz in the ascending order of combined thickness.

TABLE 2. The statistical results of velocity estimation in different combined thickness ranges which is calculated by adding the thickness of the measured pair of samples together.

Combined Thickness Range	**No. of Pairs**	**Average Relative Error**
< 2.0 mm	2	4.80%
2.0-3.0 mm	13	6.02%
3.0-4.0 mm	6	6.90%
> 4.0 mm	1	0.04%
Overall	22	5.88%

IV. CONCLUSIONS

The transmission-echo method provides a feasible and reliable means to simultaneously assess the thickness and ultrasonic wave velocity for double-layer thin bone samples which can be performed as a mimic model of long bones measured in UCT. In the case of effective thickness estimation, *i.e.* the thickness is larger than half ultrasound wavelength, 40 out of 44 measurements are successfully assessed and the success rate is above 90%. The average relative errors of sample thickness measurement are 4.87% and 7.13% for 1MHz and 2.25MHz transducers respectively. The results demonstrate good agreement to caliper measurement with correlation coefficient of 0.9628. For ultrasonic wave velocity estimation, all pairs with effective sample thickness are successfully measured, and the mean relative errors are 4.65% for 1MHz and 5.88% for 2.25MHz transducers. Moreover, the TE method shows more robustness and stability during velocity measurement since the results are less influenced by the difference of sample properties such as thickness. For both thickness and velocity measurement, the experiments in low frequency provide more accurate estimations than high frequency, however as the disadvantage, the larger wavelength will result in the lower resolution on thickness estimation. However the method reveals sensitivities on complex structures of subjects, for example irregular shapes of bone samples and parallel alignment of two layers. Nevertheless, the transmission-echo method shows a potential to simultaneously estimate the cortical thickness and ultrasonic wave velocity for long bone model, which can be applied to improve the initial modeling for the UCT.

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