Microstructure Characterization of Cancellous Bone Based on Ultrasonic C-Scan Imaging

Ying Li, Chengcheng Liu, Feng Xu, and Dean Ta

Abstract

Ultrasonic backscatter signals can reflect the microstructural information of cancellous bone. The goal of this study is to characterize the microstructure of cancellous bone in the mesoscale and estimate trabecular thickness (Tb.Th), trabecular bone separation (Tb.Sp), bone volume fraction (BV/TV) and structure model index (SMI) based on ultrasonic C-scan imaging. Nine cuboid cancellous bone samples were prepared in this experiment. The bone samples were scanned using an ultrasound C-scan equipment with a 30 MHz focused transducer. The −6 dB lateral resolution of the transducer was 0.157 mm. The scanning interval was 0.05 mm. The scanning region of interest was 10 × 10 mm in the center of the cancellous bone sample. The cancellous bone images were obtained based on time of flight (TOF) and amplitude (AMP). The trabecular microstructure information was analyzed based on the ultrasonic C-scan images and compared with those obtained by μ-CT. The microstructure of trabecular bone can be clearly seen in the TOF and AMP images. The microstructure estimated based on the ultrasonic images was similar to the μ-CT provided results. The estimated parameters including Tb.Th, Tb.Sp, BV/TV and SMI had an average estimation error of 21, 22, 17 and 12% with a moderate correlation to the μ-CT measured results. The results demonstrated that ultrasonic C-scan imaging can be used to evaluate cancellous bone's microstructure.

Keywords

Ultrasound backscatter • C-scan imaging • Cancellous bone

1 Introduction

Osteoporosis is a bone disease that can reduce bone density and deteriorate bone microarchitecture [1]. Over 200 million people worldwide are suffering from this disease, 75% of which are not diagnosed and properly treated [2]. Referring to the World Health Organization (WHO), osteoporosis is defined as "a systemic skeletal disease characterized by low bone mass and microarchitectural deterioration of bone tissue with a consequent increase in bone fragility and susceptibility to fracture" [3]. Fractures will increase morbidity and mortality, lower life quality and highly cost in healthcare [4]. Early diagnosis and treatment is important for the people who are at the risk of osteoporotic fractures.

Dual energy X-ray absorptiometry (DXA) is clinically used as the golden standard to diagnose osteoporosis. However, DXA has shortcomings of radiation, large equipment, highly cost and limited resources, which limit the DXA as an appropriate tool in osteoporosis diagnose. The bone mineral density (BMD) which measured by DXA can only provide 60–80% variability of the bone strength. The microstructure information, bone geometry and elastic

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properties of the bone that are important to evaluate the fracture risk, which cannot be assessed by X-ray based methods [5].

Recently, quantitative ultrasound (QUS) has been used to assess the fracture risk. Laugier et al. [6, 7] used ultrasonic transmission method to scan the bone. The ultrasonic parameters include speed of sound (SOS) and broadband ultrasound attenuation (BUA), which can reflect the distribution of BMD. Image processing methods were used to help doctors to select the lowest BMD area as a region of interest (ROI) for diagnostic.

Unlike ultrasonic transmission method, ultrasonic backscatter method uses a single transducer and works in the pulse echo mode, which can access some common skeletal sites for analysis. Ultrasonic backscatter can reflect the microstructural information and elastic properties of cancellous bone [8]. The trabecular bone structure can directly indicate the skeletal health status. Compared with DXA, the QUS techniques have the advantages of easier usage, more portability, time saving, less expense and nonionizing radiation. Cancellous bone is anisotropic and the DXA method can provide the 3D analysis of the bone. Although the high attenuation of the bone may limit the accuracy of the ultrasound backscatter method. Only the surface of the bone was available, which can also provide a way to detect the bone status. The QUS has the potential to be a more effective tool to diagnose osteoporosis.

The goal of this study is to characterize the microstructure of cancellous bone in the mesoscale based on ultrasonic C-scan imaging. The trabecular thickness (Tb.Th), trabecular bone separation (Tb.Sp), bone volume fraction (BV/TV) and structure model index (SMI) were estimated and compared with the standard values measured by μ-CT.

2 Materials and Methods

2.1 Sample Preparation

Nine cancellous bone samples were prepared in this experiment. The bone samples were cut from the distal end of bovine femur with dimensions of 2.0 × 2.0 × 2.0 cm. The surface of the specimen was parallel to the main stress orientation of the trabecular network. The bone marrow inside the trabeculae was flushed out using a water jet. The specimens were degassed using vacuum pump to remove air bubbles before the ultrasonic measurements. A μ-CT scanner (Skyscan 1076, Skyscan, Antwerp, Belgium) with a spatial resolution of 36 μm was used to obtain the three dimensional CT images of the cancellous bone samples.

2.2 Experimental Setup

The Tb.Th of the normal people is in the range of 0.10–0.17 mm and the Tb.Sp is in the range of 0.46–0.98 mm [9]. In order to clearly assess the microstructure of the cancellous bone, a focused transducer with a high spatial resolution is used. The spatial resolution is greatly affected by the beam diameter. The lateral resolution is determined by the −6 dB beam width (BD) in the focal plane:

$$BD = \frac{1.02Fc}{fD} \tag{1}$$

where BD is the beam width, F is the focal length, c is the speed of the ultrasound transmitted in the medium, f is the frequency, and D is the diameter of the ultrasonic probe [10].

The bone samples were scanned using an ultrasonic C-scan equipment (UPK-T10, PAC, USA) with a 30 MHz focused transducer (V375, 30 MHz central frequency, diameter is 0.25 inches, focal length is 0.75 inches, Panametrics, USA). Figure 1 shows the experimental system for ultrasonic C-scan imaging.

The −6 dB lateral resolution of the transducer was 0.157 mm. The scanning interval was 0.05 mm. The scanning region of interest was 10 × 10 mm (200 × 200 points) in the center of the cancellous bone sample. The UltraPAC stepper motor controller controlled the transducer to move in the x-y plane line by line. At each point, the transducer excited ultrasonic wave and receive the backscattered signal with 64 times averaging. The backscattered signals were acquired from each of the bone samples. The signals were stored on the computer for further analysis.

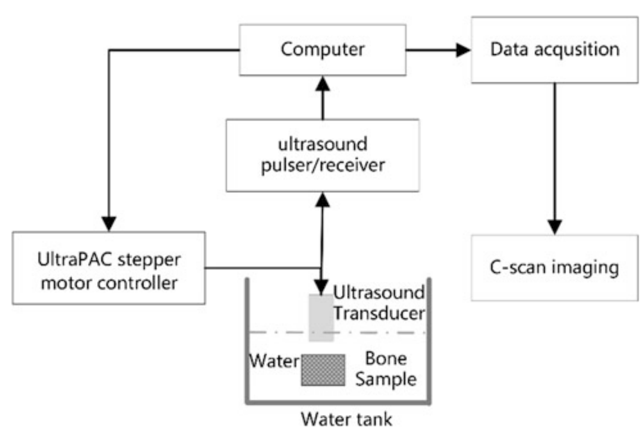

Fig. 1 The experimental system for ultrasonic C-scan imaging

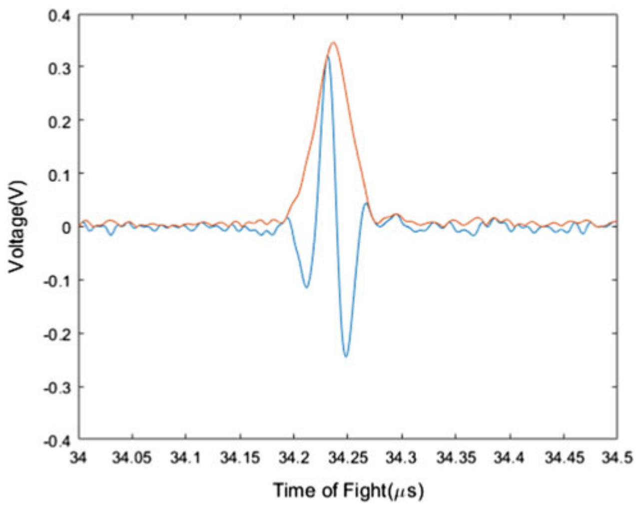

Fig. 2 Hilbert transformed envelope of a backscattered signal

2.3 Signal Processing

The cancellous bone images were obtained based on time of flight (TOF) parameter and amplitude (AMP) parameter. The RF data stored on the computer contains the entire information for imaging. Before the reliable parameter estimation, a type II Chebyshev bandpass filter is used to remove DC and high frequency components. However, the sampling frequency is 100 MHz in our system, which is close to the Nyquist limit. In order to estimate the ultrasonic imaging parameters accurately, a fast fourier transform (FFT) based interpolation is used to up sampling the signal. The TOF and AMP parameters can then be detected from the position and the value of the maximum point of the Hilbert transformed envelope signal [10]. The TOF and AMP data arrays were mapped to 8-bit images and then the images were threshold into binary images. As TOF and AMP are almost the same, only AMP images were used for further analysis. Figure 2 shows the Hilbert transformed envelope of a backscattered signal. Figure 3 shows (a) a TOF image of a cancellous bone and (b) a AMP image of a cancellous bone.

2.4 Image Analysis

Both ultrasonic C-scan images and μ-CT images were analyzed using BoneJ Software to extract the microstructure information, including Tb.Th, Tb.Sp, BV/TV and SMI. BoneJ (version 1.4.1) is a plugin for bone image analysis in ImageJ (version 1.50b) [11]. The trabecular microstructure information was analyzed based on the ultrasonic C-scan images and compared with those obtained by μ-CT. Note that because the ultrasound has a high attenuation in bone samples, the C-scan images only reflect the surface or subsurface of the bone specimen. The μ-CT images were also chosen from the same surface that the ultrasound scanned.

3 Results and Discussion

The microstructure of trabecular bone can be clearly seen in the TOF and AMP images. Table 1 shows the results measured from μ-CT images and ultrasonic C-scan images. The microstructure parameters estimated based on the ultrasonic images were similar to the μ-CT provided results. The estimated parameters including Tb.Th, Tb.Sp, BV/TV and SMI had an average estimation error of 21, 22, 17 and 12% to the μ-CT measured results, respectively. The quality of the ultrasonic image has a great effect on the microstructure parameter estimation. The spatial resolution of μ-CT measurement was 36 μm while the lateral resolution of

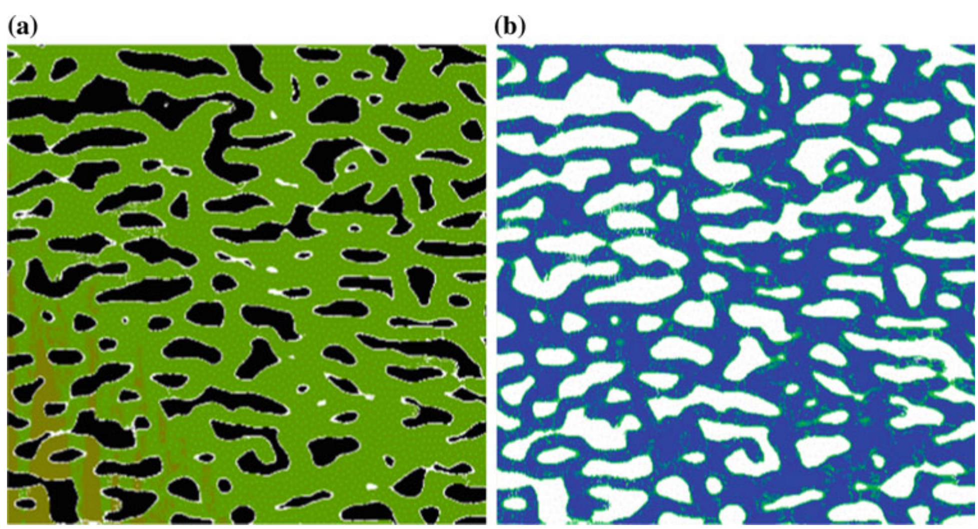

Fig. 3 **a** A TOF image of a cancellous bone and **b** a AMP image of a cancellous bone

Table 1 Ultrasonic C-scan measured microarchitecture of bone specimens

Bone	Tb.Th		Tb.Sp		BV/TV		SMI	
No.	μ-CT (mm)	C-scan (EPE) (mm)	μ-CT (mm)	C-scan (EPE) (mm)	μ-CT	C-scan (EPE)	μ-CT	C-scan (EPE)
1	0.30	0.20 (0.35)	0.67	0.57 (0.15)	0.28	0.34 (0.20)	4.80	4.26 (0.11)
2	0.20	0.21 (0.06)	0.55	0.56 (0.01)	0.26	0.32 (0.23)	6.05	3.94 (0.35)
3	0.23	0.13 (0.42)	0.72	0.99 (0.38)	0.20	0.14 (0.31)	6.82	7.11 (0.04)
4	0.24	0.25 (0.06)	0.58	0.76 (0.33)	0.29	0.26 (0.11)	4.55	4.05 (0.11)
5	0.22	0.20 (0.10)	0.57	0.59 (0.03)	0.27	0.32 (0.21)	4.67	4.11 (0.12)
6	0.29	0.19 (0.33)	1.17	1.03 (0.12)	0.16	0.16 (0.00)	4.66	4.16 (0.11)
7	0.41	0.32 (0.21)	0.49	0.48 (0.03)	0.51	0.57 (0.12)	2.71	2.75 (0.02)
8	0.26	0.24 (0.08)	0.70	1.24 (0.79)	0.26	0.17 (0.35)	4.23	4.77 (0.13)
9	0.35	0.26 (0.26)	0.91	1.02 (0.12)	0.24	0.23 (0.01)	4.00	4.53 (0.13)
Average	0.28	0.22 (0.21)	0.71	0.81 (0.22)	0.27	0.28 (0.17)	4.72	4.41 (0.12)

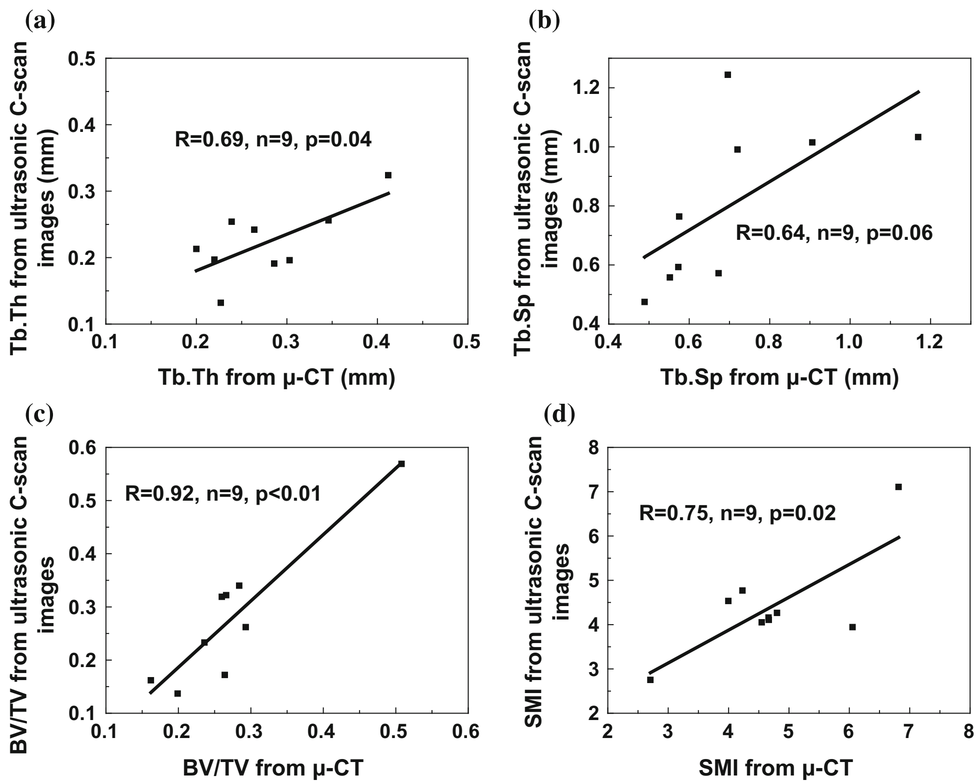

Fig. 4 Correlation between μ-CT image results and ultrasonic C-scan image results on **a** Tb.Th; **b** Tb.Sp; **c** BV/TV; **d** SMI

ultrasonic C-scan images was 157 μm. Considering the mean value of Tb.Th was 0.28 mm and the mean Tb.Sp is 0.71 mm for the cancellous bone specimens used in this study, the lateral resolution of ultrasonic C-scan measurement was relatively large. That might be the main reason for relatively big estimation error for some bone specimens. The noise from the stepper motor and the unparalleled specimen surface also had some influence on ultrasonic C-scan measurements. The multiple reflected waves between trabeculae and phase cancelations might also produce some random errors for the estimation of trabecular microstructure based on the ultrasonic C-scan images.

Figure 4 shows the correlation between μ-CT image results and ultrasonic C-scan image results on (a) Tb.Th; (b) Tb.Sp; (c) BV/TV; (d) SMI. The correlation coefficient values are 0.69 ($p < 0.05$), 0.64 ($p = 0.06$), 0.92 ($p < 0.01$) and 0.75 ($p < 0.05$), respectively. The ultrasonic C-scan image results have a moderate correlation with μ-CT image results since the lateral resolution of the focused ultrasonic transducer used in this experiment is close to the trabecular thickness, which may cause the imprecise estimation of the parameters and low correlation. The ultrasonic backscattered C-scan images can reflect the microstructure parameters. The BV/TV parameter extracted from the ultrasonic backscattered C-scan images has a significantly high correlation (R = 0.92, $p < 0.01$) with the result obtained by μ-CT. Which indicates that ultrasonic backscattered C-scan measurements might have the potential to be a cheaper, easier and non-ionizing potable tool in BV/TV estimation for cancellous bone evaluation.

4 Conclusions

In this study, the cancellous bone microstructure was analyzed using ultrasonic C-scan imaging. The estimated parameters including Tb.Th, Tb.Sp, BV/TV and SMI from the ultrasonic C-scan images were compared with the μ-CT results. The ultrasonic backscatter imaging method provides a cost effective, easy to use and accurate way for research and has the potential of clinical practices. The results demonstrated that ultrasonic C-scan imaging can be used to evaluate cancellous bone's microstructure.

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