Ultrasound in Med. & Biol., Vol. 41, No. 11, pp. 2955–2965, 2015

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2015.06.016

● *Original Contribution*

IMAGING INTERNAL STRUCTURE OF LONG BONES USING WAVE SCATTERING THEORY

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(*Received* 18 *December* 2014; *revised* 13 *June* 2015; *in final form* 19 *June* 2015)

Abstract—An ultrasonic wavefield imaging method is developed to reconstruct the internal geometric properties of long bones using zero-offset data acquired axially on the bone surface. The imaging algorithm based on Born scattering theory is implemented with the conjugate gradient iterative method to reconstruct an optimal image. In the case of a multilayered velocity model, ray tracing through a smooth medium is used to calculate the traveled distance and traveling time. The method has been applied to simulated and real data. The results indicate that the interfaces of the top cortex are accurately imaged and correspond favorably to the original model. The reconstructed bottom cortex below the marrow is less accurate mainly because of the low signal-to-noise ratio. The current imaging method has successfully recovered the top cortical layer, providing a potential tool to investigate the internal structures of long bone cortex for osteoporosis assessment. (E-mail: lawrence.le@ualberta.ca and rui.zheng@ualberta.ca) **© 2015 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Ultrasound imaging, Cortical bones, Image reconstruction, Born approximation, Osteoporosis.**

INTRODUCTION

Osteoporosis is a major bone disease in the aged population, especially postmenopausal women. The disease causes bone thinning and brittle bones, leading to a high risk of skeletal fractures and negatively impacting quality of life (Riggs et al. 2004; Werner 2005). Currently, mainly ionizing and non-ionizing radiation techniques are used in imaging. The former includes DEXA (dual-energy X-ray absorptiometry), QCT (quantitative computed tomography) and μCT (micro-computed tomography); the latter, mainly MRI (magnetic resonance imaging) and QUS (quantitative ultrasound) (Guglielmi 2013).

The use of QUS to assess osteoporosis and predict fracture risk has attracted considerable interest since 1990s (Genant et al. 1996; Laugier 2006; Laugier and Haiat 2010; Siffert and Kaufman 2007; Wuster and Hadji 2001). Camus et al. (2000) studied the lateral wave (head wave) and found it had potential in evaluation of the mechanical properties of cortical bone using arrival time and velocity. Wear (2003) applied the autocorrelation and cepstral methods with a constant radial ultrasonic velocity of 3800 m/s to measure the cortical thickness of six tibia samples; the estimated precision of the two methods was 0.3 ± 0.1 and 0.5 ± 0.2 mm, respectively. Zheng et al. (2007, 2009) used multiple reflected signals in the pulse-echo mode to estimate the normalized broadband ultrasound attenuation (nBUA) of cortical bone. Xu et al. (2010, 2012, 2014) and Song et al. (2011) analyzed the propagation of guided waves in long bone structure to evaluate bone quality and fracture. Le et al. (2010) used waveform simulations and traveling time calculations to investigate the nature of ultrasound wave propagation in long bones. Nguyen and Naili (2012a, 2012b) developed a spectral finite-element algorithm to calculate ultrasonic wave response in the viscoelastic anisotropic cortical bone plate model. Moilanen et al. (2007a) inverted the cortical bone thickness (U_{Th}) of human radius specimens using an L1 norm inversion scheme and found good agreement with the cortical thickness measured by peripheral quantitative computed tomography. Moilanen et al. (2007b, 2007c) also found that the measured phase velocity could be well modeled by a simple bone model despite the variations in cortical thickness along the bone

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axis. Recently, Foiret et al. (2014) reported a combined estimation of thickness and velocity using ultrasound-guided waves in human bone samples.

Ultrasound wavefield imaging based on scattering and inversion theories is another promising method for investigating the internal structure of long bones. The technique is widely used in geophysics to explore the Earth's interior and extract material properties such as velocity and reflectivity (Beylkin and Burridge 1990; Miller et al. 1987; Weglein 1982). This imaging method makes use of waves scattered in all directions by the scatterers to image the bone interior, which leads to more accurate image reconstruction.

In medicine, Greenleaf (Greenleaf 1983; Greenleaf and Bahn 1981) appeared to be the first to develop ultrasound computer-assisted transmission tomography to detect breast cancer. Pratt et al. (2007) combined the time-of-flight method and 2-D acoustic waveform inversion to image breast tissues and recover the spatial distribution of sound speed and attenuation. Duric et al. (2005) developed a prototype ultrasound tomographic scanner to study breast imaging using a phantom and a cadaver breast. They concluded that it was possible to image structures with a 0.4-mm spatial resolution and discriminate soft tissues with a small sound speed variation of 5 m/s.

Similar wave scattering principles can be applied to image and characterize bones. The research group led by Lasaygues was perhaps the first and leading group to successfully study inverse wave scattering in bones with many interesting results. Transmission data, reflection data or a combination was used to reconstruct the cross-sectional image of long bone shafts (Lasaygues and Lefebvre 2001). A multistep compensation technique (Lasaygues et al. 2004; Ouedraogo et al. 2002) was also developed to enhance the reconstructed images, where the reflection tomography provided information on the shape of the object, and transmission tomography was used to invert for the spatial variations of the inner structure. By use of a 2-D ring antenna with mechanical and electronic steering systems, ultrasonic–tomographic techniques were used to image the cross section of human femur shafts and estimate the cortical thickness of long bone shafts in children (Lasaygues 2006; Lasaygues et al 2005). The difference between mechanical and acoustical measurements of thickness was <0.5 mm (Lasaygues 2006). Furthermore, Lasaygues and Le Marrec (2008) applied the intercepting canonical body approximation (ICBA) to solve imaging problems involving material with high-impedance contrast with the surrounding medium. The inversion results they obtained were better than those obtained with the classic reflection tomography method using simulation data for infinite elastic cylindrical tubes. For other groups, Li et al. (2013) used the split-step Fourier imaging method to reconstruct fractured bone models and properly mapped the time sections to the depth images.

In this article, we describe a Born-based inversion technique to reconstruct the internal structure of long bones along the axial direction *in vitro*. The feasibility and robustness of the algorithm are examined using a simulated zero-offset reflection data set. The method is then applied to image a real bovine tibia bone sample.

METHODS

In vitro experiment

Bone sample. A bovine tibia was obtained from a local butcher shop. The sample was 237 mm long, and the minimum diameter was 35.2 mm in the midshaft. The average thickness of the cortex layer was about 8 mm. The sample was defrosted overnight at 20°C room temperature, cleaned to remove the soft tissue and then preserved in a 70% alcohol solution. During preservation, the marrow in the sample shrank, and some cavities formed in the structure. The properties of cortical bone changed because of dehydration, which would result in decreased velocity and increased attenuation in the bone tissue because of the intruded air. A computed tomography (CT) scan was obtained prior to the ultrasound experiment to gather thickness information for further comparison.

Zero-offset experiment. Offset is the distance from source to receiver. Figure 1a illustrates the in-house-designed device used to hold the sample in place (Tran et al. 2014). The transducer was directly positioned on the bone surface, coupling with the ultrasound gel at room temperature. A steel bar was placed on top of the transducer to maintain constant pressure between the transducer and the sample. A Panametrics 5800 computer-controlled pulser/receiver (Panametrics, Waltham, MA, USA) and a LeCroy wavesurfer 422 oscilloscope (LeCroy, Chestnut Ridge, NY, USA) were used to pulse the transducer and to record the time signals, respectively. Time signals were collected along the axial direction of long bone samples at 1-mm intervals. Each signal was averaged 128 times in real time. Further details of the setup are provided by Zheng et al. (2007).

A Panametrics 2.25-MHz CHC706 dual-head P-wave composite transducer (Fig. 1b) was used to transmit and receive the signal. The diameter of the active element is 0.5 in. (13 mm). Two piezoelectric crystals are housed in the same case with a small inclination, acting as transmitter and receiver separately. We consider this a zero-offset configuration. The transmission mode of the pulser was used because it provided shorter trigger signals with a measured duration <1.2 μs. A layer of shielding material protects the crystals and causes an additional measured delay time of 4.94 μs in the receiving signals.