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● *Original Contribution*

ASSESSMENT OF THE FUNDAMENTAL FLEXURAL GUIDED WAVE IN CORTICAL BONE BY AN ULTRASONIC AXIAL-TRANSMISSION ARRAY TRANSDUCER

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Abstract—The fundamental flexural guided wave (FFGW), as modeled, for example, by the A0 Lamb mode, is a clinically useful indicator of cortical bone thickness. In the work described in this article, we tested so-called multiridge-based analysis, based on the crazy climber algorithm and short-time Fourier transform, for assessment of the FFGW component recorded by a clinical array transducer featuring a limited number of elements. Methods included numerical finite-element simulations and experiments in bone phantoms and human radius specimens ($n = 41$). The proposed approach enabled extraction of the FFGW component and determination of its group velocity. This group velocity was in good agreement with theoretical predictions and possessed reasonable sensitivity to cortical width ($r^2 = 0.51$, $p < 0.001$) in the *in vitro* experiments. It is expected that the proposed approach enables related clinical application. Further work is still needed to analyze in more detail the challenges related to the impact of the overlying soft tissue. (E-mail: warma@iki.fi) © 2013 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Quantitative ultrasound, Axial transmission, Guided waves, Cortical bone, Osteoporosis.**

INTRODUCTION

Ultrasonic axial transmission is a method of skeletal quantitative ultrasound (US) adapted to assessment of long cortical bones, such as the radius and tibia (Barkmann et al. 2000; Lowet and Van der Perre 1998; Moilanen 2008). In this approach the transmitters and receivers are placed on the same side of the bone shaft, so as to enable excitation and detection of US signals along the long axis of the bone. In this case, bone can be considered as an elastic waveguide for US-guided waves (Moilanen 2008), also known as Lamb waves (Viktorov 1967).

Most typically the method of axial transmission is associated with measurement of the so-called first arriving signal. The first arriving signal is a transient mode generally consistent with a lateral longitudinal wave or the S0 Lamb mode (Bossy et al. 2002; Camus et al. 2000). It has been shown to characterize several properties of bone, such as elastic stiffness, mineral density, porosity and cortical thickness (Bossy et al. 2004b; Kilappa et al. 2011; Raum et al. 2005). Moreover, it has been shown to have clinical potential as a predictor and discriminator of osteoporotic fractures (Hans et al. 2003; Hartl et al. 2002; Knapp et al. 2004; Moilanen et al. 2013; Talmant et al. 2009). On the other hand, a number of studies have focused on the assessment of additional slower Lamb modes in bone (Le et al. 2010; Lefebvre et al. 2002; Moilanen et al. 2003; Nicholson et al. 2002; Ta et al. 2006). In particular, the fundamental flexural guided wave (FFGW), consistent with the A0 Lamb mode, has gained considerable interest because of its clinical relevance (Moilanen et al. 2003; Nicholson et al. 2002). The clinical relevance of FFGW arises from the high thickness sensitivity of its phase velocity (Moilanen et al. 2006). It has been shown in *in vitro* and modeling studies that the measured phase velocity of the FFGW indeed enables estimation of cortical thickness with good accuracy (Moilanen et al. 2007a, 2007b, 2007c).

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Previously, to measure the FFGW, our group used a method based on mechanical scanning with a US receiver along the long axis of bone with a fixed US source (Moilanen et al. 2003). This scanning approach was used to record a spatiotemporal signal, after which the 2-D fast Fourier transform method (Alleyne and Cawley 1991) was used to separate wave modes and assess the corresponding phase velocities. We also proposed a method for group-velocity filtering before the 2-D fast Fourier transform to facilitate accurate extraction of the FFGW from measured signals plagued by interference (Moilanen et al. 2006). The group-velocity filter was essentially a Hanning window gate, the position of which was determined *a priori* by estimation of the group velocity.

Such a scanning approach is, however, not appropriate for *in vivo* measurements because of the bulkiness of the device, inaccuracies related to positioning and slow scanning. Instead, hand-held array probes are typically preferable in clinical applications as they enable flexible positioning and rapid electronic scanning of different source–receiver distances (Barkmann et al. 2000; Foldes et al. 1995; Talmant et al. 2009). Moreover, a bidirectional array technique has been shown to be essential for correcting soft tissue effects (Bossy et al. 2004a). To this end, we recently introduced a bidirectional array probe and used it successfully for *in vivo* measurements of first arriving signals (Kilappa et al. 2011). The fixed spacing of the receivers (6 mm) in this probe, in comparison to the typical FFGW wavelength in bone (10 mm), does not, however, provide sufficient resolution for spatial sampling to satisfy the Nyquist–Shannon criterion with the 2-D fast Fourier transform. Therefore, another signal processing method is needed to enable assessment of guided modes, such as the FFGW, with the array probe.

A method suitable for clinical array probes must separately process the signals measured at each source–receiver distance to avoid the problem of limited resolution of spatial sampling. To this end, algorithms based on time–frequency representation (TFR) (Niethammer et al. 2000; Prosser et al. 1999), singular-value decomposition (Minonzio et al. 2010; Sasso et al. 2008), joint approximate diagonalization of eigen-matrices (Song et al. 2011) and dispersion compensation (Xu et al. 2012) have been proposed. Recently, a method called multiridge-based analysis (Xu et al. 2010) was proposed to facilitate mode separation in the time–frequency plane and to reconstruct waveforms representative of individual guided modes. This approach is based on the so-called crazy climber (CC) algorithm (Carmona et al. 1999; Gilks et al. 1995), which uses random walkers uniformly distributed in the potential field formed by TFR. These walkers are trapped in the local maxima of TFR and thereby form ridges that represent trajectories of dispersion curves of the corresponding guided modes. These ridges are then used to reconstruct temporal signals. CC-based methodology thus enables temporal extraction of individual wave modes. The main advantage of this new approach, compared with group-velocity filtering, is that CC extraction is independent of any *a priori* information and can operate on single time-domain signals.

The purpose of the present study was, thus, to test the suitability of CC-based TFR for assessment of FFGW in signals recorded with our ultrasonic array probe. We focus on evaluating the suitability of the new approach for the assessment of group velocity of the FFGW extracted by the CC-TFR method. To this end, we explore signals produced by numerical finite-element simulations and experimental recordings from acrylic plate phantoms. Moreover, we analyze previously recorded *in vitro* signals from human radius samples.

METHODS

Samples

Seven acrylic plates 2–12 mm thick were used as bone phantoms. For *in vitro* results, we reanalyzed former experiments on human radius specimens ($n = 41$) (Moilanen et al. 2007a; Muller et al. 2005, 2008). When the samples were originally collected from donors (Bossy et al. 2004b), ethical approval was granted by the Human Ethics Committee of the Institute of Anatomy at the University René Descartes (Paris, France). The tissue donors or their legal guardians provided informed written consent to provide their tissues for investigation in accordance with legal clauses stated in the French Code of Public Health (Code de la Santé Publique Français).

Experimental setup

The custom-made array US device was composed of a receiver block and two transmitter blocks, rigidly connected together as depicted in Figure 1a. The two transmitter blocks each included a transducer element; the receiver block was composed of six equally spaced (pitch, 6 mm) transducer elements, providing a 30-mm array of receivers. Each of the three blocks was bound together by a soft frame material (polyurethane). The blocks were rigidly connected, but acoustically insulated from each other. Bidirectional measurements (Bossy et al. 2004a) were thus possible with this probe, and the source–receiver distances between transducer elements covered a range similar to that in the scanning US device. A custom-made pulser was used to excite the transmitters. The center frequency of excitation signal was 200 kHz, and the bandwidth was 400 kHz (–16 dB). A digital oscilloscope (DAQCard-5102, National