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● *Original Contribution*

PHOTO-ACOUSTIC EXCITATION AND OPTICAL DETECTION OF FUNDAMENTAL FLEXURAL GUIDED WAVE IN COATED BONE PHANTOMS

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Abstract—Photo-acoustic (PA) imaging was combined with skeletal quantitative ultrasound (QUS) for assessment of human long bones. This approach permitted low-frequency excitation and detection of ultrasound so as to efficiently receive the thickness-sensitive fundamental flexural guided wave (FFGW) through a coating of soft tissue. The method was tested on seven axisymmetric bone phantoms, whose 1- to 5-mm wall thickness and 16-mm diameter mimicked those of the human radius. Phantoms were made of a composite material and coated with a 2.5- to 7.5-mm layer of soft material that mimicked soft tissue. Ultrasound was excited with a pulsed Nd:YAG laser at 1064-nm wavelength and received on the same side of the coated phantom with a heterodyne interferometer. The FFGW was detected at 30-kHz frequency. Fitting the FFGW phase velocity by the $F_{LC}(1,1)$ tube mode provided an accurate (9.5 ± 4.0%) wall thickness estimate. Ultrasonic *in vivo* characterization of cortical bone thickness may thus become possible. (E-mail: petro.moilanen@jyu.fi) © 2014 World Federation for Ultrasound in Medicine & Biology.

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

INTRODUCTION

There is an economic and societal need for cost-effective assessment of the risk of bone fractures, as these require expensive treatment and cause human suffering and disability (Kannus et al. 2006). The present clinical standard, dual-energy X-ray absorptiometry (DXA), does not fulfill this need as it is expensive and rarely available in clinical practice. Moreover, DXA may fail to identify patients who later sustain fracture (Bolotin and Sievänen 2001). To this end, skeletal quantitative ultrasound (QUS) is a promising approach (Glüer 2008; Hans and Krieg 2008). Its potential relies on the sensitivity of ultrasonic elastic waves in probing the mass (bone mineral content) and architecture of bone. This allows QUS to more accurately predict bone fragility than DXA, which only characterizes the bone mass. Moreover, QUS can provide accurate, easy-to-use and relatively low-cost modalities suitable for everyday clinical use. Verifying the clinical relevance of QUS still requires extensive fundamental research on modeling, device development and clinical testing. In particular, mediation of ultrasonic signals through the overlying soft tissue when conventional ultrasound transducers are used constitutes a major challenge, as some of the most clinically useful ultrasonic modes cannot as yet be accurately detected from the top of the soft tissue.

To improve skeletal QUS, a number of studies have focused on multi-mode axial transmission based on excitation and detection of ultrasound-guided waves that propagate in the wall of long cortical bones (Le et al. 2010; Lefebvre et al. 2002; Minonzio et al. 2010; Moilanen 2008; Moilanen et al. 2003; Nicholson et al. 2002; Ta et al. 2006; Tatarinov et al. 2005). The most commonly used guided wave for bone assessment is the first arriving signal (FAS). The FAS is a transient in the time domain, whose apparent propagation velocity is explained by those of the fundamental symmetric Lamb mode (S0) and the lateral compression wave (Bossy et al. 2002, 2004a). FAS velocity has been found *in vitro* and *in vivo* to characterize material properties (bone mineral density, porosity and elastic stiffness) and

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thickness of cortical bones (Bossy et al. 2004b; Kilappa et al. 2011; Muller et al. 2008; Raum et al. 2005). This velocity is affected by several properties of bone, but the individual effects of these properties may not be inferred from a single FAS measurement. Therefore, employing several modes for their inference can improve the sensitivity of ultrasonic characterization of bone properties.

In our effort to develop a multi-mode method, we focus here on another wave mode, the fundamental flexural guided wave (FFGW), the experimentally measured phase velocity of which is consistent with that of the fundamental anti-symmetric Lamb mode (A0) in plates or an analogous mode in curved shells (Moilanen et al. 2003, 2007a). This wave mode can be used to accurately predict cortical thickness (Moilanen et al. 2007b, 2007c). However, measurement of FFGW *in vivo* is challenging because the signal is excited and detected through an overlying soft tissue (Moilanen et al. 2008).

Soft tissue affects the FFGW mode in several ways. Its phase velocity may be altered by coupling between the soft coating and bone (Moilanen et al. 2006; Yapura and Kinra 1995). Sound absorption in the coating may also play a role that is not yet understood. Furthermore, even though the FFGW displacement amplitude is detectable in embedded bone, the amplitude of the related displacement is low outside the bone, as predicted by the model for fluid-coated plates (Yapura and Kinra 1995). Also, soft coating provides a signal path causing interference in the coupled waveguide, which makes it hard to identify the FFGW (Moilanen et al. 2008). Consequently, *in vivo* excitation and detection of FFGW are challenging, and may be impossible using frequencies above 100 kHz. Such frequencies are typical in studies with contact ultrasound transducers (Lefebvre et al. 2002; Minonzio et al. 2010; Moilanen et al. 2008).

To efficiently excite FFGW *in vivo*, ultrasonic frequencies as low as possible should be used, as this is predicted both to improve the excitability of an A0-type fundamental flexural mode (Nunez et al. 2000) and to reduce the damping of the related displacement as observed with a receiver on top of the coating. Moreover, the ultrasound source should preferably reside inside the soft coating, close to the bone. The footprint of the source should be small compared with the wavelength, so as to efficiently excite the FFGW. To fulfill these requirements, we propose the use of a photo-acoustic (PA) method for skeletal QUS. A PA source is flexible in comparison, for example, with a focused conventional transducer, which also permits generation of a small acoustic source inside the tissue. The low-frequency piezo transducer needed for that would be bulky, and tuning its focus would require specific arrangements (such as a gel bag) for its acoustic coupling.

Photo-acoustically generated guided waves have been widely used in non-destructive testing (Krishnaswamy 2003) to characterize the thickness and mechanical properties of plates and thin films (Gao et al. 2003; Hernandez et al. 2002). There are also several biomedical applications of photo-acoustics, such as PA imaging (Laufer et al. 2009; Li and Wang 2009; Payne et al. 2003b; Wang 2009; Xu and Wang 2006; Zhang et al. 2008), assessment of the viscoelastic properties of cartilage (Ishihara et al. 2005; Sato et al. 2011) and assessment of glucose concentration in blood (Zhao 2002). Photo-acoustically generated surface acoustic waves can assess elastic properties of soft tissue-mimicking phantoms (Li et al. 2011) and can also be used to inspect dental enamel (Wang et al. 2009). Until now, photo-acoustics has not been used to excite guided waves in human bone. In a recent conference abstract, we presented preliminary results on the use of PA-QUS to assess guided waves in tubular bone phantoms representative of the human radius, embraced by a thin (2.5 mm) coating mimicking soft tissue (Moilanen et al. 2012). The present study extends that analysis, using an improved experimental setup and phantoms with improved optical properties and a thicker coating (5.0–7.5 mm).

Photo-acoustic excitation and optical detection provide a wideband ultrasound source and receiver, with flat frequency response, whereas the bandwidth of piezo transducers is narrower and their response is less flat. Photo-acoustics therefore permits guided waves to be excited and detected at frequencies corresponding to the maxima of the related transfer function (Nunez et al. 2000), that is, at frequencies at which these modes are most energetic. That is not always possible with piezo transducers. In the present case, photo-acoustics specifically allows excitation of FFGW at very low ultrasonic frequencies ($f < 100$ kHz) with a small footprint.

The objective of the study described here was to apply PA excitation and optical detection to wideband analysis of FFGW measurements through the soft coating that embraces axisymmetric bone phantoms representative of the size of the human radius. Specifically, we sought to determine the optimal frequency band at which the FFGW is naturally excited and detected in our samples and to investigate experimentally the damping of the FFGW displacement amplitude away from the bone surface by comparing it on top of the coating and at the soft-solid interface. We wanted to determine if PA excitation and optical detection permit FFGW-based estimation of wall thickness, for the first time, in coated waveguides representative of human bone.