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● *Original Contribution*

MODELING OF FEMORAL NECK CORTICAL BONE FOR THE NUMERICAL SIMULATION OF ULTRASOUND PROPAGATION

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Abstract—Quantitative ultrasound assessment of the cortical compartment of the femur neck (FN) is investigated with the goal of achieving enhanced fracture risk prediction. Measurements at the FN are influenced by bone size, shape and material properties. The work described here was aimed at determining which FN material properties have a significant impact on ultrasound propagation around 0.5 MHz and assessing the relevancy of different models. A methodology for the modeling of ultrasound propagation in the FN, with a focus on the modeling of bone elastic properties based on scanning acoustic microscopy data, is introduced. It is found that the first-arriving ultrasound signal measured in through-transmission at the FN is not influenced by trabecular bone properties or by the heterogeneities of the cortical bone mineralized matrix. In contrast, the signal is sensitive to variations in cortical porosity, which can, to a certain extent, be accounted for by effective properties calculated with the Mori-Tanaka method. (E-mail: quentin.grimal@upmc.fr) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Cortical bone, Elasticity, Fracture risk, Femur, Quantitative ultrasound, Homogenization, Porosity, Acoustic microscopy.**

INTRODUCTION

The hip is a site of fracture among elderly people associated with high morbidity and mortality (Cummings and Melton 2002; Keene et al. 1993). Areal bone mineral density (aBMD) assessment at the hip by dual X-ray absorptiometry (DXA) is currently the standard reference method used to characterize fracture risk (Watts 2011). However, DXA alone is not sufficient to assess bone strength and often fails to predict fracture (Siris et al. 2004). A significant risk of fracture exists for men and women with an aBMD higher than the osteoporotic range (Siris et al. 2004; Stone et al. 2003; Wilkin and Devendra 2001). Further, increases in aBMD after therapy do not fully explain the observed efficacy of osteoporosis drug treatments (Delmas and Seeman 2004; Gallacher and Dixon 2010).

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Although diagnostic bone measurements have focused mainly on trabecular bone, several recent reports have provided evidence that cortical bone also contributes to a significant amount of the strength of the femoral neck (FN) (Bousson et al. 2006; Manske et al. 2009). This has suggested that risk assessment should include evaluation of cortical bone to improve identification of individuals at risk.

Quantitative ultrasound (QUS) assessment of the proximal femur has recently been investigated with the goal of achieving enhanced fracture risk prediction (Barkmann et al. 2008). In a clinical pilot study, femur QUS allowed good discrimination between women with recent hip fractures and controls (Barkmann et al. 2010). In an *ex vivo* study, we found that targeted ultrasound measurement of the FN cortical compartment is possible (Grimal et al. 2013); furthermore, the measurement is highly correlated with bone strength. In this method, the arrival time of the first ultrasonic signal (FAS) measured in transmission through the neck is determined. The FAS is associated with the propagation of waves guided circumferentially in the cortical shell (Grimal et al.

2013; Grondin et al. 2010; Nauleau et al. 2012). As opposed to X-rays, ultrasound is intrinsically sensitive to mechanical properties, which contribute to bone integrity. We assumed that enhanced risk prediction may be achieved through ultrasonic assessment of the proximal femur cortex. This assumption motivated the research reported here on analysis of the propagation of ultrasound in the cortical shell of the FN.

Ultrasound transmission through the FN is complex. Measured signals are influenced by bone size, geometry and material properties. The respective effects of each of these factors must be thoroughly understood to design efficient signal processing methods. At frequencies used in clinical devices (0.5–1 MHz), the wavelength in bone is a few millimeters, much larger than the typical microstructural heterogeneities (50–200 μm for the diameter of vascular pores) (Grimal et al. 2011a). Hence ultrasound is sensitive to effective properties that are determined by the elastic properties of the mineralized matrix and by the pervading porous network. Matrix properties (Bergot et al. 2009; Bousson et al. 2011; Roschger et al. 2008) and porosity (Bousson et al. 2004; Zebaze et al. 2010) change with age, pathological status and use of therapeutic agents. It is thus important to assess the impact of such changes on ultrasonic signals, for example, by using numerical simulations.

The advent of powerful desktop computers and the availability of finite-difference and finite-element software dedicated to elastic wave propagation have encouraged rapid expansion of the numerical simulation of ultrasound propagation in bone. During the last decade the research methodology in QUS has shifted from essentially experimental research to research in part guided by the results of simulations. The approach has been validated in some cases in which the main propagation characteristics observed experimentally could be accurately predicted by numerical simulations (Bossy and Grimal 2010; Bossy et al. 2004a, 2005; Luo et al. 1999).

The objective of the work described here was to determine which bone properties have a significant impact on ultrasound propagation in FN cortical bone and to assess the relevancy of some models differing in complexity. For these purposes, we introduce a methodology for the modeling of ultrasound propagation, with a focus on the modeling of elastic properties. We propose that the microscopic features of bone tissue (pores, inhomogeneities of mineralization or other material properties) do not have to be accounted for explicitly. Instead, they may be represented by effective elastic properties.

Scanning acoustic microscopy (SAM) was used to obtain maps of FN material properties and microstructure, which served as a basis for the modeling of elastic properties. SAM is the state-of-the-art method for providing sample-specific (individualized) quantitative assessment of the microstructure and elastic properties of mineralized tissues (Malo et al. 2013; Raum 2008; Raum et al. 2007; Rohrbach et al. 2012; Saïed et al. 2008).

METHODS

Sample preparation and scanning acoustic microscopy

Nine FN cross-sectional slabs about 10 mm thick were obtained from seven human donors (age: 64.4 ± 8.8 years) who received a hip implant. The experimental protocol was approved by the ethics commission of the Martin Luther University, and informed consent for the study was obtained from all subjects. Cross sections were cut approximately perpendicular to the FN axis between the femoral head and the central region of the FN (Fig. 1). After fixation and dehydration in ethanol, the samples were embedded in polymethylmethacrylate, ground and polished (Lakshmanan et al. 2007). An orthonormal frame and a system of coordinates (x_1, x_2, x_3) were associated with the FN based on anatomical landmarks: direction 3 was attached to the neck axis, and directions 1 and 2 to the antero-posterior and supero-inferior directions, respectively.

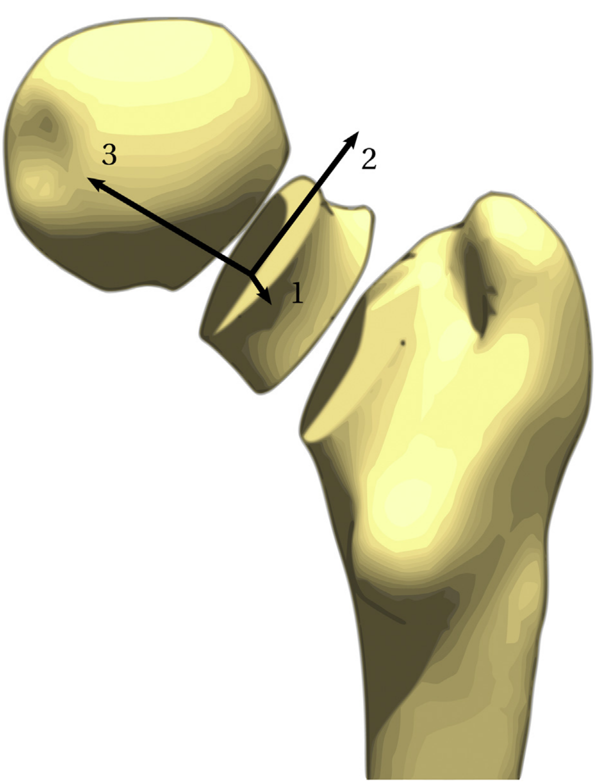

Fig. 1. Femoral neck cross-sectional slabs cut perpendicular to the neck at a thickness of about 10 mm were obtained from human donors and prepared for measurements with scanning acoustic microscopy (SAM).