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● *Original Contribution*

RADIAL ANATOMIC VARIATION OF ULTRASONIC VELOCITY IN HUMAN CORTICAL BONE

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Abstract—Quantitative ultrasound techniques can be used to retrieve cortical bone quality. The aim of this study was to investigate the anatomic variations in speed of sound (SOS) in the radial direction of cortical bone tissue. SOS measurements were realized in 17 human cortical bone samples with a 3.5-MHz transverse transmission device. The radial dependence of SOS was investigated in a direction perpendicular to the periosteum. For each sample, bone porosity was measured using an X-ray micro-computed tomography device. The mean SOS was 3586 ± 255 m/s. For 16 of 17 specimens, similar radial variations in SOS were observed. In the periosteal region, SOS first decreased in the direction of the endosteum and reached a minimum value approximately in the middle of the cortical bone. SOS then increased, moving to the endosteal region. A significant negative correlation was obtained between SOS and porosity ($R = -0.54$, $p = 0.02$). (E-mail: guillaume.haiat@univ-paris-est.fr) © **2013 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Cortical bone, Quantitative ultrasound, Velocity, Speed of sound, Tissue mineral density, Porosity, Transverse transmission.**

INTRODUCTION

Osteoporosis represents an important public health issue (Klibanski et al. 2001; Taylor et al. 2001) and is characterized by a decrease in bone mass density and deterioration of the micro-architectural and mechanical properties of bone tissue. Currently, dual-energy X-ray absorptiometry (DXA) is the "gold standard" for the diagnosis of osteoporosis via the estimation of bone mineral density (BMD) (Kanis 2002). However, quantitative ultrasound (QUS) techniques have become important non-invasive modalities for the investigation of bone strength (Haiat et al. 2009b). The QUS parameters—broadband ultrasonic attenuation (BUA) (Sasso et al. 2007, 2008) and speed of sound (SOS)—are now well-established modalities and are used as clinical factors predictive of fracture risk (Gluer and Barkmann 2003; Khaw et al. 2004). Absence of ionizing radiation, low cost and portability are potential advantages of QUS techniques compared with DXA. Moreover, QUS techniques take advantage of the sensitivity of elastic waves to the mechanical properties of the tissues investigated.

Initially, most applications of QUS techniques in bone were confined to characterization of cancellous bone, because the most common devices evaluate bone quality at the heel, which is mostly composed of trabecular bone. However, cortical bone exploration is of interest (Rico 1997) because it represents about 80% of the skeleton, supports most of the load of the body and is involved in many types of osteoporotic fractures. The development of new QUS techniques such as axial transmission (Barkmann et al. 2000a; Foldes et al. 1995) allowed cortical bone evaluation *in vivo*. Transverse transmission can also be used to evaluate cortical bone at such sites as the wrist, phalanx (Barkmann et al. 2000b; Mano et al. 2006) and femur (Haiat et al. 2005).

Despite their clinical use, QUS techniques are still limited because the interaction between ultrasound and cortical bone remains unclear. Cortical bone has a complex hierarchical microstructure spanning many length scales. In addition to its multi-scale nature, cortical bone is heterogeneous at the organ scale. Porosity in the radial direction (associated with the cross section) is heterogeneous at all ages and for both sexes (Bousson

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et al. 2001; Thomas et al. 2005), the mean porosity being higher in the endosteal region than in the periosteal region. Moreover, according to recent studies by our group (Sansalone et al. 2010, 2012), tissue mineral density (TMD) also depends on radial location. The aforementioned heterogeneity of bone porosity and TMD leads to a gradient of bone material properties that may affect bone quality and susceptibility to fracture, as well as SOS spatial variations. Finite-element analyses have been used to illustrate that the gradient of material properties in the bone radial direction related to porosity and tissue mineralization has an important effect on its ultrasonic response (Haiat et al. 2009a, 2011; Naili et al. 2010) obtained using axial transmission devices (Vavva et al. 2009). The radial dependence of SOS is a datum of interest because it influences the ultrasonic response of bone at the organ scale (*e.g.,* using axial transmission) (Desceliers et al. 2012; Haiat et al. 2009a; Naili et al. 2010). However, the dependence of SOS variation in the radial direction in human cortical bone remains unknown.

Several studies have investigated the behavior of SOS in human cortical bone. Different *in vivo* studies have investigated the behavior of cortical bone ultrasonic velocity using clinical devices on a large number of patients (Antich et al. 1993; Lee et al. 1997; Weiss et al. 2000), but their approach remains of limited interest to investigation of the intrinsic value of SOS, because the results are influenced by various factors such as soft tissues and probe positioning. Therefore, different groups have realized *in vitro* measurements to investigate spatial variations in SOS in a single cadaveric bone sample (Ashman et al. 1984; Bensamoun et al. 2004a, 2004b). Granke et al. (2011) and Grondin et al. (2012) recently considered several human bone samples, providing a range of variation in ultrasonic velocity in human cortical bone. However, the ultrasonic measurements were realized at a given location in the sample and, thus, did not allow estimation of the anatomic dependence of SOS, which still remains unknown.

In addition to the anatomic dependence of SOS, the range of variation in SOS values obtained in a given sample is also an important parameter because stochastic models have recently been developed to account for the intrinsic variability of bone mechanical properties in cortical bone in the context of axial transmission devices (Desceliers et al. 2008, 2009, 2012; Macocco et al. 2006). However, the precise intra-specimen variability of SOS remains unknown, and empirical methods have so far been used as input data in probabilistic models instead of reliable SOS measurements.

The aims of the present study were (i) to determine the spatial dependence of SOS in human cortical bone as a function of bone cross section; (ii) to determine the degree of heterogeneity of SOS values within cortical bone; and (iii) to investigate the relationship between SOS and the pore volume/total volume ratio (PoV/TV).

To do so, 17 cortical bone samples obtained from different donors and different anatomic locations were measured using an *ex vivo* transverse transmission technique with a dedicated ultrasound device. The radial dependence of SOS values was investigated by considering profiles of SOS variations as a function of the distance from the periosteum. For each sample, PoV/TV was measured using an X-ray micro-computed tomography device.

METHODS

Specimen preparation

Seventeen cortical bone samples were prepared from femurs of 11 human donors (mean donor age: 81.4 y, range: 53–97 y). Nine femurs were obtained from females (mean age: 83.2 ± 12.9 y; range: 53–97 y), and two from males (72 and 74 y). No data were available regarding cause of death, previous illnesses or medical treatments for these individuals. Collection of these human tissue specimens was conducted according to pertinent protocols established by the Human Ethics Committee of INSERM. The 17 samples were cut from three different anatomic locations in the femur: 9 in the diaphysis, 2 in the superior neck and 6 in the inferior neck (see Fig. 1a). The samples were obtained by machining slices (around 10 mm thick) in the femoral neck and diaphysis of the femurs (see Fig. 1b). All samples had a cortical thickness >2 mm. The samples were maintained at –20°C. All slices had parallel sides.

Transmission ultrasonic device

Ultrasonic measurements were performed on samples immersed in a container filled with water at room temperature. The device is described in Figure 2 and is composed of a pair of broadband focused transducers (Panametrics, Waltham, MA, USA) with a center frequency of 3.5 MHz. The diameter (25 mm) and focal length (30 mm) in water of the transducers result in a beam width at the focus in water of approximately 0.5 mm. The first transducer is used as an emitter, and the second is used as a receiver; both transducers have their focal point confounded (confocal device). Axes x, y and z are defined in Figure 2. Both transducers are carefully aligned using goniometers, parallel to the y direction. The supporting electronics comprise a pulse-receiver amplifier (5052 A, Panametrics) and an A/D conversion card of 100-MHz sampling frequency with 12-bit resolution (Spectrum, Grosshansdorf, Germany).