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● *Original Contribution*

ULTRASOUND SPEED OF SOUND MEASUREMENTS IN TRABECULAR BONE USING THE ECHOGRAPHIC RESPONSE OF A METALLIC PIN

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Abstract—Bone quality is an important parameter in spine surgery, but its clinical assessment remains difficult. The aim of the work described here was to demonstrate *in vitro* the feasibility of employing quantitative ultrasound to retrieve bone mechanical properties using an echographic technique taking advantage of the presence of a metallic pin inserted in bone tissue. A metallic pin was inserted in bone tissue perpendicular to the transducer axis. The echographic response of the bone sample was determined, and the echo of the pin inserted in bone tissue and water were compared to determine speed of sound, which was compared with bone volume fraction. A 2-D finite-element model was developed to assess the effect of positioning errors. There was a significant correlation between speed of sound and bone volume fraction (R^2 = 0.6). The numerical results indicate the relative robustness of the measurement method, which could be useful to estimate bone quality intra-operatively. (E-mail: guillaume.haiat@univ-paris-est.fr) **© 2015 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Trabecular bone, Quantitative ultrasound, Speed of sound, Biomechanics.**

INTRODUCTION

Spinal degeneration is present in around 90% of the population over 63 y of age (Szpalski and Gunzburg 2003). Degenerative discopathy (DD) is one of the most common etiologies of spinal degeneration and may require spine surgery (Hughes et al. 2012). Different surgical options using implantable medical devices have been developed to treat ailments stemming from intervertebral disc (ID) degeneration, such as spinal fusion and total disc replacement (TDR).

In spinal fusion, two adjacent vertebrae are connected using such devices such as cages, plates, screws and a variety of other fusion materials (Brislin and Vaccaro 2002; Haid et al. 2004; Kirzner et al. 2011; Starkweather 2006). The deleterious consequences of intervertebral fusion include persistent pain, abnormal spinal curvature and accelerated degeneration of adjacent segments (Lee 1988). To decrease these risks, bone fusion may be complemented with external fixations (such as pedicle screws) to reinforce the biomechanical stability of the vertebral structure. However, the choice of method used for pedicle screw insertion (use of cement, length and diameter of the screws) remains empirical and depends on bone biomechanical quality (Shea et al. 2014).

Total replacement of the intervertebral disc has been developed as an alternative to spinal fusion to preserve spinal motion (Vital and Boissiere 2014) and maintain mobility between the two adjacent vertebrae (Hughes et al. 2012). However, long-term biomechanical stability of the different devices used for TDR remains difficult to obtain. Problems with bony fixation and anchorage to the host spine, which are achieved through the osseointegration phenomenon, have been mentioned (Schmiedberg et al. 1994). The quality of the osseointegration phenomenon is a critical problem in spine surgery. Another problem lies in the risk of impaction fracture of the vertebrae, which also depends on bone quality. Therefore, bone biomechanical properties of the vertebral body determine the success of TDR surgery because the surgery affects the osseointegration phenomenon and impaction fracture,

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particularly for osteoporotic patients, as the incidence of vertebral fracture increases markedly with age (European Prospective Osteoporosis Study [EPOS] Group et al. 2002).

Dual X-ray absorptiometry (DXA) is currently the only method available in the clinic to estimate vertebral bone quality and is sometimes used pre-operatively for spine surgery. However, DXA has limitations as it is a radiate-emitting on and expensive technology. In addition, DXA technique only provides information on bone mineral density, which is not sufficient to accurately estimate bone quality. Moreover, it remains difficult to use DXA to obtain a reliable information on vertebra L-5 (which is an important site of DD), because of the presence of soft tissue disrupting the measurements.

Quantitative ultrasound (QUS) represents an interesting alternative to DXA, because it is non-invasive, non-radiating and relatively inexpensive (Laugier and Haïat 2011). Moreover, as ultrasound is composed of mechanical waves, it can be used to retrieve useful information on bone biomechanical properties and therefore provide information additional to that provided by bone mineral density (BMD) estimation alone (Haïat et al. 2008a). QUS is now widely used in the clinic in the context of osteoporosis to estimate bone quality at such sites as the calcaneum (Chin and Ima-Nirwana 2013), phalanx (Olszynski et al. 2013), tibia (Maatta et al. 2014), femur (Barkmann et al. 2008) and radius (Sasso et al. 2009) using transverse (Mathieu et al. 2013) and axial (Tatarinov et al. 2014) transmission devices. Speed of sound (SOS) is a QUS parameter (Haiat et al. 2005b) that has been found to be related to bone strength (Haiat et al. 2009b). However, QUS techniques have not been applied so far intra-operatively to assess vertebral bone quality and would be useful as a decision support system for the surgeon in the context of TDR and spinal fusion surgery. The main difficulty in intra-operative QUS lies in the positioning of several transducers around the vertebral body during surgery. Fortunately, when anterior approaches are employed, surgeons commonly use metallic cylindrical pins inserted in the vertebral body to maintain soft tissues during the surgical procedure. These pins are removed from bone tissue after surgery. In the study described here, these pins were used as ultrasound reflectors in a pulse-echo mode to measure SOS in bone tissue located between the transducer and the pin.

The aim of this work was to establish the proof of concept of a QUS method that could be applied in the future during surgery and consisted of use of a surgical pin as a reflector to assess trabecular bone quality. A dedicated ultrasonic setup was used to measure SOS in 21 trabecular bone samples in which a pin was inserted. The results were compared with bone volume fraction measurements obtained using X-ray micro-computed tomography.

METHODS

Sample preparation

Twenty-one trabecular bone samples were obtained from bovine femurs purchased at the local butcher shop. Soft tissues were removed manually, and the samples were then cut in the proximal region to obtain cubic samples (approximately 25 × 25 × 25 mm) using an electric saw (Minitom, Struers, Copenhagen, Denmark). All cubic samples had parallel sides, and orthogonality was carefully checked using digital calipers (AEI-CAL-2, AEI-ITC, Lillois, Belgium), to reach a maximum error of orthogonality $<1°$ in all directions.

The same pin (Surgiway, Paris, France) used during surgery to hold soft tissues was used in the present study. The pin is a 4-mm-diameter, 240-mm-long cylinder made of stainless steel (Fig. 1). As detailed below, the pin is used as a reflector of ultrasonic waves and is nailed into the bone sample, similarly as is done in the operating room.

Ultrasound measurements

The dedicated device comprising an ultrasonic transducer and allowing precise positioning of the pin relative to the axis of the transducer is illustrated in Figure 2. Ultrasonic measurements were performed in immersion mode in a tank filled with water at room temperature to mimic *in vivo* conditions. The setup comprised a broadband planar transducer (CMP 89, Sonaxis, Besançon, France) with a center frequency of 500 kHz and a diameter of the active surface equal to 16 mm. The ultrasonic transducer is used in echographic mode. The choice of the characteristics of the transducer will be justified in the Discussion. The supporting

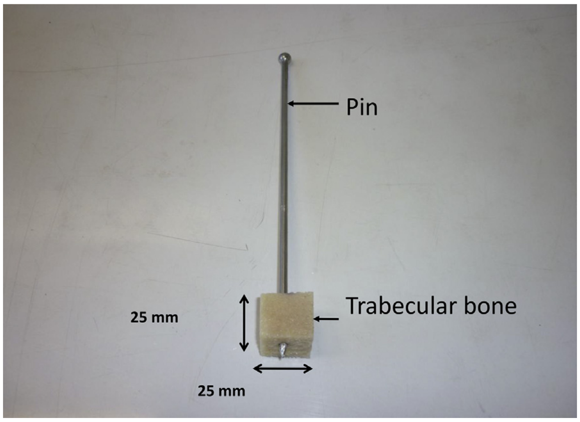

Fig. 1. One of the bone samples with the inserted pin used as a reflector for ultrasonic waves.