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● *Original Contribution*

QUANTITATIVE ULTRASOUND MEASUREMENTS AT THE HEEL: IMPROVEMENT OF SHORT- AND MID-TERM SPEED OF SOUND PRECISION

Melanie Daugschies,* Kim Brixen,† Pernille Hermann,†‡ Kerstin Rohde,*
Claus-Christian Glüer,* and Reinhard Barkmann*

* Sektion Biomedizinische Bildgebung, Klinik für Radiologie und Neuroradiologie, Universitätsklinikum Schleswig-Holstein, Kiel, Germany; † Department of Medical Endocrinology, Odense University Hospital, Odense, Denmark; and ‡ Department of Internal Medicine, Kolding Hospital, Kolding, Denmark

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Abstract—Calcaneal quantitative ultrasound can be used to predict osteoporotic fracture risk, but its ability to monitor therapy is unclear possibly because of its limited precision. We developed a quantitative ultrasound device (foot ultrasound scanner) that measures the speed of sound at the heel with the aim of minimizing common error sources like the position and penetration angle of the ultrasound beam, as well as the soft tissue temperature. To achieve these objectives, we used a receiver array, mechanics to adjust the beam direction and a foot temperature sensor. In a group of 60 volunteers, short-term precision was evaluated for the foot ultrasound scanner and a commercial device (Achilles Insight, GE Medical, Fairfield, CT, USA). In a subgroup of 20 subjects, mid-term precision (1-mo follow-up) was obtained. Compared with measurement of the speed of sound with the Achilles Insight, measurement with the foot ultrasound scanner reduced precision errors by half ($p < 0.05$). The study indicates that improvement of the precision of calcaneal quantitative ultrasound measurements is feasible. (E-mail: m.daugschies@rad.uni-kiel.de)

Key Words: **Quantitative ultrasound, Calcaneus, Mid-term precision, Osteoporosis.**

INTRODUCTION

The increasing life span in industrial countries leads to an aging population, and thus, disorders of old age become more relevant. Osteoporosis is the most prevalent metabolic bone disease and one of the most frequent diseases in the elderly population (Jones et al. 1994; Warming et al. 2002). It is characterized by bone loss and, hence, increased risk of fractures, which can cause immobilization (Hall et al. 1999) and increased mortality (Center et al. 1999). Because a large proportion of the population (about 39% of the women older than 50 in Germany [Häussler et al. 2007]) have osteoporosis, high-quality diagnosis, prognosis and therapy monitoring are essential. Today, the clinical gold standard for these tasks is the assessment of areal bone mineral density (aBMD) of the hip and spine by dual X-ray absorptiometry (DXA).

Address correspondence to: Melanie Daugschies, Sektion Biomedizinische Bildgebung, Klinik für Radiologie und Neuroradiologie, Universitätsklinikum Schleswig-Holstein, Am Botanischen Garten 14, Kiel 24118, Germany. E-mail: m.daugschies@rad.uni-kiel.de

Dual X-ray absorptiometry of the spine or hip and quantitative ultrasound (QUS) measurements at the heel permit estimation of osteoporotic fracture risk with comparable performance (Bauer et al. 2007; Hans et al. 1996; Pinheiro et al. 2006). Therapy monitoring is also relevant, but here the performance of QUS methods remains controversial (Blake and Fogelman 2007; Krieg et al. 2008). DXA monitoring of the spine (Faulkner 1998) is more sensitive compared with that of the hip, as the vertebrae consist mainly of cancellous bone, which is more responsive to changes in bone metabolism because of the larger surface compared with cortical bone. However, degenerative changes of the vertebrae—that is, calcifications, especially those on or near the outer surface of the cortex of the vertebrae—are a major source of error, which limits the potential to use spinal DXA for monitoring (Guglielmi et al. 2005). In addition, drugs such as bisphosphonate minimize fracture risk even if no or only minimal changes in aBMD are measured (Chapurlat et al. 2005; Watts et al. 2004). In contrast to DXA, ultrasound, as a mechanical wave, is influenced by other aspects and is related to bone microstructure and stiffness (Goossens et al. 2008; Hodgskinson et al.

1997; Nicholson et al. 1998). Nevertheless, it is unclear if ultrasound measurements can yield more information about the development of fracture risk during therapy. Some longitudinal studies of different therapies did not prove the feasibility of using QUS for monitoring (Frost et al. 2001; Gonnelli et al. 2002, 2006; Sahota et al. 2000). One contributing factor might be the poor (long-term) precision of current QUS devices as criticized by the International Society for Clinical Densitometry (ISCD) (Krieg et al. 2008). Furthermore, adequate studies reporting the ability of QUS to monitor therapy are lacking, although the ISCD recognized some evidence of this potential. QUS at the heel seems to be better suited for this task than QUS assessments at other sites (*e.g.*, radius and phalanges) because of a stronger response to anti-resorptive treatment of the QUS parameters at this site (Krieg et al. 2008). The common QUS parameters measured by commercial devices at the heel include the apparent speed of sound (SOS) and broadband ultrasound attenuation (BUA). Gonnelli et al. (2002) reported a five times higher monitoring time interval for BUA compared with SOS in monitoring bisphosphonate treatment. Therefore, in this study we focused on SOS as the more sensitive parameter of changes in bone status. The sensitivity to detect changes is related to responsiveness (*i.e.*, changes in the reading of the given method over a specific interval) and the long-term precision error (Glüer 1999). Thus, increases in sensitivity may be obtained by decreasing errors in precision. Common error sources in QUS include repositioning of the foot along with the placement of the region of interest (ROI) and the temperature of the coupling medium as well as of the soft tissue (Njeh et al. 1999). The device developed in our lab (foot ultrasound scanner [FUS]) was constructed using innovative design features with the aim of minimizing the impact of these issues by using an ultrasound array to generate an image, mechanics for adjusting the ultrasound incident beam angle, temperature stabilization of the coupling medium and a sensor to measure the temperature of the foot. The FUS was built and tested to assess whether achievement of substantial improvements in SOS mid-term precision compared with commercially available devices is feasible and to estimate the impact of the design features introduced on the precision of calcaneal QUS.

METHODS

Principle underlying the measurement

For QUS measurements of the calcaneus, the foot is placed between two transducers, one acting as emitter and the other as receiver (Fig. 1). In both the Achilles Insight (GE Medical, Fairfield, CT, USA) and the FUS, membranes filled with a liquid acoustical coupling medium are used between the foot and transducers. The emitter excites an ultrasound wave that passes through the coupling medium, the soft tissue of the foot and the calcaneus. For SOS measurements, the time between excitation and arrival of the ultrasound wave at the receiver, called time of flight (TOF), is evaluated. TOF is influenced mainly by the properties of the bone in the ultrasound path, but also by the temperature-dependent ultrasound velocities of the coupling medium and the overlying soft tissue.

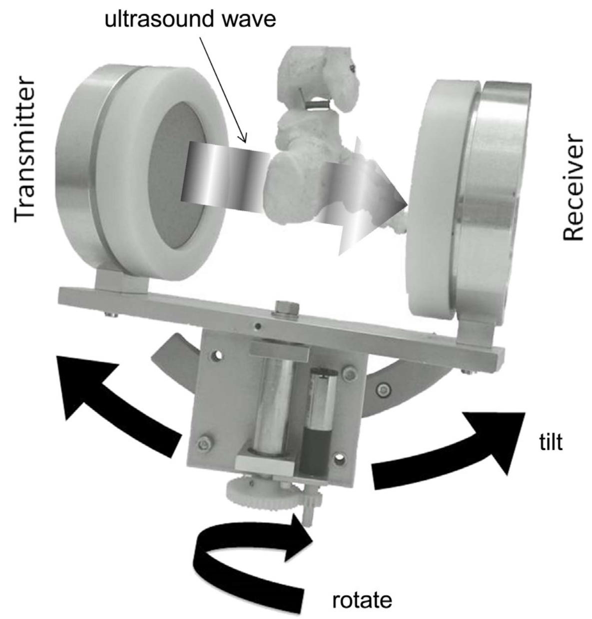

Fig. 1. Arrangement of the transducers at the heel and adjustment of the incident beam angle. Two membranes filled with a coupling liquid can be inflated and, moistened with ethanol, provide the coupling to the skin. The ultrasound wave is excited by the emitter, travels through coupling medium, soft tissue and the calcaneus and arrives at the receiver. The *arrows* indicate the rotation around a vertical axis and tilting movement around a horizontal axis to adjust the incident beam angle.

Devices

An overview of technical aspects of the two devices can be found in Appendix A.

Achilles Insight. In the commercial ultrasound heel scanner Achilles Insight, two quarter wave-matched broadband elements are used as transducers with a center frequency of 0.5 MHz. Their relative position is fixed, providing only one ultrasound beam angle for the measurement. For coupling with the skin, two flexible membranes are filled with 33°C water. The Achilles comprises an ultrasound array as receiver and a single transducer as emitter. It produces an image for controlling the correct positioning and coupling of the skin with the membranes. Only cells in a circular subarea with a diameter of