Original Article

Assessment of the Geometry of Human Finger Phalanges Using Quantitative Ultrasound In Vivo

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Abstract. Quantitative Ultrasound (QUS) methods have been shown to be useful in the assessment of bone status. Nevertheless, ultrasound transmission depends on a variety of skeletal parameters, and a detailed understanding of ultrasound propagation through bone is important for the accurate interpretation of QUS results. In this study we wanted to elucidate the pathways of an ultrasound wave through finger phalanges and determine correlations between geometric and QUS parameters. Phalanges of a subject group were measured using QUS and magnetic resonance imaging (MRI). MRI was used for the derivation of the geometric parameters. Similar assessments were performed on cylindrical tubes and with a simulation program. New parameters related to speed of sound (SOS) and amplitude of the wave (A2P) were calculated. Strong correlations between QUS parameters and morphologic cross-sectional areas were observed in vivo and in phantoms. Similar correlations could be found in the calculations using the simulation software. Cross-sectional cortical area, medullary canal area and relative cortical area could be calculated from the QUS parameters (subjects: $R^2 = 0.71$ for cortical area, $R^2 = 0.45$ for medullary canal area and $R^2 = 0.61$ for relative cortical area; phantoms: $R^2 = 0.98$ for cortical area, $R^2 = 0.78$ for medullary canal area and $R^2 = 0.77$ for relative cortical area). In vivo, phantom and simulation results consistently showed that SOS was correlated with cortical area but not with medullary canal area while the opposite was found for A2P. Pathways of the ultrasound wave through solid cortical bone and the medullary canal could be identified and the propagation of the wave could be depicted. These results help to interpret QUS findings and provide information that may be helpful in improving the performance of QUS.

Keywords: Bone geometry; Novel parameters; Phalanges; Quantitative ultrasound

Introduction

Quantitative ultrasound (QUS) techniques can be used to assess fracture risk [1–10]. However, there is continuing debate about what is measured by QUS devices. Do QUS parameters mostly reflect bone mass or are they affected by other properties such as bone geometry, microstructure or material properties? For accurate interpretation of QUS results as well as for further improvements of the method it is important to gain a more detailed understanding of the mechanism of ultrasound interactions when passing through bone.

Because the most common fracture regions, femur and spine, are difficult to measure using ultrasound methods, several peripheral regions, among them the fingers of the hand, have been investigated [3,11–22]. With aging and osteoporosis the phalanges undergo morphologic changes such as widening of the medullary canal and increased tunneling in the cortex, which should be detectable by ultrasound. Using the DBMSonic 1200 (IGEA, Carpi, Italy) a significant decrease in ‘Amplitude-Dependent Speed of Sound’ (AD-SoS) due to aging [17,23,24], strongest in early postmenopausal women,
and an increase in AD-SoS during hormone replacement therapy [25] have been observed. AD-SoS is the standard speed of sound parameter of the device, calculated as the ratio between transducer distance and time-of-flight (TOF) between the transducers. TOF is the difference in time between transmission of the ultrasound pulse and detection of the signal received. The received signal is detected by the electronics when it reaches a certain trigger level. Therefore, TOF also depends on the amplitude of the signal received, e.g. in a signal with a lower amplitude the trigger level is reached at a later time. Initial results also indicate the usefulness of phalangeal SOS in the assessment of rheumatoid arthritis [26,27] and disorders of growth and puberty in children [28]. It has been shown that AD-SoS allows the discrimination of osteoporotic from normal subjects [10,17,23].

One potential advantage of QUS measurements over radiologic bone density measurements is the complexity of ultrasound transmission. Ultrasound transmission depends on a variety of skeletal parameters. At first sight, this may be considered to be a disadvantage since it complicates the interpretation of the results. However, it may become possible to extract a variety of ultrasound parameters from ultrasound received signals, each reflecting somewhat different aspects of skeletal status. In order to exploit more of the information contained in the measured signal the Ultrasound Bone Profile Score (UBPS) was introduced. This parameter characterizes the shape of the received signal, which is related to the status of the bone [25]. However, the interpretation of changes in UBPS is still unclear. To study the impact of bone morphology, associations with geometric parameters of the phalanges have been investigated. Significant correlatons between AD-SoS and the metacarpal index were observed [29]. Metacarpal index is the ratio between combined cortical thickness and width of the metacarpal, usually measured on hand radiographs. Axial drilling as well as perforation of the cortex caused a decrease in velocity (AD-SoS) and energy of the transmitted signal in pig phalanges [15]. In phantoms a linear relationship between cortical index and AD-SoS was observed [30].

The aim of our study was to refine the knowledge about the pathways of the ultrasonic wave through the phalanges. The standard velocity parameter AD-SoS combines velocity and attenuation aspects of the transmitted ultrasound wave. To investigate potential determinants of AD-SoS we introduced separately velocity and attenuation parameters and studied their relationship with geometric properties of the phalanges. These relationships were investigated both experimentally using magnetic resonance imaging (MRI) for the assessment of finger geometry and by theoretical simulation studies using a newly introduced software tool. These methods allowed us to study the pathways of the wave through the bone in order to identify geometric parameters, which could be predicted from ultrasound transmission measurements.

Materials and Methods

Measurements on Subjects In Vivo

Twenty-two volunteers (17 women, 5 men; age 25–78 years) were recruited during a public osteoporosis meeting. No selection criteria were applied except the giving of informed consent to participate in the study. No exclusions regarding diseases or risk factors affecting bone were made. Two consecutive QUS measurements of phalanges II to V of the left hand were performed according to the manufacturer’s recommendations. Because of the relatively long measurement time for MRI (15 min) only phalanx III (middle finger) was measured using MRI, and only data on this phalanx were evaluated.

Phantom Measurements

The metaphysis of the human finger phalanges contains both cortical and trabecular bone. The shape of the cortical cross-section varies between an ellipsoid and a ‘half-moon’, depending on the location. A simplified model of this site is a circular-shaped tube. We built several tubes of polyvinylchloride (PVC) with a material velocity of 2300 m/s covering a range of typical outer and inner diameters and of areas of the cortex and the medullary canal. Outer diameters were 6, 8 and 10 mm with cored holes between 2 and 8 mm diameter in 1 mm increments. Tubes were measured in the radial direction and were placed centrally between the probes. The transducer distance was kept constant at 14.73 mm. Demineralized water at room temperature (20 °C) was used as coupling medium. Unlike tap water, which has a variable salt content, the sound velocity of demineralized water is well known. Water acts as a surrogate for the soft tissue layers surrounding the phalanx. Transducer distance was held constant to avoid introducing another variable parameter.

Ultrasound Measuring System

Ultrasound measurements were carried out using a modified version of the DBMSonic 1200 (IGEA, Carpi, Italy). This instrument uses two opposing ultrasonic probes mounted on a caliper a variable distance apart. A soundwave of 1.25 MHz center frequency is generated by the sender and detected by the receiver after having crossed the medium in between. The instrument was designed to measure the metaphysis of the human phalanges, but it can be used to measure the transmission of ultrasound through any medium that can be positioned between the probes. The instrument stores the received signal in a computer, thus facilitating a more sophisticated analysis of the signal.

For measurements on phantoms we used a research version of the DBMSonic that allows the probes to be immersed in a water-bath. To enable precise measure-