RELATIONSHIPS BETWEEN BONE PARAMETERS AND ULTRASOUND MEASUREMENTS IN AXIAL TRANSMISSION TECHNIQUE

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Abstract

Axial transmission technique is based on velocity measurement of ultrasound waves propagating along the interface between bone and soft tissue in the direction of long bone axis. The measured parameter under concern here was the velocity of the first arriving signal. Numerical simulations of ultrasound propagation and QCT measurements were used to explore the interactions of ultrasound at 1 MHz with the radius. As expected by numerical simulations, axial transmission technique reflects bone thickness only for thinnest radius (thickness smaller than 2 mm) and bone mineral density, when evaluated in the whole cortical thickness, is a moderate determinant of the ultrasound parameter.

Introduction

Recently, new ultrasound devices have been designed to investigate cortical bone in vivo, based on the so-called axial transmission technique. Cortical bone usually becomes thinner and more porous with osteoporosis and/or advancing age, as a result of endosteal resorption. Determining the relationships between the measured ultrasonic velocity and bone properties is a major issue. If such relationships were known, optimization of devices would be more guaranteed and potential new ultrasound parameters would be preferentially exploited. Our approach to address this issue was to combine different tools: ultrasound, X-ray CT measurements and numerical simulations of ultrasound propagation. Confrontation of these different results gives more insight into ultrasound measurements in cortical bone.

Materials and methods

Samples

Experiments were performed on 51 excised human radius with removed soft tissue. Samples were kept frozen between measurements and warmed at room temperature for experiments. The mean age value was 73 years (45-95 years).

Ultrasound measurement

Speed of sound (SOS) measurements were performed on 3 standardized regions of interest in the third distal radius in air using a standard ultrasound coupling gel between the probe and the specimens.

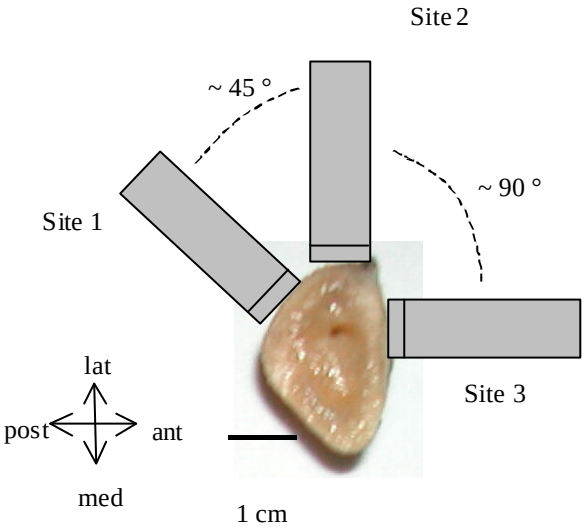


Figure 1 : Illustration of the 3 different regions that were measured using ultrasound (post : posterior ; lat : lateral ; ant : anterior ; med : medial).

The regions were the postero-lateral, lateral and antero-lateral aspects of the cortical shell (Fig 1).

The length of the regions probed by the device was 1 cm in the axial direction parallel to the bone axis. The inter-operator precision was assessed by triplicate measurements performed by two distinct operators on each specimen with intermediate repositioning.

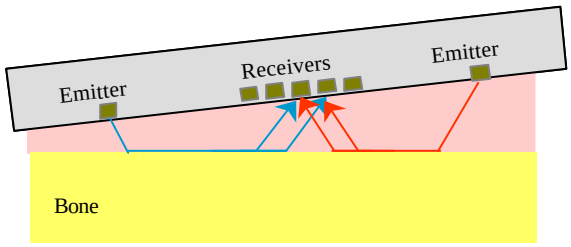


Figure 2. Schematic representation of bidirectional axial transmission method

Axial transmission SOS measurements were carried out using a proprietary new 1 MHz bi-directional probe based on an array technology[1]. Briefly, the axial transmission relies on measurement of the velocity of ultrasonic waves which propagate along the interface between soft tissue and bone. Dedicated devices consist in a linear arrangement of emitters and

receivers placed on a same side of a cortical bone site in contact with the skin. Attention is focused on the first arriving signal and its velocity. Factors which may influence velocity measurements precision include soft tissue properties such as the variations of soft tissue thickness in the region of interest inspected by the probe. We designed new ultrasonic probes based on a bi-directional transmission method, depicted in Figure 2, which allow simple and robust compensation for soft tissues, without requiring intermediate measurements of soft tissues properties. Two sources are placed on both sides of a unique set of receivers. Briefly, combination of times of flight of the first arriving signal associated to ultrasound propagation in the two opposite directions provides the required correction for soft tissue properties[1].

QCT measurements

Quantitative computed tomography (Siemens, Somaton 4 Plus) was performed at distal shaft sites of the radius immersed in a water bath. A stack of 2D CT slices were measured in order to get a 3D reconstruction of the geometry and of the volumetric bone mineral density (BMD) of the samples (Fig. 3).

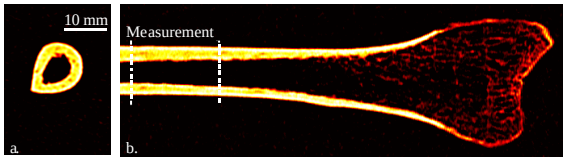


Figure 3 : Transverse and axial cross sections of a human radius obtained by X-ray computed tomography.

The focal spot was 0.7 mm large. The available field of view on the 2D sections was 5 cm^2, resulting in a pixel size of 97.7×97.7 μm^2 (512×512 points). The slice thickness was 500 µm for both geometry and BMD reconstruction. The consecutive cross-sectional slices were reconstructed in steps of 200 µm for 3D geometry reconstruction and 1 mm for 3D BMD maps in the axial direction. As CT values were calibrated to BMD using phantom measurements, values are here reported in Hounsfield units.

BMD and cortical thickness were specifically evaluated from the 3 regions of interest (ROI) investigated with the ultrasound probe. The length in the axial direction of the ROI was 1cm, corresponding to the spatial extent of ultrasound receivers. Cortical BMD and thickness were determined by measuring a profile of absorption values perpendicular to the cortical shell (Figure 4). Thickness was defined by the full width at half maximum of the profile; BMD was measured similarly[2-3].

Mean cortical thickness or BMD were estimated by averaging 3 local measurements on each of the 3 bone aspects performed on several 2-D sections distributed over the 1 cm long volumes of interest.

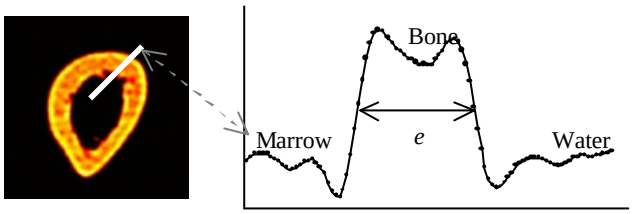


Figure 4 : Principle of the measurement of cortical bone thickness and BMD.

Simulations

Simulations were performed using a finite difference code implemented in our group, which computes a numerical solution to the 3-D linear elastic wave propagation in non-absorbing, heterogeneous, anisotropic and elastic media[4]. The discretization of the propagation equations according to Virieux scheme[5] was chosen for its ability to accurately model propagation for both fluids and solids, and for a convenient implementation of 3-D perfectly matched layers on sides and edges of the simulation mesh, essential to efficiently avoid spurious numerical reflections.

Soft tissue and marrow were assumed to be water, with a density of 1000 g/cm^3 and a bulk wave velocity of 1500 m/s. Cortical bone material was first modeled as a homogeneous and isotropic medium. It was characterized by its density (1850 g/cm^3), compressional bulk wave velocity (c_L=4000 m/s) and shear bulk wave velocity (c_T=1800 m/s) consistent with typical values found in the literature.

In a further step, anisotropy was introduced. According to Ref. 6, cortical bone may be described as a transversely isotropic medium, which means that the bone tissue is isotropic for ultrasonic waves in any plane normal to the bone axis. Briefly, in comparison to the isotropic model, anisotropy modified the compressional bulk wave velocity in directions normal to the bone axis, which was around 3400 m/s.
A 3D map of the bone geometry reconstructed by QCT was introduced in the simulation code. A fixed threshold was applied to discriminate between bone and marrow. Those discriminated materials were then assigned the elastic properties of bone and water respectively. The QCT scans were converted to cubic voxels. The 3-D spatial pitch was set to 100 µm, corresponding to a fifteenth of the shortest wavelength involved (wavelength in water, λ_w = 1.5 mm at 1 MHz).

The emitter and receivers were operated in axial transmission mode, following the probe design used in ultrasound measurements[1]. Each ultrasonic emission consisted in a 1 MHz center frequency broadband pressure pulse. Signal detection was based here on signal extrema. Briefly, local velocity values were calculated by dividing the distance separating two

adjacent receivers (typically 1 mm apart along bone surface) by the differences in time-of-flight measured at the two receivers[1]. A mean value was then derived by averaging all local velocity values for all the adjacent pairs of receivers.

Results

Simulations

Figure 5 illustrates the snapshot of the absolute particle velocity when the source excites a QCT reconstructed radius. No difference is seen between 3D bone and tubular geometries, regarding the first detected wave. Cortical thickness and anisotropy influences were assessed on a 3-D tubular geometry. The outer radius was set to a fixed value of 8 mm, in agreement with typical dimension found at the distal third of a human radius. Cortical thickness was varied from 0.5 mm to 7 mm, by changing the inner radius. Results are reported on figure 6.

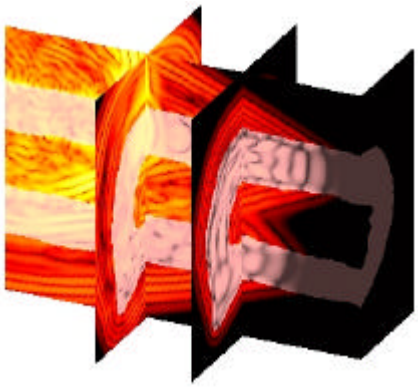


Figure 5. Snapshot of the particle velocity modulus in the longitudinal plane. The source excites a QCT reconstructed radius (left) and a flat plate (right).

SOS varies with thickness, due to a change in the physical nature of the ultrasound wave associated with the first arriving signal. For thick phantoms, the FAS is identified as a compressional lateral wave. Consequently, SOS equals the compressional bulk wave and is insensitive to thickness. For intermediate thickness, guided modes contribute altogether to the received signal due to their re-radiation in the soft tissue and the velocity of the first arriving signal is then affected by interference between modes. For very thin phantoms, the FAS is associated to the lowest order symmetrical mode (S_0 Lamb mode) propagating slower than the compressional bulk wave.

When anisotropy is taken into account, sensitivity to thickness occurs in a narrow thickness range, from $\lambda_{bone}/4$ to $\lambda_{bone}/2$.

Measurements Precision

The inter-operator precision of ultrasound measurements, expressed as RMS coefficients of variation, was 0.5% for site 1, 0.7% for site 2 and 0.9% for site 3. The mean SOS value, pooling all sites, was 3937 ms^{-1} (range 3713-4167 ms^{-1}).

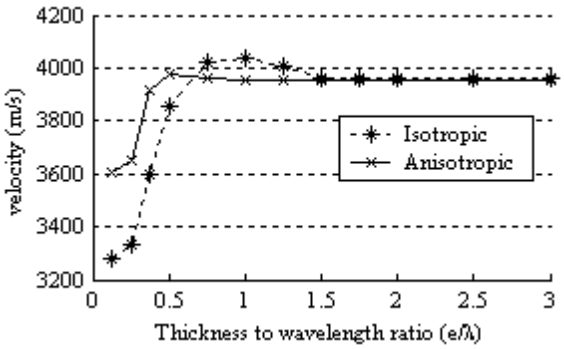
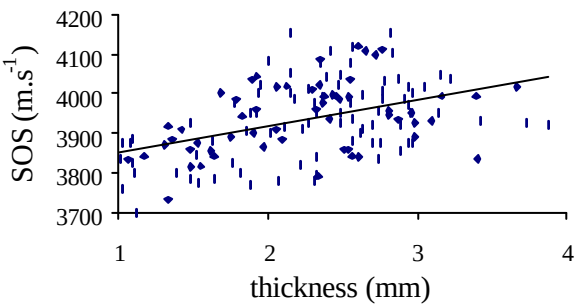


Figure 6. Sensitivity of SOS to thickness (predictions from simulations on isotropic and anisotropic tubes)

A significant correlation was found between thickness and BMD when the whole thickness range was considered, which disappeared when only thicker bone (thickness 2mm) were considered. As quoted in several papers [2-3], cortical BMD can only be measured accurately if the cortical thickness is larger than a critical value. In our experiments, reliable BMD measurements were obtained for thickness larger than 2 mm, as validated using a calibration phantom.

Correlation between SOS values and bone parameters

SOS values are plotted as a function of cortical thickness and BMD on Figure 7. Regression lines are indicated as continuous lines. Highly significant but moderate (R^2=0.20, $p<10^{-5}$) correlation is observed between SOS and cortical thickness values. Furthermore, if data were reduced to thick samples (thickness larger than 2 mm), no significant correlation was found. If data were reduced to thin samples (thickness smaller than 2 mm), a significant correlation was found. Highly significant but moderate correlation (R^2=0.20, $p<10^{-4}$) is observed between SOS and BMD values for specimens with cortical thickness larger than 2 mm.



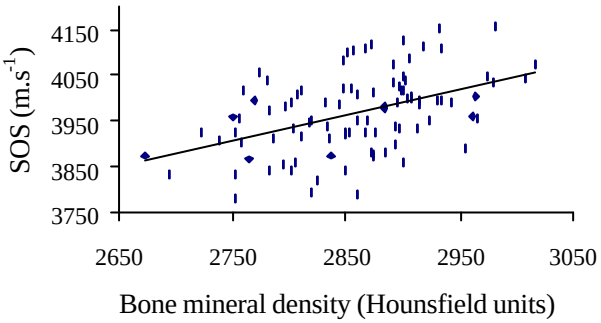


Figure 7. SOS values as function of QCT bone thickness and QCT BMD

Discussion

Sensitivity to thickness

Numerical simulation of ultrasound wave propagation predicts that the three-dimensional aspect of bone geometry in terms of curvature is not a determinant of SOS at 1 MHz, while anisotropy has a major influence in determining the thickness range for which SOS becomes sensitive to thickness. Indeed, it was found that cortical thickness is a determinant of the SOS for cortical to wavelength ratio ranging from 0.25 to 0.5. Practically, 1 MHz measurements should be insensitive to thickness for bones thicker than 2 mm. Such a conclusion agrees with observed relationships between SOS and thickness in our *in vitro* experiments. This agreement partially validates the analysis of the physical nature of the ultrasound wave associated to the first arriving signal based on previous academic models[7]. This suggests the use of lower frequencies for radius investigation in order to optimize cortical thickness sensitivity of the velocity of the first arriving signal.

Sensitivity to BMD

At the radius at a comparable frequency and for comparable BMD ranges, the correlation reported in our study agree with results reported by Sievanen et al.,[7] (R^2=0.3, N =51).

However, simulations (results not shown here) predict that axial transmission SOS measurements at 1 MHz reflect bone properties over a cortical depth of about 1-1.5 mm[3]. This suggests that the correlation between BMD and SOS was moderate because BMD as measured by QCT was a value averaged on the whole cortical thickness while SOS measurement reflects material properties at best in the 1.5 mm-thick superficial cortical layer. In a further publication, we will show that higher resolution tomographic measurements are in agreement with our analysis.

Conclusion

As predicted by 3D numerical simulation, SOS measurements on radius at 1 MHz is correlated to cortical thickness only for bones thinner than 2 mm. SOS measurements at 1 MHz on radius reflects bone properties in a superficial bone layer of around 1 to 1.5 mm thick. As a consequence, only a moderate correlation between SOS measurements and BMD was found, as density measurements performed by QCT correspond to a value averaged on the whole bone thickness.

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