A NEW PROBE DEDICATED TO CORTICAL BONE STRENGTH ASSESSMENT

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Abstract

We have designed an axial transmission device based on a proprietary new probe, which minimizes the effects of error sources encountered in *in vivo* velocity measurements on bone. One major error source is induced by variations of surrounding soft tissues thickness. Intermediate measurements of soft tissues properties are avoided in our technique, which is based on measurement on a same set of receivers of the time of flight of the first signal originating from direct and opposite excitation. The validity of the measurement principle was demonstrated by tests performed on Aluminum and Perspex flat plates. After correction for inclination, the residual relative error on velocity measurement falls in the range 0.2-0.3%. The system provides a short term *in vivo* precision (RMS CV) assessed on the one third distal radius with a 1 MHz probe of 0.4-0.5 %.

Introduction

Quantitative ultrasound techniques have been developed in an attempt to provide a cheap radiation-free assessment of skeletal status. In the domain of osteoporosis, devices based on ultrasonic transmission through peripheral sites such as the calcaneus have been successful to predict fracture risk equivalently to X ray absorptiometry.

For investigation of radius or tibia, axial transmission techniques are more adequate to comply with the complex geometry of the bone. Axial transmission devices, consisting in a set of transducers placed on a same side of the skeletal site, measure the velocity of elastic waves propagating along the bone axis and radiating into soft tissues.

We designed a device for clinical use based on a proprietary new probe, which minimizes the effects of error sources encountered *in vivo*. One major error source is induced by variations of surrounding soft tissues thickness. To correct for soft tissue, additional measurements of thickness and/or velocity in soft tissues have been devised. On the other hand, the technique we have developed does not require such intermediate measurements, but uses the principle of propagation along the bone surface in two opposite directions from two sources placed on both sides of a unique group of receivers. Combination of time delays of signals generated by each of the two sources and received on a unique group of receivers yield an accurate local estimate of speed of sound.

Experiments were performed on academic materials such as Aluminum and Perspex, in order to demonstrate the validity of the measurement principle. The residual relative error on velocity measurement after correction for inclination between the probe and the sample was reduced to 0.2%. The *in vivo* precision falls in the range 0.4%-0.5% for the 1 MHz new probe.

Background

The principle of the axial transmission technique we refer to is depicted on Figure 1. Emitters and receiver(s) are placed on the same side of the bone. As in clinical evaluation, our interest is focused on the first arriving signal (FAS), which involves elastic propagation along the bone and radiation into soft tissue. The critical angle β under which one such wave is excited and which defines the direction of radiation is given by Snell-Descartes law:

$$\sin\beta = \frac{c_F}{c_S} \qquad (1)$$

where c_F is the sound velocity in soft tissue and c_S is the phase velocity along the bone axis of the propagating wave.

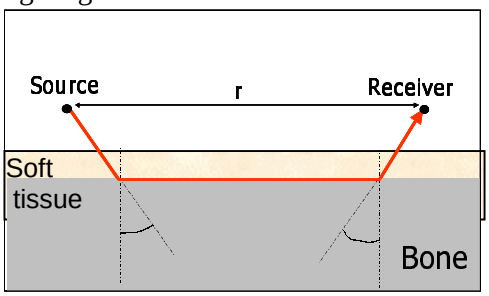

Figure 1: Principle of axial transmission technique for bone inspection

We have addressed the question of the physical nature of the FAS previously [1] on the basis of numerical simulation of the ultrasound wave propagation on bone mimicking phantom constituted of a plate or a tube of homogeneous material immersed in water. Briefly, the nature of the FAS has been shown to continuously change between the long and short wavelength limits (compared to the thickness of the bone phantom). As a consequence, the velocity (SOS) of the FAS decreased continuously as the thickness decreased. For phantoms thicker than the

compressional wavelength in the material, the FAS was identified as a lateral wave of compressional type and the SOS was then closed to the compressional bulk wave (around 4000 m/s for a cortical bone). For intermediate thickness, guided modes were excited in the layer and contributed altogether to the received signal due to their re-radiation in the soft tissue. When the thickness was typically less than a quarter of a wavelength, the FAS was associated to the lowest order symmetrical mode (S_0 Lamb mode) propagating slower than the compressional bulk wave.

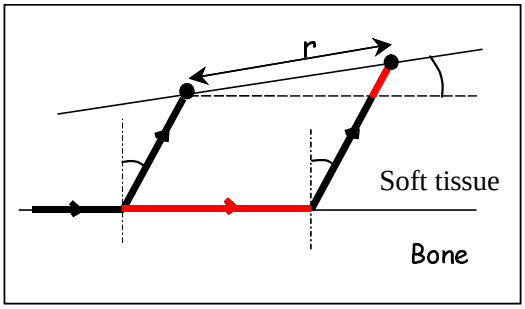

Figure 2: Geometry of measurements when the transducers and the surface to be inspected are inclined of an angle α

Velocity measurement principle

Classically, assuming a non dispersive wave, the FAS velocity c_S is measured in the time domain as the ratio of the distance between two successive receivers Δr by the corresponding difference in times-of-flight Δt_0:

$$c_s = \frac{\Delta r}{\Delta t_0} \qquad (2)$$

However, when there is an inclination angle (noted α) between the co–linear arrangement of transducers and the surface to be inspected, the time delay is modified due to the geometry of the measurement depicted on Figure 2. The new time delay Δt^+ of the FAS at two receivers separated by a distance Δr, is:

$$\Delta t^+ = \Delta t_0 \left(1 + \frac{\tan\alpha}{\tan\beta} \right) \cos\alpha \qquad (3).$$

The ratio of the distance Δr by the time delay Δt^+ leads to an apparent velocity V^+ which depends on the angle of inclination and on the critical angle.

In order to correct the velocity for such bias, our approach was to take advantage of direct and inverse transmission : an additional source is placed on the right of the receivers. Derived for the two receivers considered before, the difference in times of flight of the FAS associated to propagation from right side is $\Delta t^- = \Delta t^-(\beta, -\alpha)$. The unknown velocity c_S is then deduced from :

$$c_S = \frac{\Delta r}{\frac{1}{2}(\Delta t^+ + \Delta t^-)} \cos\alpha \qquad (4).$$

Finally, assuming small inclination angles α, as expected *in vivo*, cosα is approximated by unity, leading to a predicted error on the radiating wave velocity lower than 0.2% for an inclination angle of 4°. Then, in our technique, the FAS velocity is obtained as the ratio of the interdistance over the average of the time delays associated to direct and inverse transmission, measured at the same pair of transducers.

Materials and methods

Probes

Based on use of direct and inverse transmission, two probes with center frequency respectively of 1 and 2 MHz, were designed. Each probe consisted in a linear 1D array of ultrasonic rectangular transducer elements, with two emitters surrounding a single group of around 15 receivers extending on 1cm. A large angular diagram was ensured along the longitudinal axis of probe, for both emitters and receivers including the critical angle associated to the compressional bulk wave in bone expected to be in the 20-25° range.

The transmitter was excited by an electric signal of 160 Volts with a short duration of half the excitation period. Analogic-digital conversion was performed at 50 MHz or 100 MHz with a 12 bit resolution. Signals were averaged over 10 acquisitions.

Signal processing

Detection criterion defined the FAS as the first contribution emerging from noise with a period close to the one of the excitation signal. The time of flight measurement was based on extrema criteria. Extrema were determined using a parabolic interpolation between three samples around the considered extremum.

For each pair of receivers, two time delays were deduced from time of flight measurements: one was obtained with the direct transmission mode and the other one results from the opposite transmission mode. Correction for inclination was achieved by averaging these two time delays. The curve representing corrected time delays versus receivers' relative positions was fitted by linear regression, and the corresponding slope used to determine the inverse of the FAS velocity.

Test material samples

Experiments were carried out on 30 mm plates of Perspex and 20 mm Aluminum plates. Specimen thickness was at least three times larger than the compressional bulk wave wavelength and therefore

our interest in these experiments was focused on lateral wave arriving as the first signal on the receivers. This materials were chosen as the lateral wave on bone is expected to correspond to critical angles around 21-26°, within the range of critical angles associated to water/Aluminum (13°) and water/Plexiglas (33°) interface. Experiments with academic plates were also performed with specimens immersed in glycerol, in which sound propagates at 1895 m/s faster than in water. Glycerol was chosen due to a viscosity close to that of soft tissue.

Calibration

Calibration of the probe is required for accurate knowledge of the positions of the receivers, which optimizes the slope method to determine the FAS velocity. It was achieved by performing lateral wave velocity measurement on thick plate of Perspex with a compressional bulk velocity of 2770(±10) m.s-1 at 18°C, using standard gel as coupling agent.

Test material experimental set-up

When necessary, probe was mounted on a mechanical displacement system, allowing translations in the 3 directions with a precision of 10 µm. Rotation around the vertical probe axis in the plane containing the longitudinal axis of the probe was available with a precision of 5 minutes: such a rotation corresponds to what we called inclination. Rotation was also achieved in the plane orthogonal to the longitudinal axis of the probe. For contact experiments, a standard ultrasonic gel was applied as coupling agent.

In vivo measurements-experimental protocol

The evaluation site was the latero-posterior aspect of the distal third of the left radius. While scanning an angular sector around the radius axis using a standard gel as a coupling agent, 3 series of 400 SOS measurements were performed within less than 5 minutes overall. For each of the 400 velocity measurements, consistency between direct and opposite transmission was checked. For each series, the system filtered biased measurements, either due to probe motion during scanning or misalignment between the probe axis and the bone axis. The SOS result for each series is the 95th percentile of the filtered SOS distribution. If the system found the 3 series consistent, the average of the results obtained for each series was reported.

Intra-operator precision was assessed in 14 healthy women aged 24-53 years using 3 repeated measurements by one experienced operator. For evaluation of inter-operator precision, duplicate SOS measurements in 9 patients aged 24-45 years were performed by two different investigators. These measurements were made in a blinded fashion, i.e. only one operator was present and the time period between measurements for each operator was several days. Precisions were determined as the root mean square average of the standard deviations of the pooled measurements.

Results

Measurements on test material

We first investigated the effects of the system degrees of freedom when a flat interface is inspected. The sample was immersed in water, the probe hold approximately 3 mm above it. The angle of inclination between the probe and the sample varied typically from -2 to 2°. For water/Perspex interface, Figure 3 compares corrected velocity V_{corr} and apparent velocities V^+ and V^- obtained from direct and inverse transmission.

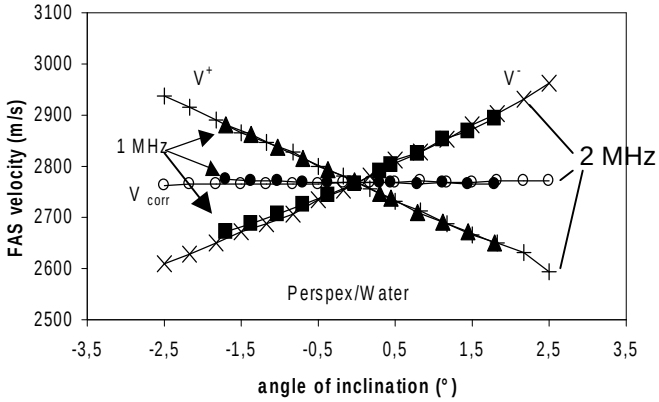

Figure 3: Experimental validation of the correction for inclination for thick Perspex plates immersed in water.

The error in evaluating the lateral wave velocity using the apparent velocity was 5% for an angle of inclination of 2°, while corrected velocity is quasi non sensitive to angle variation: relative variations of the corrected velocity, evaluated by dividing half of the range (min-max) by the average were lower than 0.15%. Average was 2768 m/s for 2770 m/s used for calibration. While considering all the experiments with Perspex and Aluminum immersed in water at 1 and 2 MHz, a relative variation lower than 0.2% was found. The experiments shown here validate the proposed correction for inclination.

In vivo, other parameters vary from one patient to the other such as the absolute value of soft tissue thickness or the velocity inside the soft tissue. In order to evaluate their impact on velocity measurements, we performed experiments mimicking the following effects:

Effects of rotation in a plane orthogonal to the longitudinal axis of the probe were evaluated. For angle of rotation less than 2°, the relative variations of the FAS velocity turned out to be around 0.05%. The effect of re-positioning the probe on the sample was tested when the probe is coupled to the sample by a standard ultrasound gel. When 4 successive

measurements are performed, relative variations of 0.05% for experiments on Perspex and of 0.08% on Aluminum were found. Finally, the distance between the probe and the interface was varied. Relative variations less than 0.2% were found for experiments in water and around 0.3% for experiments in glycerol, when the distance between probe and sample varied from 0.5 to 5 mm.

These experiments performed on flat interfaces show that the major bias on the SOS is induced by inclination between the linear array and the samples and validate the proposed correction for inclination. *In vivo*, due to the complexity of bone geometry, additional degrees of freedom had to be taken into account. The effect of the misalignment of the probe axis with respect to the bone axis was studied. Underestimated FAS velocity values of the order of 2-3% are obtained for misalignment ranging from 5 to 10° on a cylinder mimicking bone phantom. As a consequence, the *in vivo* protocol measurement included a search of stable zones of maximum velocity considered as unbiased by misalignment of both axis.

In vivo precision

Precision results are shown on Table 1.

	Average SOS (m/s)	RMS SD (m/s)	RMS CV %
Intra-operator			
1 MHz	4020(N=14)	15	0.4
2 MHz	4113(N=14)	22	0.5
Inter-operator			
1 MHz	4033(N=9)	20	0.5
2 MHz	4098(N=7)	44	1.05

Table 1. Intra and inter-operator short–term precision

Discussion

Experiments performed on flat plates emphasized that variation of soft tissue thickness is a major determinant of the precision of velocity measurement. The highest relative error turned out to be around 0.2-0.3% for corrected measurement, while inclination between the probe and the surface of a sample yields to relative errors at least of 3% for a small inclination of 1° for uncorrected measurements. Experiments on cylindrical flat samples have shown that misalignment between the bone axis and the probe axis systematically yields underestimated velocity values. A specific *in vivo* data processing was therefore designed to select unbiased values.

Whatever the type of wave that propagates along the cortex and contributes to the FAS, it is observable only from and beyond a critical distance which increases with the thickness of the overlying soft tissue. Our 1 MHz probe was designed in the aim of inspecting more specifically skeletal sites as radius or tibia with an averaged soft tissue thickness of 3-5 mm, larger than that expected at sites such phalanges, for which the 2 MHz probe was specifically designed. Consequently, our 2 MHz probe has reduced performances at the radius.

At 1 MHz, precision evaluation in vivo suggests that our protocol provides a precise and operator-independent measurement. While comparison of precision with published results is rather delicate as the considered populations are different, our results appear to be among the best published ones. The RMS SD (15-20 m/s) is between the value obtained in [2](8-11 m/s) and those obtained in [3] (26 m/s), and similar to those presented in [4] (17 m/s). The intra-operator RMS CV is 0.4% equal to the value in [5] and lower than the value in [6]. The inter-operator precision is one of the lower results obtained with devices based on axial transmission. However, further measurements should be acquired in order to increase the number of patients and to include postmenopausal subjects.

Conclusion

The technique of opposite transmissions allows to easily and robustly compensating for variation of the soft tissue thickness in the region of measurement. This technique throws off preliminary measurements of velocity in soft tissue or soft tissue thickness and yields precise *in vivo* velocity estimates.

REFERENCES

[1] E. Bossy et al, Effect of bone cortical thickness on velocity measurements using ultrasonic axial transmission, J. Acoust. Soc. Am., 112, 297-307, 2002

[2] R. Barkmann et al, "A new method for quantitative ultrasound measurements at multiple skeletal sites," Journal of Clinical Densitometry, 3, pp. 1-7, 2000

[3] K.M. Knapp et al, Multisite quantitative ultrasound : precision, age and menopause related changes, fracture discrimination, and T-score equivalence with dual energy X ray absorptiometry, Osteoporosis Int., 12, pp 456-464, 2001.

[4] W. Drake et al, Multisite bone ultrasound measurement on North American female reference population, Journal of Clinical Densitometry, 4(3), pp 239-248, 2001.

[5] M. Weiss et al, Reference database for bone speed of sound measurements by a novel quantitative multi-site ultrasound device, Osteoporosis Int., 11, pp 688-696, 2000.

[6] J. Damilakis et al., Ultrasound velocity through the cortex of phalanges, radius, and tibia in normal and osteoporotic postmenopausal women using a new multisite quantitative ultrasound device, Investigative Radiology, 38(4), pp 207-211, 2003.