THE ROLE OF SOFT TISSUE IN ULTRASONIC GUIDED WAVE MEASUREMENTS IN BONE

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Abstract

Previously we have reported the possibility of observing the fundamental antisymmetric (A0) Lamb wave propagating in the human tibia and radius. However, A0 velocity (1300-2000 m/s) overlaps that of soft tissue (1500 m/s), and it is therefore possible that signals propagating through soft tissue may be mistaken for an A0 wave in bone. In order to clarify this issue, measurements were performed with water or a silicon rubber layer on top of bone phantoms and specimens, and on human tibia in vivo. It was shown that the intensity of A0 mode attenuated rapidly and its velocity decreased slightly with increasing thickness of soft overlayer. In addition, A0 was detectable better through an overlying layer of water than overlying silicon rubber. Thin soft tissue had only a slight effect on the detectability of A0 mode in vivo and A0 could be measured in 70% of the human subjects.

Introduction

Human long bones are effectively hollow tubes with irregular cross-section, and potentially support the propagation of guided wave modes in addition to the first arriving signal (FAS) measured by existing clinical devices [1]. Guided modes are attractive because they propagate throughout the bone thickness, are less attenuated with distance, and may yield a more complete picture of the bone material and geometrical properties. The possibility of measuring guided waves in bone using an axial transmission technique has been recently described [2,3]. Lefebvre and colleagues showed that Lamb wave theory for plates closely predicted the results for bones measured in vitro.

However, interactions of the guided waves with the surrounding media, i.e. soft tissue and bone marrow, makes the clinical measurement of any guided modes from bone challenging. The guided wave may loose energy into the surrounding media (i.e. attenuate) or form new complicated wave modes with other waves propagating in the soft tissue or bone marrow. As a consequence the wave attenuates, its velocity may alter, and the interpretation of the received signal becomes difficult.

Difficulties in signal interpretation may arise from a couple of factors. Soft tissue is a fluid-like but slightly viscous layer with its thickness comparable to that of the cortical bone. Thus it may independently support propagation of direct longitudinal waves and certain types of guided waves (Fig 1a). However, the guided modes from bone and soft tissue can be supposed to couple with each other assuming that the particle motions at the common boundary remain continuous. As a consequence, no pure bone or soft tissue guided modes propagate but new, coupled modes will be formed (Fig 1b). The work by Yapura and Kinra [4] points out that the simple theory of Lamb waves is not applicable to such fluid-solid bilayers, and therefore we need a more complicated theory. The bilayer theory predicts that we indeed measure guided waves in the combination of bone and soft tissue, and that the velocities of the modes alter depending on the thickness ratio of soft tissue and cortical bone.

Previously we have reported the possibility of measuring A0 like Lamb waves in the human tibia and radius propagating at about 1300-2000 m/s [3]. We refer to this as the 'second wave' to distinguish it from the FAS which propagates close to the bulk velocity in cortical bone (3600-4200 m/s). A0 is classified as a so-called leaky Lamb mode, thus it attenuates rather rapidly with distance. In addition, the range of A0 velocities in bone is very close to that for the bulk longitudinal wave in soft tissue (1500 m/s). Firstly, Snell's law predicts that no axially propagating signal can be measured from bone at a velocity lower than that in soft tissue. However, since A0 is a leaky mode it has a strong displacement component normal to the bone surface, and due to this we might still be able to measure an A0 mode with a velocity below 1500 m/s through a layer of soft tissue. Secondly, distinction from the bulk wave in soft tissue might be difficult if it is received with dominant amplitude. We might expect that a bulk wave is absent in thin soft tissue, but appears when tissue thickness becomes

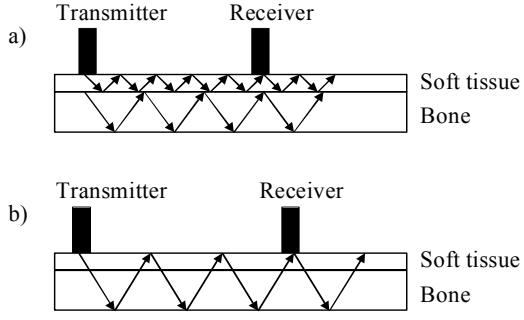

Figure 1. Guided waves could propagate either
a) separately in the bone and soft tissue, or
b) in the combination of bone and soft tissue

comparable to or greater than the wavelength of the bulk wave.

The purpose of this work was to clarify how the presence of soft tissue, and its thickness and properties, affect the attenuation and velocity, and thus the detectability of the second wave in phantoms and bones in vitro. An objective was to evaluate the role of soft tissue in problems encountered with measurements in vivo.

Materials and methods

A 3.6mm thick acrylic and a 4 mm aluminium plate were used as bone phantoms. The plates were measured a) in air, b) underwater at 16 different immersion depths ranging from 0.5 to 30 mm, and c) with a 2 mm thick silicon rubber layer on top of the plate (Soudal Silirub HT). During the immersion measurements the immersion depth was measured from the water surface to the top surface of the specimen, and the transducer heads touch the water surface.

Two cadaver pig bones were measured with and without soft tissue. In addition, 2 cadaver right hand human radius bones were measured without soft tissue in air and underwater at 9 different immersion depths ranging from 0.5 to 10 mm.

In vivo subjects consisted of 67 postmenopausal females, age ranging from 32 to 90 years with a mean age of 55, who were measured at the mid-shaft of the tibia. Four scans per subject were performed on the bone, and one additional scan on the soft tissue beside the bone.

An axial transmission device, consisting of one transmitter and one receiver normal to the limb or specimen, was used to measure the ultrasound velocities. Ultrasound gel was used to ensure a proper acoustic contact, and in the immersion set-up the signal was mediated through water. The pulse excitation included a main band centred at 100 kHz and two slightly weaker bands at 200 and 300 kHz. The receiver was moved progressively away from the transmitter, and the ultrasonic signal was recorded at 40 discrete locations 2 to 5 cm apart from the transmitter. The recorded signals were stored in computer memory as a distance-time matrix, which was then displayed as a grey scale contour plot, hereafter called as the rt diagram. From the rt diagram we determined two distinct wave fronts, the weak first arriving signal, consistent with the longitudinal wave in bone, and a slower second wave which we have shown to be consistent with the A0 Lamb wave [3].

2-D fast Fourier transform was then applied to the distance-time matrix, and a corresponding wave number-frequency matrix was obtained. The latter matrix was observed at the centre frequency of the excitation's main band (100 kHz). At this given frequency, the wave number spectrum was plotted. Intensity maxima were observed in the wave number spectrum corresponding to certain propagating wavelengths. Then, the phase velocity was determined as the product of frequency and wavelength, and the wave number spectrum was converted to a phase velocity spectrum. Finally, the intensity maxima in the phase velocity spectrum were identified by comparing peak locations with the velocities of Lamb wave modes, or bilayer modes, at the given frequency. The theoretical velocities were computed by a numerical solution of the dispersion equation for the Lamb waves [5] or bilayer waves [4].

In addition, Peripheral quantitative computer tomography (pQCT, Norland/Stratec XCT 2000, Stratec Medizintechnik, Pforzheim, Germany) was used for the clinical study. From the pQCT scans cortical and soft tissue thicknesses were determined locally and site-matched with the ultrasound measurements using Bonalyse software (Geanie 2.0, Bonalyse Oy, Jyväskylä, Finland).

Results

In plates or bones without an overlying layer of water, silicon rubber or soft tissue, the rt diagrams clearly showed the presence of two propagating waves: a first arriving signal (FAS) propagating close to the bulk solid velocity, and a second wave with a velocity consistent with the Lamb A0 mode (Fig. 2a). When a water layer was present there was little effect on the first arriving wave but the second wave became less clear (Fig. 2a). Looking at the effect of the increasing water layer thickness on the rt diagrams (Fig. 2b), it was clear that detection of the second wave was slightly affected even by a very thin (1mm) water layer. However, the velocity of the second wave was identifiable until 3 mm immersion depth in the radius specimens within 20% error compared to the velocities measured in air. A direct wave propagating in the water layer was not seen, unless the water layer thickness was greater than 6 mm, after which the wave from water appeared as the first arriving signal at short transmitter-receiver distances. In addition, at water thicknesses of 2 or 3 mm upwards, there was some evidence, in the form of parallel wavefronts with high phase velocity, of higher guided waves propagating in the water layer or water-solid bilayer (Fig. 2b).

In aluminium and copper plates, and in bone, the second wave could, in most cases, be detected and measured through a thin silicon rubber layer or through animal skin placed over the solid. However, some difficulties were observed at phase velocities close to the sound velocity in the overlying layer.

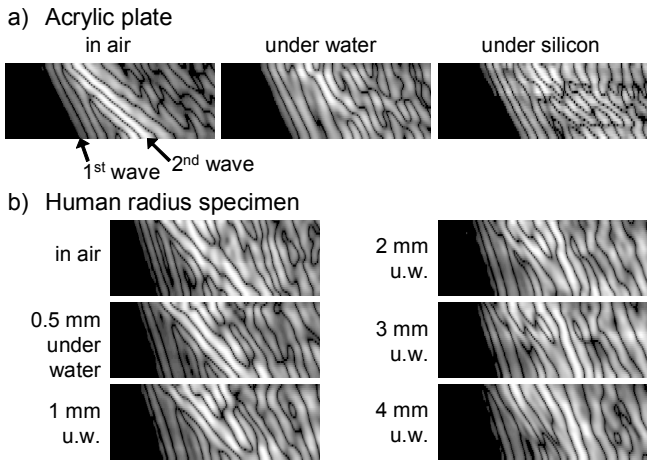

Figure 2. a) Acrylic plate measured in air, 2mm underwater and through 2mm layer of silicon rubber. b) The effect of water layer thickness on the rt diagrams measured from a human radius specimen that has been immersed in saline. For reference, an rt diagram from the same specimen measured in air has also been shown.

In the phase velocity spectra (at 100 kHz) for plates or bone specimens without overlayers, we observed a clear intensity maximum corresponding to an A0 Lamb wave. For the 3.6 mm acrylic plate this intensity maximum was located at (910±30) m/s (Fig 3). When plates or bones were measured underwater, the phase velocity of A0 was slightly lower than in air. Until 1 mm depth the velocity had decreased (15±4)% for acrylic and on average (7±3)% for the radius specimens, when comparing to results in air. The theoretical differences were roughly (9±2)% and (5±2)%, respectively. In addition, we found that the intensity of the maximum decreased rapidly with the increased immersion depth. The attenuation of the A0 mode peak intensity was (-14±1) dB/mm for the acrylic plate, (-6±1) dB/mm for the radius specimens, and only (-3±1) dB/mm for the aluminium plate (Fig 4).

For the acrylic plate, A0 mode was identifiable only up to 2 mm thickness of the overlying water (Fig 3). However, beginning at about 2 mm thickness we observed another mode at a higher phase velocity. In

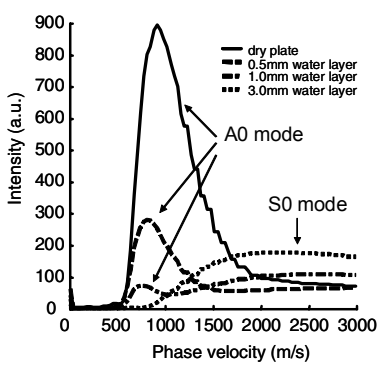

Figure 3. Phase velocity spectrums at 100kHz for a dry and immersed 3.6mm acrylic plate, showing the effects of immersion depth.

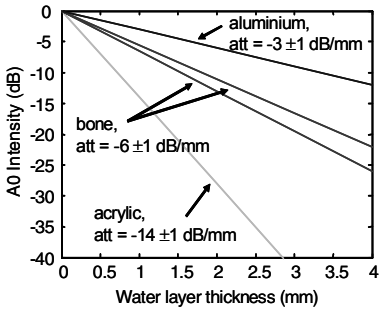

Figure 4. Attenuation of A0 wave intensity as a function of water layer thickness in bone, acrylic and aluminium.

human radius specimens we were able to identify the A0 up to 3 mm thickness, and another mode with a higher velocity began to appear at this same thickness. This mode was apparently consistent with a coupled S0 mode propagating in the bilayer. However, in the aluminium plate we had no problems with measuring the A0 mode at 20 mm thickness, after which the coupled S0 began to appear.

From the animal bones with soft tissue (~3mm) and without soft tissue we measured the second wave velocities, and they were very similar. However, we could not identify an A0 mode from the rt diagram if the soft tissue had been cut between the transmitter and the receiver.

In the in vivo measurements we had three kinds of cases in principle for obtaining reliable results for the velocities of FAS and the second wave (Fig 5a). For 70% of the subjects we were able to clearly identify and reliably measure both wave modes (class 1). In a subset of 27% of the cases, we were still able to measure the velocity of FAS from bone, but at short transmitter-to-receiver distances we obtained a signal from soft tissue (propagating at about 1500 m/s) prior to any signal from bone. Therefore, we did not attempt to measure the velocity of the second wave (class 2). For a 3% subset we only recorded the signal from soft tissue (at 1500 m/s), and no clear sign of any signal from bone (class 3). In addition, with 10% of the subjects we had problems related to a weak or deteriorated second wave signal. However, these cases

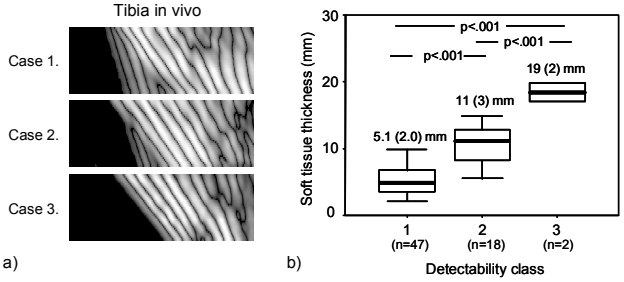

Figure 5. a) Reliability classification for in vivo measurements; case 1: potentially reliable results, case 2: soft tissue signal before the 1st arriving signal from bone, and case 3: soft tissue signal overlaps totally all signals from bone. b) Soft tissue thicknesses in the reliability classes for wave 2.

were all associated with skinny legs and poor contact between the transducer and soft tissue. After repositioning and repeated measurement, and using some signal processing, the weak cases were all found to belong to class 1. The mean soft tissue thicknesses were 5.1, 11 and 19 mm in classes 1-3, respectively (Fig 5b).

Discussion

The results show that measurement of the second wave is in general possible through a silicon rubber layer, but not through a thick water layer. The density of silicon rubber is similar but its sound velocity is lower (1000 m/s) than those of water. In addition, silicon rubber is a soft solid that supports propagation of shear waves, whereas water, a fluid with relatively low viscosity, does not (or at least does so only over very limited distances). The ability to support shear strains between the solid layer and the transducers is likely to be a key factor explaining the observed behavior. The properties of real soft tissue are likely to be somewhere between those of silicon and water, and may vary between individuals.

When comparing the obtained decrease in the A0 phase velocity in the presence of a water overlayer with the theoretical predictions calculated within reasonable ranges of parameters for a fluid-solid bilayer, we found that the experimentally obtained tendency followed the theoretical predictions. However, the experimental results were slightly greater than the theory predictions, possibly due to limited experimental phase velocity resolution, and that the theory did not take into account the water below the plate. In addition, the experimental results suggest that the intensity of the coupled A0 mode decreases, and the coupled S0 becomes dominant after certain thickness depending on the material properties. At this stage we do not have analytical or numerical theory predictions available for the effect of fluid layer thickness on the mode intensities. However, these results suggest that a) we are measuring a coupled A0 mode propagating in the bilayer of thin water and solid, b) the intensity of this mode becomes undetectably low after certain fluid thickness, and c) after this thickness we apparently begin to measure some other bilayer mode with a higher phase velocity.

Also, the measurements on animal bones with and without soft tissue suggest that in vitro we might be measuring a coupled A0 in a soft-tissue-bone bilayer. If we introduce an irregularity in the wave path by cutting the soft tissue, then propagation of A0 is hampered.

It is expected then that the ability to detect and reliably measure the second wave in bone in vivo will depend on the properties and thickness of the soft tissue layer. The human results confirm that increased overlying tissue thickness is associated with difficulties in measuring the second wave. However, tissue thickness does not seem to be the only factor, suggesting that differences in the material properties of the soft tissue may also play a role.

These findings indicate that clinical measurement of the A0 guided wave is possible in the majority of the subjects with thin overlying soft tissue. However, soft tissue may lead to formation of coupled wave modes propagating in the soft-tissue-bone bilayer. To overcome the difficulties with the rest one third of the subjects with thick overlying soft tissue, different ways of exciting and detecting guided waves in solid bone beneath soft tissue may be needed.

For clarity, we have used the labelling associated with the Lamb wave modes also for the fluid-solid bilayer modes throughout this paper. However, the modes propagating in the bilayer cannot be unambiguously identified as symmetric or antisymmetric, and thus a coding 1,2,3, etc (corresponding to A0, S0, A1, etc.) has been used in the literature.

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