DUAL-FREQUENCY METHOD FOR ULTRASONIC ASSESSMENT OF BONES: MODEL STUDY

A.Tatarinov, A.Sarvazyan
ARTANN Laboratories, Inc., 1753 Linvale-Harbourton Rd, Lambertville, NJ, USA
armen@artannlabs.com

Abstract

The propagation of acoustic waves along bones occurs in the form of various guided waves. Application of low and high frequency ultrasound provides a possibility to differentiate contributions of the elasticity modulus and the bone thickness due to geometrical dispersion of the propagation velocity. Model study with dual-frequency (100 and 500 kHz) device confirmed this possibility. Three types of bone phantoms modeling characteristic changes in long bones were developed and tested: 1) tubular specimens of polymer materials modeling combined changes of material stiffness and cortical wall thickness; 2) layered specimens modeling porosity in compact bone progressing from endosteum towards periosteum; 3) natural bone specimens involving both cortical and trabecular components. In all phantoms the ultrasound velocity at 100 kHz monotonously and nonlinearly changed with variations of thickness of intact cortical layer, while at 500 kHz it remained nearly constant, depending mostly on the material stiffness.

Introduction

In different forms of osteopenia and during osteoporosis development, bone fragility is influenced by bone size, shape, architecture and tissue ''quality" [1]. The resorption prevailing over bone formation causes both porosity inside the bone volume and the cortical thinning that results from trabecularization of the inner part of the cortex and expansion of the medullary cavity. The term tissue "quality" implies intrinsic properties of the material responsible for bone mechanical behavior that can be influenced by the porosity, accumulation of microcracks or mineralization defects. That's why the knowledge about both elastic properties of bone material and changes of geometrical parameters is diagnostically valuable.

The thickness of bones and their structural components is of the order of millimeters, close to and smaller than the longitudinal wavelength in the range of frequencies typically used for bone assessment (0.1 – 1 MHz). Consequently, the propagation of acoustic waves along bones occurs in the form of various guided waves having propagation speed equally dependent of both elasticity modulus and the bone thickness. Varying the frequency of acoustic waves results in changing the relative roles and contributions of mechanical and geometrical factors thus providing a possibility to differentiate these major characteristics of bone quality. In extensive *in vitro* studies on human tibia, it was demonstrated [2] that, in low frequency band about 100 kHz, a wave similar by properties to the flexural wave propagates in the cortical shell and the topographical distribution of the velocity has many common features with the spatial organization of bone substance.

Although several commercial QUS devices for long bones assessment measuring ultrasound velocity in compact bone by axial transmission has been produced [3], no one of them explores the geometrical dispersion effects to evaluate changes of cross-sectional parameters of bones. Meanwhile, the approach involving "slow" waves showed better sensitivity to osteoporotic changes than long bones QUS measuring only the velocity of fast longitudinal wave in high-frequency band [4].

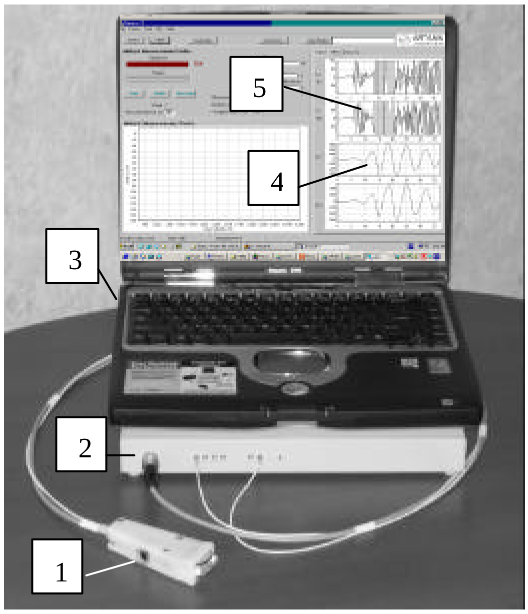

Figure 1 : Prototype dual-frequency long bones QUS, compiling scanning probe (1); electronic unit (2); and laptop PC (3) for processing low (4) and high (5) frequency ultrasonic signals

The objective of present study was to test on models sensitivity of the dual-frequency method proposed by the Artann Laboratories [5].

Methods

Measurement device

A prototype dual-frequency ultrasonometer for long bones of Artann Laboratories shown in Figure 1 was used. A specially designed waveform generator forming programmed ultrasonic signals of the desired frequency and shape excited a broadband ultrasonic transmitter. Sine 100 and 500 kHz ultrasonic pulses were formed to provide low and high frequency bands. The pulses length was restricted by Gauss envelope. Ultrasonic signals propagated along the object in the surface transmission mode were acquired by a symmetric receiver, amplified and transferred to a PC for processing and display. Basically, emitted and received ultrasonic signals had the same frequency characteristics. Arrival times detected by processing first periods of low and high fequency signals were used to calculate velocities of the flexural and longitudinal waves correspondingly.

Models

Three types of phantoms modeling characteristic changes in long bone in osteoporosis were developed and tested:

1) Tubular specimens modeling combined changes of material stiffness and cortical thickness in middleshafts of long bones. The specimens were made of various polymers and polymer composites with longitudinal wave velocity ranging from about 2200 to 3900 m/s and the wall thickness varying from 1 to 6 mm.

2) Layered specimens modeling porosity in compact bone progressing from endosteum towards periosteum. Small quasi-cylindrical rubber particles (bulk velocity about 1500 m/s) as pores were incorporated in the homogeneous solid epoxy matrix. Effectiveness of the similar technology has been shown in earlier studies [6]. The thickness of the solid nonporous layer varied from 0.5 to 8 mm, 20 and 50% content of the soft inclusions dosed the porosity.

3) Specimens prepared from a bovine proximal tibia, involving both cortical and trabecular components. The specimens were cut as axial segments with natural variation of cortex from zero to several millimeters. To simulate increased porosity in the trabecular bone, multiple 0.5 – 2 mm diameter pores were drilled and filled by water in the other series of specimens.

Results and discussion

Tubular phantoms

Figure 2 shows the results of the flexural wave velocity measurements at 100 kHz. A strong dependence of the flexural velocity on the wall thickness was obtained. The characteristic monotonous non-linear dependence on the thickness in all tested materials is similar to the known one for the anti-symmetric Lamb waves in plates. These experiments indicate that the geometric dispersion phenomenon responsible for the significant dependence of sound speed on the dimensions of simple objects can be utilized also for characterization of natural bone having a more complex shape than plates. The velocity graph *vs* thickness has a steep slope over the thickness range of 1-4 mm, which indicates a possibility for sensitive detection of changes in the cortical thickness of long bone metaphyses.

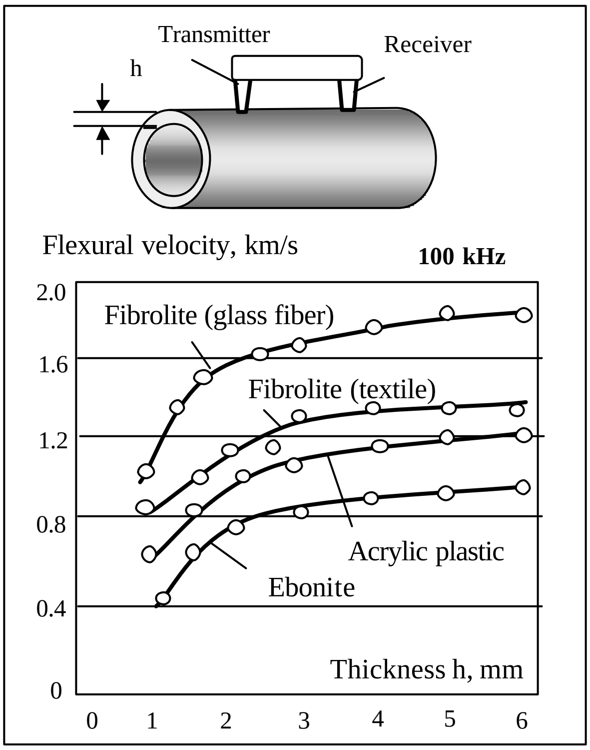

Figure 2 : Dependence of flexural wave velocity determined at 100 kHz frequency on wall thickness in tubular phantoms made of different polymer materials

Table 1 : Ultrasound velocity of longitudinal wave C_l ±S.D. at 500 kHz in tubular phantoms made of different polymer materials and approximate minimal wall thickness h, at which deviation of C_l does not exceed measurement error

	Fibrolite (glass fiber)	*Fibrolite (textile)*	*Acrylic plastic*	*Ebonite*
C_l	*4850 ±50*	*3120 ±120*	*2530 ±20*	*2280 ±50*
h	*1 mm*	*1 mm*	*2 mm*	*3 mm*

Velocities of longitudinal wave at 500 kHz in the phantoms are summarized in Table 1. They have no expressed deviation within series of the same material but differ strongly between the materials accordingly to the material elasticity modulus.

Phantoms modeling porosity in compact bone progressing from inner layer

Figure 3 shows how a gradual increase of porosity from inner layer (opposite to the surface of transducers application) can affect ultrasound velocity

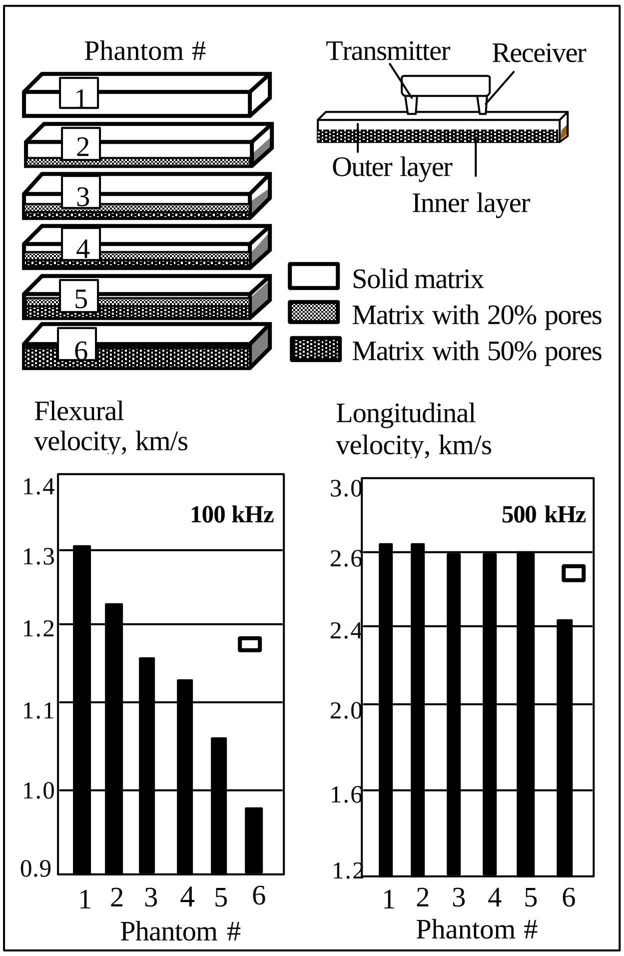

Figure 3 : Changes of velocities of flexural and longitudinal waves obtained correspondingly at 100 and 500 kHz frequencies in phantoms #1-6 mimicking progressing porosity from inner layer of compact bone. Measurement resolution is shown by separate rectangles in the graphs.

at low and high frequencies. If the ultrasound wavelength is higher than the specimen thickness (100 kHz), the propagation velocity is extremely sensitive to decrease of the intact solid layer. At the same time, high frequency ultrasonic waves start to reveal changes only when the porosity reaches outer surface of the cortex where the waves propagate.

This experiment evidently shows the advantage of introduction of low frequency mode for detection of early stage of osteoporosis that starts from the endosteum.

Natural bone specimens

By moving from epiphysis towards diaphysis, the cortical thickness increases several times from parts of one millimeter to several millimeters. As shown in Figure 4, this highly influences the flexural velocity and establishes the requirement for topographical references of measurements in real bones. For instance, it can be realized as it is done in the

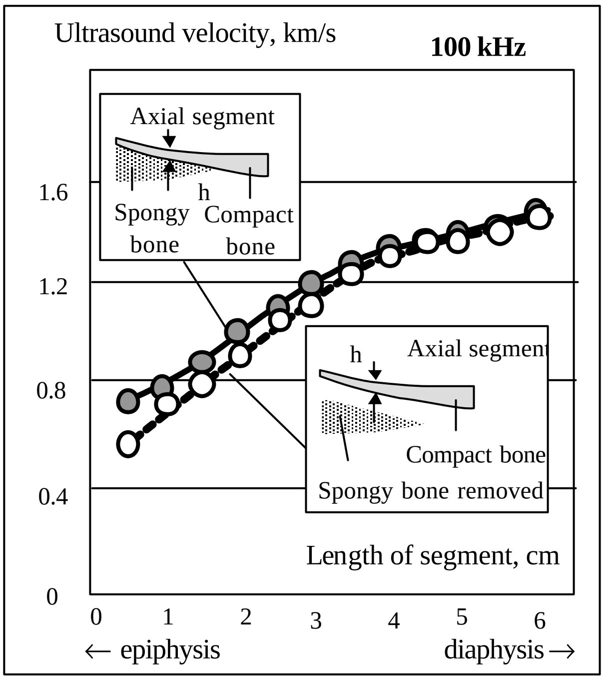

Figure 4 : Distribution of flexural wave ultrasound velocity at frequency of 100 kHz by the length of axial segment cut from bovine tibia before and after removal of spongy component.

proposed Artann device by discrete readings along the bone by means of manual scanning procedure. The experiment also demonstrated the main contribution of cortex to ultrasound measurement data in axial propagation. Removal of the underlying spongy component leads to some decrease of the velocity only in metaphyseal areas close to physis, where the compact bone is thin and there is no distinct partition border between the spongy and compact components.

Figure 5 presents results on simulated increased porosity in the underlying spongy bone. After measurements upon the surface of intact composite compact/spongy specimens, the porosity in the spongy component was artificially increased by about 50% by drilling a periodic mesh of holes through the specimen and the measurements were repeated. It is clearly seen that the flexural wave velocity at the low frequency is sensitive to the changes in the underlying spongy bone. The effect of the spongy bone disappears with the increasing frequency and choosing the longitudinal mode instead of the flexural one.

Conclusions

1.Dual-frequency approach demonstrated, in model studies, the potential sensitivity to such manifestations of osteopenia in long bones as decreased effective thickness of the cortex and increased porosity progressing from inside layers.

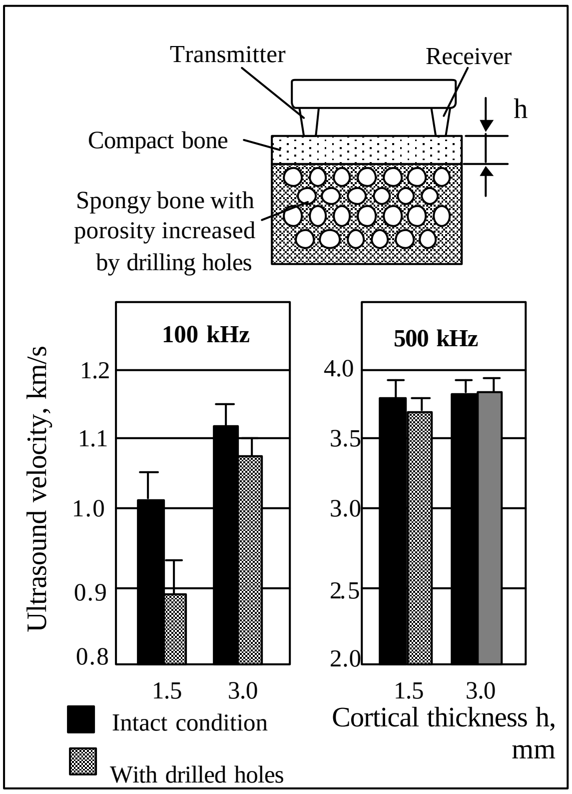

Figure 5 :Changes of ultrasound velocity at frequencies of 100 and 500 kHz in composite bone specimens with different thickness of cortical layer h depending on artificially increased porosity in underlying spongy component.

2. Effect of geometrical dispersion of ultrasound velocity in low frequency band can be exploited to detect changes of cortical thickness.
3.Ultrasound longitudinal wave velocity at high frequencies is less sensitive to changes of cortical thickness and can be used for evaluating the intrinsic material properties of compact bone.
4. Further studies are needed to validate the dual-frequency method for *in vivo* assessment of long bones and osteoporosis diagnostics.

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