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ON OBSERVATION OF SLOW ULTRASONIC WAVES IN CANCELLOUS BONES

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The two-phase model of saturated cancellous bones predicts the existence of two longitudinal waves in the materials. The paper disscusses experimental results concerning ultrasonic studies of the slow longitudinal wave. Results available in the literature are reviewed and compared with author's data obtained through broadband ultrasonic spectroscopy. The essential properties of the measured slow wave as well as technical and material difficulties in interpretation of the data are highlighted.

Key words: saturated porous bones, ultrasonic waves, phase velocity, attenuation.

1. Introduction

Along with the growing importance of diagnostic and therapeutic use of ultrasonic methods in medicine, a considerable development of theoretical and experimental studies of dynamics of biomaterials is observed. The situation concerns also ultrasonic inspection of bones and bone tissues which traditionally have been tested through radiological techniques. The clinical applications of knowledge on dynamical properties of bone tissues are mostly related to assessment of changes of bone density as a diagnostic premise of osteoporosis, [3]. Biological materials such as bones are inhomogeneous and anisotropic media at different scales, and are composed of a few phases. As a result, in order to determine mechanical or structural properties of the materials it is necessary to use not only advanced experimental techniques but also an appropriate methodology for interpretation of the obtained results, [2]. During the last two decades, a number of laboratory experiments were performed (see e.g. [9]) using ultrasounds from kilo- to mega-hertz frequencies and various measurement techniques to evaluate material properties of bones including density, strength, Young's modulus, fatigue, etc. The studies have been performed for human and the other mammalian bones under various conditions e.g. dry, wet, intact and as a function of numerous parameters,for example orientation, temperature, frequency, pathology, etc. As it should be expected, in such circumstances there are often considerable differences in the reported data or properties evaluated by ultrasonic tests for the biological materials. Until the eighties, in most theoretical works it had been assumed that bones are single-phase materials. Such approach allows one to determine bulk mechanical characteristics of bones (e.g. Young's modulus) but does not yield information on the properties of individual phases and particularly, on structural characteristics of the materials such as porosity, permeability and tortuosity. More recently multiphase models are often accepted for description of dynamical behavior of cancellous bone, [5, 6, 7, 11]. The bone is treated then as consisting of solid matrix saturated with fluid (marrow, fat, etc.). The model is usually based on Biot's theory of propagation of elastic waves in fluid saturated porous medium published in 1956, [1], and predicts one shear wave and two bulk compressional waves called fast and slow ones (of first and second kind). The relative motion between fluid and solid for the two compressional waves takes place in phase and out of phase, respectively. The phase velocity of the slow wave V_{slow} in approximation corresponding to the relatively stiff skeleton can be evaluated in relation to the wave velocity in fluid, V_{fluid}, according to the equation $V_{\text{slow}} = \frac{V_{\text{fluid}}}{\sqrt{\alpha}}$, where α denotes tortuosity of the medium. The attenuation of the slow wave predicted by the Biot's theory which assumes the relative motion of phases as the main source of attenuation, is much higher than the attenuation of the fast wave. Although the Biot's model has been already applied by many investigators to determine both the mechanical and structural parameters of bones (see e.g. [2, 11]), the existence of the slow wave in bones and its basic properties are the subject of still open discussion. The particular reason of the discussion is the fact that while the two-phase model predicts that the attenuation of the slow wave is higher than that of the fast one, in the whole frequency range only a few recently published results show an opposite relation between attenuation of the two modes, [5 – 7]. This paper highlights the controversies around the measurements of the slow ultrasonic waves in cancellous bone and discusses technical and physical sources of difficulties associated with observation of the waves. The results of different studies are reviewed and compared with the authors data from broad-band ultrasonic spectroscopy.

2. Review of literature

The first information about the measurement of a new kind of longitudinal wave, the slow one in wet bone, has been published by LAKES *et al.* [8]. The experiment was performed for human and bovine cortical bone and the measured velocity of the slow wave was between 1.88 and 2.34 km/s. The thorough discussion of the results obtained by Lakes *et al.* has been presented in the paper by WILLIAMS [11], who noticed that taking into account the relation between the velocity of slow wave and the velocity in fluid, which is about 1.48 km/s, even the lower value measured by Lakes *et al.* seems high when compared to the wave velocity in fluid (marrow).

Thus, Williams concludes that it appears unlikely that Lakes *et al.* measured the slow wave and suggests that the measured wave is rather the shear wave than the slow one. In the same paper Williams has shown a set of theoretical and experimental results for ultrasonic parameters, phase velocity and attenuation, taking into account randomly and well oriented samples of cancellous bone with the removed marrow, and discussed how those results might be predicted by the Biot's theory. In the experiments made by Williams the slow wave was not observed. The main conclusion of the article was that the Biot theory is a well suited basis to modeling cancellous bone filled with water, but he has noticed a need of further studies to understand the influence of the natural fluid component (marrow) on the acoustical parameters of intact bones.

Several recent papers devoted to observation of different longitudinal modes in ultrasonic studies of water saturated and intact bovine cancellous bone were presented by HOKOSAWA *et al.* [5, 6]. They have confirmed the existence of both fast and slow wave in such materials and related the properties of the waves to volume fraction, trabecular arrangement and structural anisotropy. The propagation velocities have been measured and compared to the values calculated from Biot's model. The calculations were done for transversally isotropic material, changing propagation angle and volume fraction. Contrary to Biot's model, Hokosawa and Otani demonstrated that the attenuation of the slow wave is higher than that of the fast one. They explain that such behavior is possible by taking into account the facts that the porosity of the cancellous bone is very high (70–90%), and that the slow wave is the one that propagates in fluid while the fast wave propagates in the skeleton. As a result, due to a particular division of energy of the incident wave at the boundary between the two longitudinal modes, the major part of energy entering the material is carried by the slow wave. It should be stressed that such understanding of the slow wave is not quite correct in the light of the Biot theory. Within the framework of the latter approach, the slow wave is not only associated with disturbances in fluid but both in fluid and skeleton. Another important result shown by Hokosawa and Otani is that above the frequency about of 3 MHz, the fast wave is highly attenuated by scattering and only the slow wave is received, [5, 6].

Similar results to those obtained by Hokosawa *et al.* concerning the relationships between amplitudes of the two longitudinal ultrasonic waves in cancelous bones have been presented by HUGES *et al.* [7]. They demonstrated that the slow wave has lower amplitude than the fast one but, contrary to the data by Hokosawa, they observed the presence of negative dispersion for both the waves. Due to the applied technique, the data by Hughes *et al.* covers a much narrower frequency range than the data by Hokosawa *et al.*

3. Experimental procedure

Experiments for femoral bovine trabecular bones have been performed by applying the pulse transmission method. In order to prepare specimens, the epiphysis was cut perpendicularly to the long axis of the bone using a diamond saw. Prior to the tests, bone samples of thickness from 8 to 13 mm have been vacuum degassed in order to remove the air bubbles. The investigation have been done for:

- intact bones saturated with bone marrow, and
- defatted bone where the marrow has been removed using high preassure water jet.

The experimental arrangement for the applied ultrasonic immersion technique is shown in the Fig. 1.

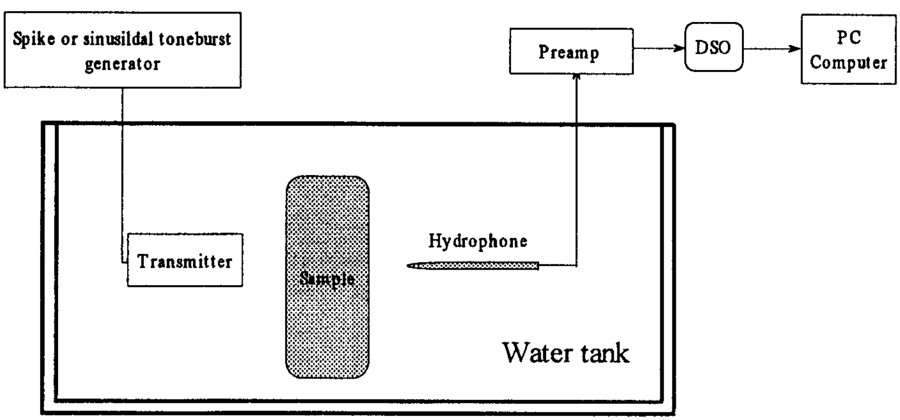

FIG. 1. Experimental setup for the ultrasonic immersion technique.

The experimental setup consists of Panametrics or Matec pulser/receiver which allow to excite electrically transmitting transducer by spike or sinusoidal toneburst pulse of different width. The transmitter is Panametrics transducer with the center frequency 1 MHz and the diameter 1.25 mm. The ultrasonic pulse from the transmitter goes through the water - sample - water path and is detected by wide band (0.1–20 MHz) SEA hydrophone. Then the pulse is amplified (up to 60 dB), acquired by DSO (Digital Storage Oscilloscope) and transferred to the PC where the spectral analysis is done using appropriate software. Having the amplitude and phase spectra for two samples of bones of different thickness, the ultrasonic parameters, phase velocity and attenuation coefficient are determined (see eg. [10]).

4. Discussion of results

Properties of bone materials, in particular high attenuation, strong inhomogeneity, anisotropy and inhomogeneity of anisotropy, force us to use relatively thin samples of the studied materials in the case of application of the pulse transmission method. Then, however, the wave pulses of different modes (fast and slow wave) and internally reflected pulses (between boundaries of the sample) may interfere, causing problems with determination of amplitude or phase spectra of the measured modes. In Figs. 2a and 2b the signals of ultrasonic waves traveling through water-saturated bone samples of thickness 13 and 8 mm are shown.

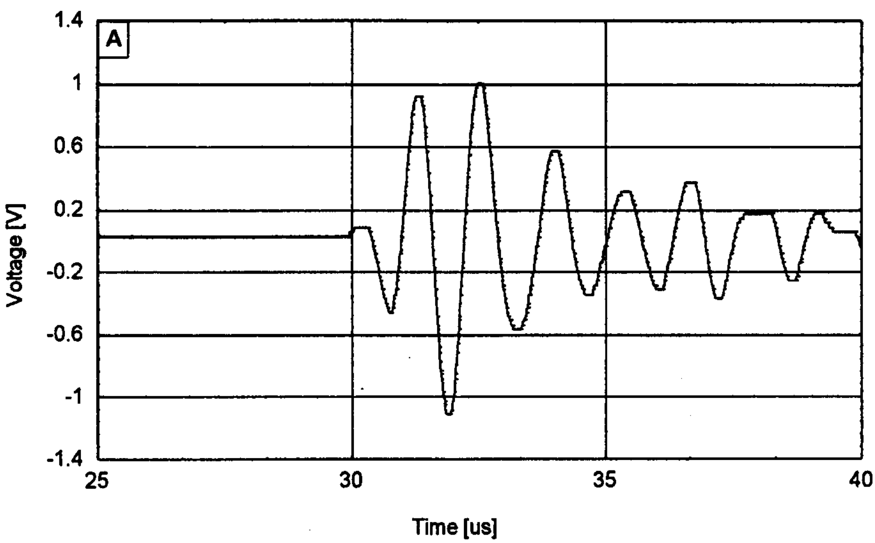

FIG. 2a

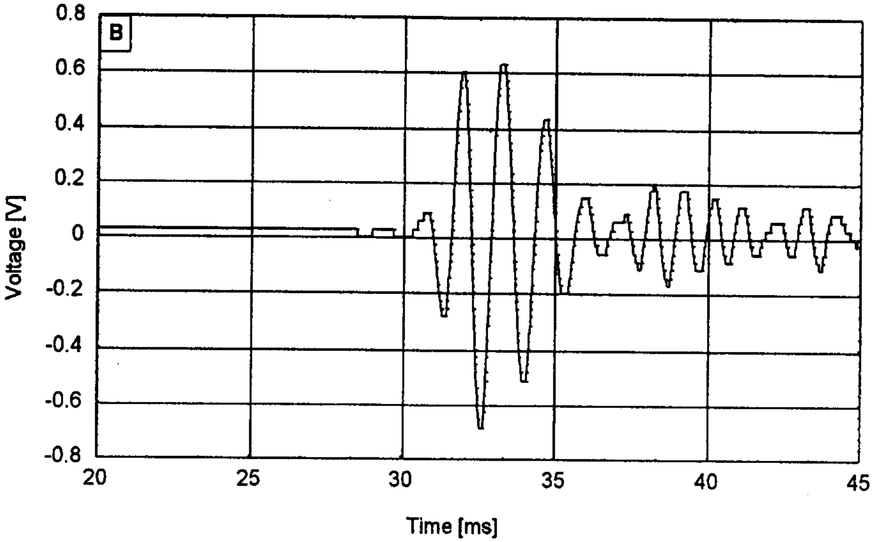

FIG. 2. Ultrasonics signals through the water-saturated samples of trabecular bone of thickness 8 (A) and 13 (B) mm.

The signal obtained for the thicker sample includes as the very first one, a pulse of the fast wave followed by pulses of the slow wave and of reflected waves. The identification of the second pulse as the slow wave can be substantiated by evaluation of the time needed for a transition of the internally reflected pulse of the fast wave. The signal detected for the thinner sample contains overlapping pulses of the fast and slow waves. From the two signals obtained it is visible that the fast wave has higher amplitude than the slow one, and values of the attenuation of both modes are comparable. Because of the relationship between attenuations, such results are not in sound agreement with the Biot's model but also differ from the results obtained by HOKOSAWA and OTANI [5, 6], and HUGES *et al.* [7]. In particular, opposite relationships for amplitudes of fast and slow waves were observed. Very similar results as those for the water-saturated bones were detected for the same bone samples but filled with marrow. The two received signals for such case are shown in the Fig. 3.

In order to compare the frequency range of transmitted signals, the amplitude spectra of the pulses corresponding to fast and slow waves in water-saturated samples are shown in Fig. 4. The amplitude spectrum of the fast wave is significantly shifted to lower frequencies while the spectrum of the slow wave covers approximately the same domain as the spectrum of transmitted wave (as detected for waves traveling through water only). The effect of truncation of higher components of the wave spectra indicates that there is an influence of scattering on the propagation of the fast wave. The presence of scattering is also visible by taking into account the distribution of attenuation coefficient and phase velocity, shown in Fig. 5.

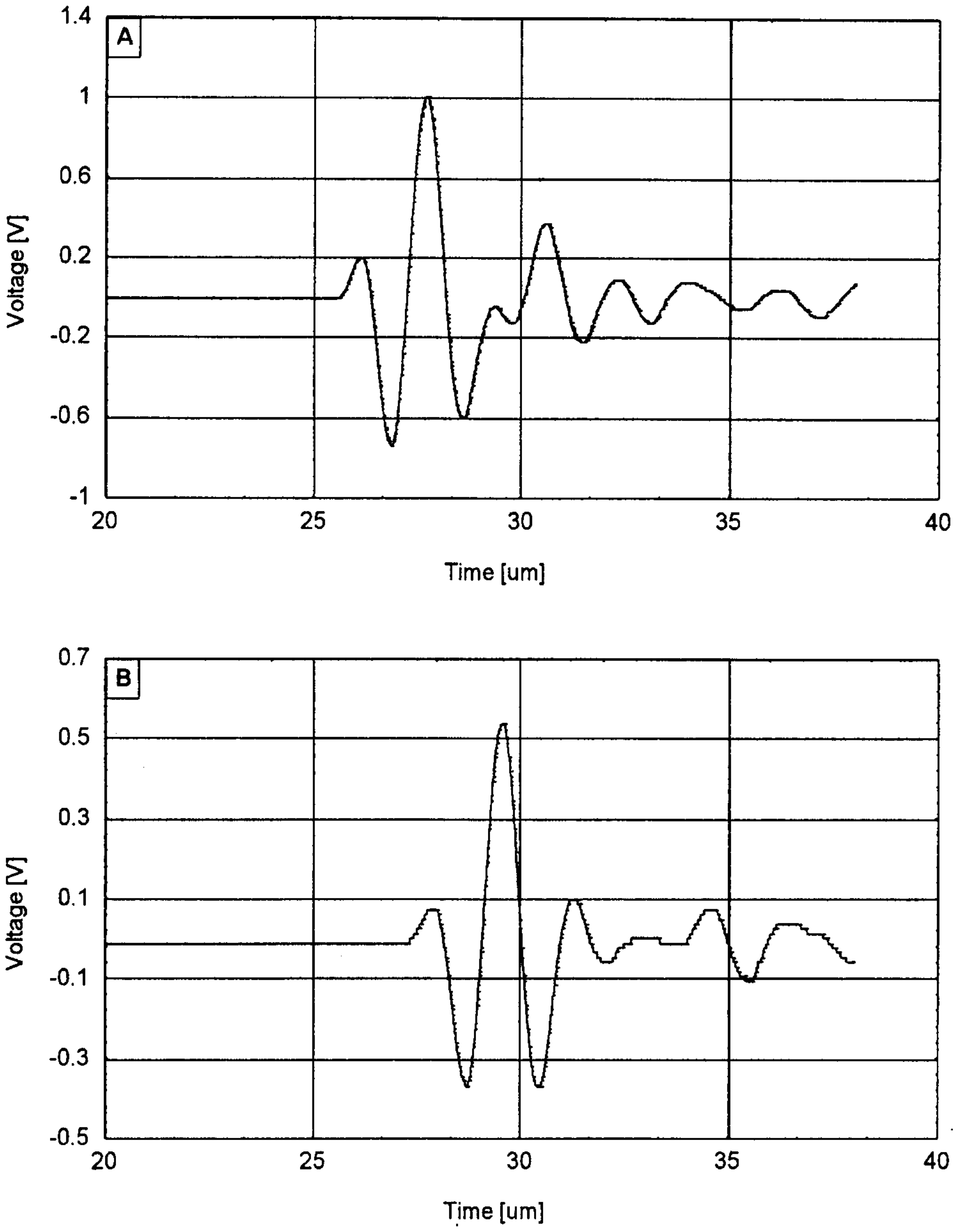

FIG. 3. Ultrasonics signals through the intact trabecular bone of thickness 8 (A) and 13 (B) mm

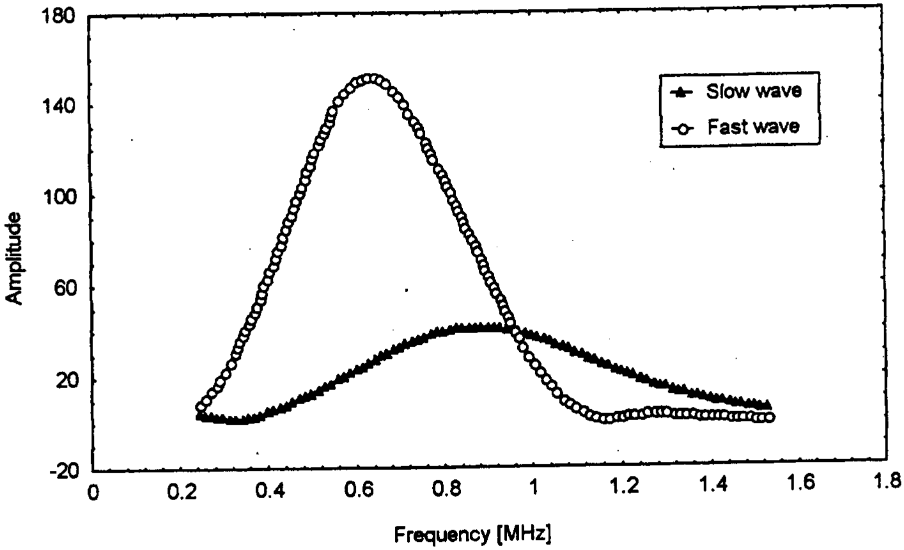

FIG. 4. Amplitude spectra for fast and slow ultrasonic pulse wave in water-saturated trabecular bone.

The attenuation in the higher frequency range is frequency-dependent up to the second power indicating the so-called stochastic scattering. For the same frequencies a negative dispersion appears. The negative dispersion of the fast wave is also noticed in studies by HUGHES *et al.* [7], while HOKOSAWA and OTANI [5, 6] have observed constant phase velocity in the wide frequency domain. Moreover, the coefficient of attenuation measured by Hokosawa and Otani shows the results similar to the present ones, a characteristic increse for higher frequencies. It is worth noticing, that although the wavelength of the slow wave evaluated at velocity of the order 1000 m/s and frequency 1 MHz is equal to about 1 mm and the characteristic size of pores of cancellous bones is of the same order, there is no visible influence of scattering on attenuation of the wave (see Fig. 4). From the point of view of the applied experimental method and inhomogeneity of bones, it is important to notice that the results of ultrasonic test are strongly site-dependent. In illustrate this effect, Fig. 6 shows signals from two different locations of hydrophone within the same sample and fixed transmitting transducer. It is visible that the overlapping pulses of the slow and fast wave have different amplitudes and shapes. Summarizing the above discussion we may say that possible sources of difficulties in evaluation of properties of the slow wave, are the anisotropy and inhomogeneity of the material within samples and differences between samples from various individuals.

In turn, the problems with interpretation of ultrasonic measurements may result from limited validity of the two-phase continuum model. The model requires that the size of representative region of averaging of macroscopic quantities should be essentially larger than the wavelength, which is not the case in the ultrasonic tests of cancelous bones. Moreover, better understanding of the role of scattering, particularly the size of objects causing scattering of the fast and slow wave, is necessary.

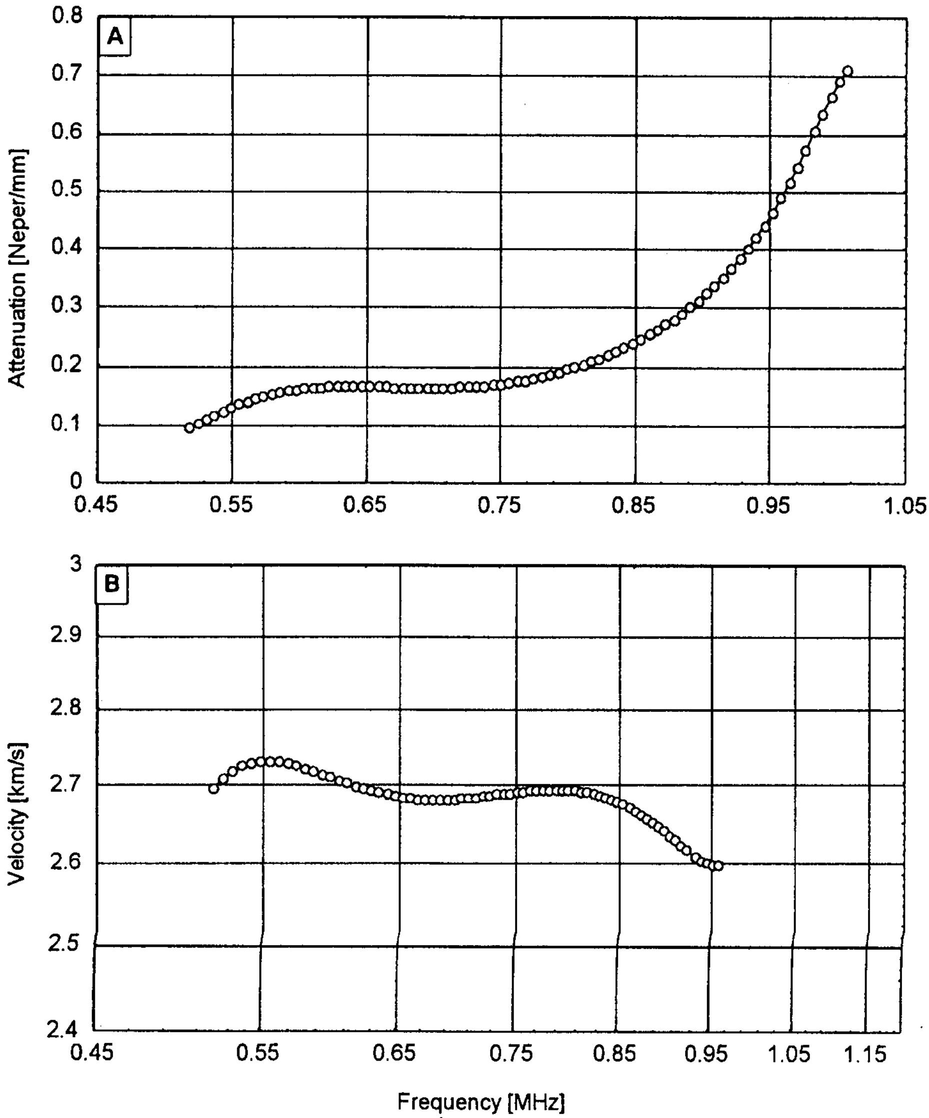

FIG. 5. Attenuation (A) and phase velocity (B) of the fast wave for water-saturated cancellous bone.

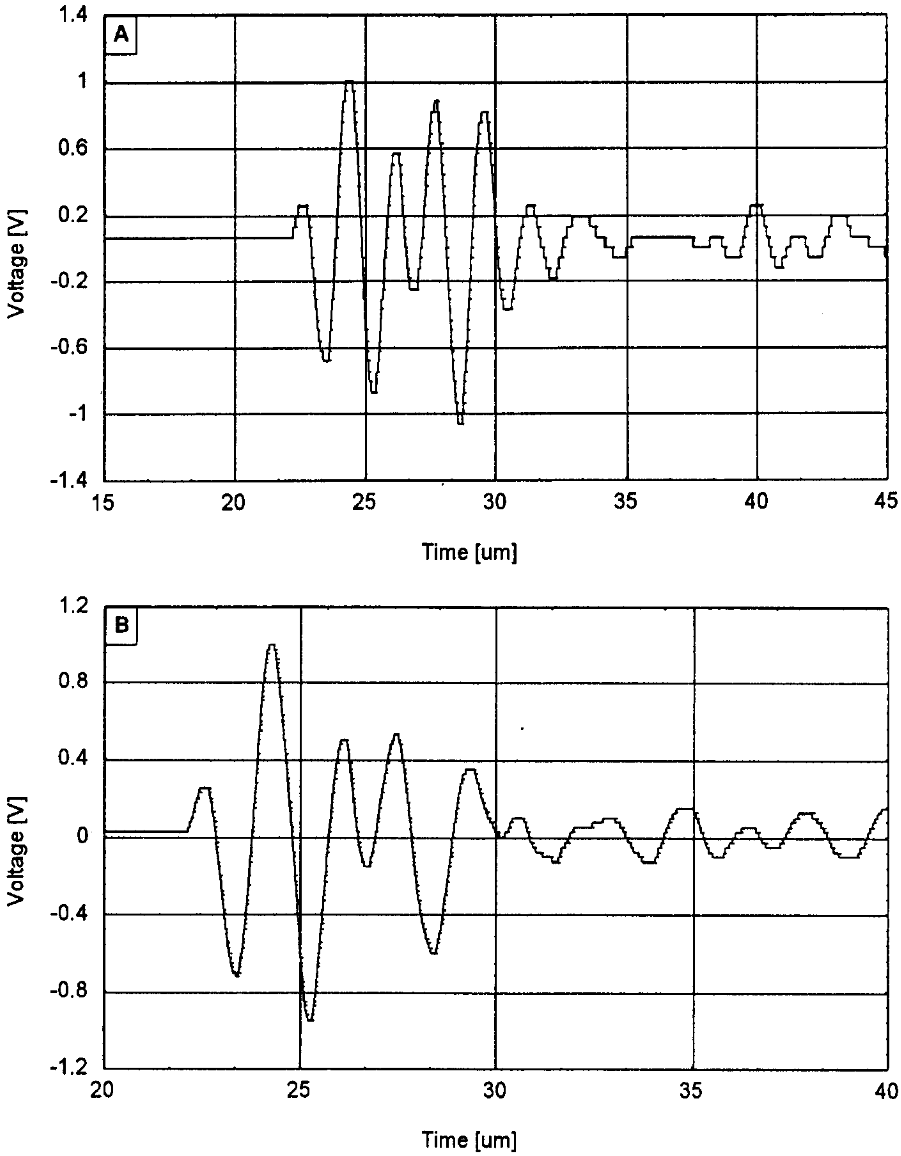

FIG. 6. Ultrasonic signals from two – different locations of water-saturated s ample of cancellous bone.

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