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The Acousto-Ultrasonic Characterization of Physical Properties of Human Bones

Burhan DAVARCIOĞLU
Department of Physics, Faculty of Science and Art, Aksaray University, 68100 Aksaray, TURKEY

Corresponding Author
e-mail: burdavog@hotmail.com

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Abstract

In this work, the acousto-ultrasonic technique was utilized to non-destructively characterize two biological parameters of human bone specimens: the weight and mineral content densities. It has been previously shown that these two parameters have great effect on bone strength, thus by employing the non-invasive acousto-ultrasonic technique one can obtain vital information about bone strength without using any ionizing radiation. In the present study, the bones were characterized both by common techniques, for example gamma rays and acousto-ultrasonic, and the results of the study indicate that the acousto-ultrasonic parameter which best correlates with the weight and mineral content densities of human bones was the peak amplitude of the received acousto-ultrasonic signals. The peak amplitude of the acousto-ultrasonic signal and the weight density of the bone specimens was found to be linearly related with a coefficient of correlation r = 0.68. The coefficient of linear correlation between the mentioned acousto-ultrasonic parameter and the mineral content density was r = 0.63. This preliminary study demonstrated the potential of employing the acousto-ultrasonic technique as a non-invasive means to determine physical properties of human bones. The results suggest that the peak amplitude of the acousto-ultrasonic signals can be related to the bone strength.

Key words: acousto-ultrasonic technique, physical properties, human bone, bone density

INTRODUCTION

Bone deseases such as osteoporosis represent a major problem of public health. They are related to bone aging, to mass loss, and to the change in bone's microarchitecture involving modifications of its mechanical properties. The study and interpretation of the properties and functions of bone tissues constitute a wide research field, and investigation methods are continuously being developed.

Bone characterization with ultrasound has been presented in many reports over the last few years and it is now accepted that ultrasound is able to evaluate bone state and pathologies. Nonultrasonic techniques are essentially based on bone imaging and allow visual examination or provide quantitative parameters like bone mineral density, which is a mass per unit of surface. Unfortunately, these techniques are generally expensive.

The avaibility of a sensitive through non-invasive method for the estimation of bone strength is of cardinal importance for the early diagnosis of bone loss and bone remodeling this order. In search of such a method, the commonly used techniques for the measurement of bone mineral content (BMC), and bone density, were developed [1, 2, 3].

The present study is an attempt to determine bone properties by acousto-ultrasonic so that the use of ionizing radiation is avoided, and acousto-ultrasonic can be employed in the clinical domain. The physical properties of bone which can be evaluated by the acousto-ultrasonic technique differ essentially from those which are obtained by any other commonly used technique [4, 5, 6]. Photon absorptiometry, computerized tomography and photon scattering, all measure the concentration of minerals or the density of the bone tissue. The parameters obtained by acousto-ultrasonic, on the other hand, are related to the structure of the bone tissue and to the manner in which the bone fibers are organized [7]. Consequently, acousto-ultrasonic has the potential of providing insight structure related mechanical properties.

MATERIAL AND METHOD

The acousto-ultrasonic technique offers the capability of monitoring structural degradation passively and in real time, and can distinguish failure mechanisms and their location through the analysis of acousto-ultrasonic parameters.

In the present paper, the use of acousto-ultrasonic technique of human bone specimens, in particular for the evaluation of hip replacement constructs is reviewed. Following this, three case studies undertaken at Akdeniz University (Antalya, Turkey) are presented, in which acoustic emission on-line monitoring has been used to evaluate the performance of simulated artifical hip replacement constructs and their constituents during static and fatigue testing. Firstly, the fatigue behaviour of human bone is characterized; and then, the residual stresses induced in the construct as a result of bone density cure are investigated; finally, the mechanisms leading to failure of a carbon fibre reinforced plastic hip stem during fatigue testing are characterized.

Thirty bone specimens were removed from fresh femoral heads of cadavers. None of the subjects was known to have any disease which affects bone status. The specimens were taken from the trabecular region under the cortical layer (Fig. 1). Fig. 2 give a description of bones that have been used in the experiments.

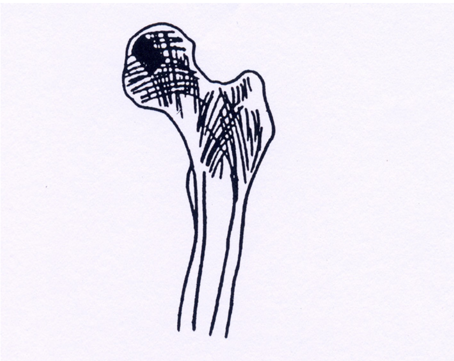

Figure 1. The location in the femoral head from which the trabecular bone specimens were taken.

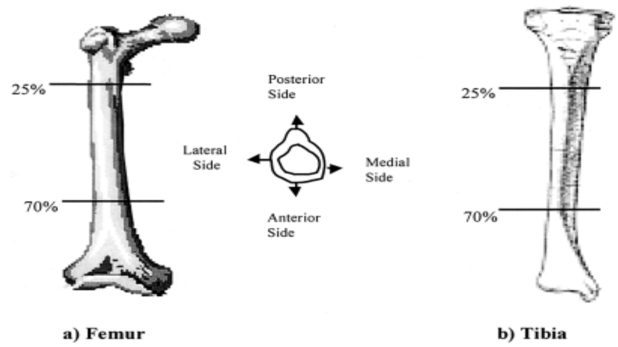

Figure 2. The bone description [6].

Each specimen had the shape of cylinder of 1 cm diameter and 1 cm height. The symmetry axis of the specimen coincided whit that of the femoral neck. In addition, thirty-two bone specimens were obtained from osteoporotic patients who had undergone hip-joint surgery. The bone specimens were air dried for 24 hours and then kept at -18 ^{o}C during the period of measurements. Four tests were performed on each of the specimens:

1. The bone density was measured using the Compton scattering technique: Cs^{137} (662 keV) was used as the radiation source and the photons, which were Compton scattered by the specimen at a 90^{o} angle, were detected by a NaI(Tl) counter. A focusing collimator was used to define the scattering angle. The method has been described in details elsewhere [7, 8]. The calibration procedure utilized various plastic cylinders of known densities and of the same dimensions as that of the bone specimens. The bone density in grams/cm^3 was calculated using the calibration curve so obtained.

2. The bone mineral content was determined by photon absorptiometry using the Noriand-Cameron Mineral Analyzer, Model 187 (Department of Physiology, Akdeniz University, Turkey). The specimens were scanned with their longitudinal axis parallel to the gamma ray beam. The bone mineral content per unit area as given by the device was divided by the sample's height in order to obtain the mineral content per unit volume (grams of mineral per cm^3) [7, 9].

3. The average attenuation coefficient of each bone specimen was determined by computerized tomography [10, 11]. The specimens were scanned by an EMI 1010A scanner for 60 seconds at 120 kV and 30 mA. The frames were transferred to a magnetic tape for further analysis on a PDP 15/76 computer.

4. The bone specimens were placed between two ultrasonic transducers, one serving as a stimulator and the other as a detector. They were coupled to the transducers by ultrasonic coupling gel, and the coupling was maintained by application of a constant pressure. The emitting transducer was an AETC (Acoustic Emission Technology Corporation) broadband FAC-500 which injected a periodically repeating series of ultrasonic pulses into the bone specimen. Each of these pulses produced simulated acousto-ultrasonic stress waves in the material.

As shown in Fig. 3, the system is composed of an emitter is fixed at a reference position zero, and a receiver placed a certain distance from the emitter. The receiver gets the energy propagated in its direction. The receiver is moved away from the emitter, and echographic signals are recorded at each position of the receiver (Fig. 3). The displacement step of the receiver is chosen according to the spatial sampling criterion that the wavelength of the step must be less than half that of the longitudinal bulk wave in the material. The signals arriving at the receiver resemble burst type acoustic emission events [6, 11, 12, 13, 14].

The receiving transducer was a piezoelectric acoustic emission AETC transducer with resonance at 375 kHz. After passing a 375 kHz filter the signals were analyzed by an AETC 5000A device [15, 16]. The analysis included an evaluation of the peak amplitude and the duration of the event. For each bone specimen 10.000 signals were analyzed and the most frequent value of each of the two parameters was chosen.

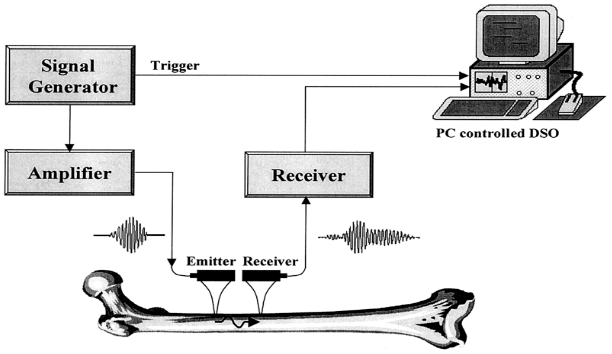

Figure 3. Principle of the method-experimental setup [6].

A tapered transducer coupled to a solid is able to generate several kinds of waves (longitudinal, shear, and surface waves) with a large angular spectrum; that is, it acts as a point source. It is composed of a piezoelectric slab bonded on a tapered wave guide. The piezoelectric element is driven by a sinusoidal burst whose frequency is tuned to the resonant frequency of the transducer. The choice of the working frequency determines the type of vibration induced in the horn. Here the axial mode is chosen such that the horn acts as a hammer on the surface of the solid. In this work, the frequency of the hammer mode is around 110 kHz. This frequency is chosen according to the following design considerations.

RESULTS

The bone samples examined were taken from two distinct populations. The first came from cadavers, none of which was known to have any disease, and the other groups of samples were removed from patients that suffered from osteoporosis. Table 1 gives some of the physical parameters (such as bone density, bone mineral content) that were determined for all samples and which show that the two populations differ significantly. In addition, the samples were also characterized employing the acousto-ultrasonic and the results are summarized in Table 1.

The characteristics of the acousto-ultrasonic signal passing through the bone samples were evaluated, and it was observed that the level of the peak amplitude of the acousto-ultrasonic signals correlated best with the physical properties of the bone samples for the healthy population (Fig. 4 and 5).

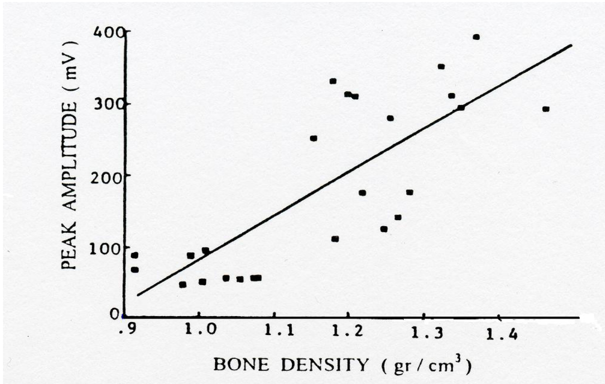

Figure 4. The peak amplitude of transmitted acousto-ultrasonic signals versus bone density.

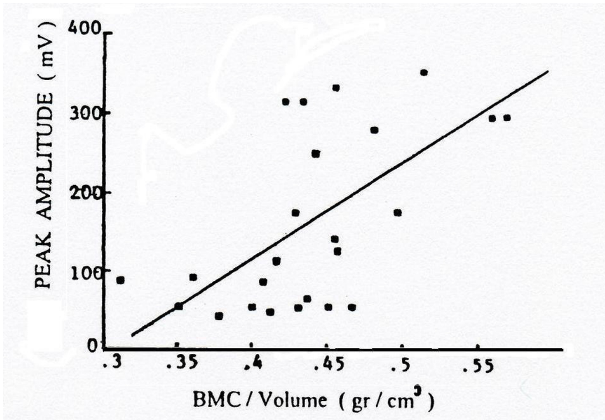

Figure 5. The peak amplitude of transmitted acousto-ultrasonic signals versus BMC.

Such as correlation was not found for the osteoporotic population. The best correlation was found to exist between the level of peak amplitude and the bone density of the healthy bone samples, r = 0.68 as shown in Fig. 4. Somewhat lower correlations however, still statistically significant were noted between the level of the peak amplitude and the bone mineral content, r = 0.63. It has to be noted that such correlation in medical results is quite significant (Fig. 5).

DISCUSSION

This preliminary study shows that the amplitude of the transmitted acousto-ultrasonic signals, which were introduced into the bone specimens by ultrasonic pulses

Table 1. Physical parameters of bone.

Parameter	Healthy	Osteoporosis	P<
Age (gr/cm^3)	63 ± 15.3	76 ± 9.2	0.0005
Bone density 940	1.198 ± 0.20	1.143 ± 0.093	0.05
Bone mineral content 910	0.332 ± 0.048	0.267 ± 0.038	0.0005
Acousto-ultrasonic peak amplitude (dB)	28.93 ± 6.97	35.89 ± 6.54	0.003

P is the level of significance for which the populations are different are related to the physical properties of the bone [5]. The density, mineral content and average attenuation coefficient of the bone have already been shown to estimate its ultimate tensile strength [17]. Thus, the results of this study suggest that the acousto-ultrasonic parameters relate to the strength as well. The exact nature of this relationship can be evaluated more specifically only after destructive testing, when the bone specimens are loaded and the fracture strength is determined. Nevertheless, the correlation between the peak amplitude and the density of the specimen may indicate stronger internal reflections with decreasing bone density.

The peak amplitude of the transmitted signal is related to the attenuation properties of the trabecular bone. However, the exact correlation between the attenuation mechanisms in bone and microstructural features is not well understood due to the complexity of the bone microstructure [18]. In addition, interconnected fluid filled pores modulate the attenuation characteristics of the bone. It is therefore not surprising that in the case of osteoporotic bones, where the volume fraction of such pores is large, no correlation between peak amplitude of acousto-ultrasonic and bone properties was obtained as acousto-ultrasonic is mainly affected by the interconnected fluid filled pores.

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