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Quantitative assessment of osteoporosis from the tibia shaft by ultrasound techniques

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Abstract

Bone mineral density (BMD) is used as a clinical estimate of the risk of fracture. Ultrasound provides an alternative or complement to X-ray based methods of bone densitometry for determining BMD. Among ultrasonic characteristics, the speed of sound (SOS) is a useful tool for assessment of osteoporosis because, as recently reported, it represents a combination of density and compressibility of bone tissue. Thus, it might provide better information on bone quality to estimate the fracture risk. In this paper, a dual-transducer ultrasound technique was employed to measure the mean ultrasound propagation speed of the cortical layer as well as the cancellous layer at the tibia shaft. Encouraging results from 18 outpatients showed a high correlation ($r = 0.93$) between measurements of BMD and those from dual energy X-ray absorptiometry (DEXA).
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Keywords: Osteoporosis; Speed of sound; Ultrasound techniques

1. Introduction

Based on a better understanding from evidence-based medicine, the definition of osteoporosis has gradually moved from a disease of fractures to a disease of fracture risks [1]. For quantification of osteoporosis, bone mineral density (BMD) is not only used as a grading scale, but also viewed as a predictor of potential problems, allowing for prevention as well as treatment [1,2]. Osteoporosis leads to increased fragility of bone and increased risk of bone fractures either spontaneously or due to relatively minimal trauma [3]. To date, the clinical assessment of osteoporosis relied mainly on BMD measurement, but it explains only 70–75% of the variance in strength. The remaining variance was supposed to be due to cumulative and synergistic effects of other factors such as bone microstructure, architecture, measurement artifact and the state of remodeling [3]. There are several BMD measurement systems commonly used in the clinic including single gamma photon absorptiometry (SPA), dual energy X-ray absorptiometry (DEXA), and quantitative X-ray computed tomography (QCT) [4–7]. However, there are still problems with these techniques such as X-ray exposure and cost.

Ultrasound techniques have become an important alternative in the assessment of osteoporosis [8–10]. The acoustic speed is definitely one of the important ultrasound properties that can be used for tissue characterization [11–13]. Although the acoustic speed has been shown to be potentially useful for identification of pathological changes in biological tissue, this parameter has not been extensively utilized in diagnosis due to the fact that pathological changes of acoustic speed in soft tissue are only of the order of several percent [13]. For bone tissue, the speed of sound (SOS) represents a combination of density and elastic modulus [14,15]. Some researchers suggest that the SOS in bone might be a better candidate parameter than BMD for evaluating osteoporosis [14,16–21]. Alves et al. [22] showed that the acoustic speed is highly correlated with

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bone density measured by dual energy X-ray absorptiometry (DEXA), and might be able to provide information of bone quality for more accurate estimates of the bone fracture risk [22].

In the past few years, several commercial ultrasound instruments have become available to evaluate osteoporosis. Most of them provide the BUA (broadband ultrasound attenuation) or SOS, or an index called stiffness which is a combination of these two parameters. The measurement sites varied, ranging from the calcaneus of the heel, the cortical bone of the tibia, the proximal phalanges of the fingers, the patella, to the distal radius [15,18,23]. The calcaneus is a major concern since, due to its high surface-to-volume ratio; it has approximately 8 times the metabolic turnover rate of cortical bone and would consequently manifest bone metabolic changes before cortical bone [24]. Moreover, the calcaneus is easily accessible and the media-lateral surface is fairly flat and parallel, making it a favorite test site for Wasnich et al. [25] and Black et al. [26]. They stated that the calcaneus appeared to the optimal BMD measurement site for routine screening of perimenopausal women to predict fracture risk. Moreover, Turner et al. [27] reported that the velocity on the calcaneus is highly correlated to the BMD on the femoral neck. However, the correlation coefficients between ultrasound velocity on the calcaneus and the BMD on the heel ranged widely, from 0.34 to 0.72. That might explain the reason why the SoundScan 2000 and Sunlight Omnisense™ systems both utilize the wave propagating along the cortical layer of the tibia shaft to obtain measurements of ultrasound velocity [17,28]. The manufacturers both claim that the cortical bone of the tibia is a more predominant contributor to fracture resistance. Unfortunately, the acoustic speed obtained from SoundScan 2000 (Myriad Ultrasound System Ltd., Rehovot, Israel) has a correlation coefficient of only 0.56 with BMD values obtained from DEXA measurements [28].

In general, the SOS is obtained from measurements of thickness and the time-of-flight (TOF) of a wave propagating through a test object. The TOF can easily be measured from the interval of pulse peaks between two boundaries on pulse echo traces, but the measurement of thickness is usually problematic as thickness is not commonly available in in vivo measurements. Some approaches have been proposed to eliminate the requirement of thickness for the SOS measurement. Ophir and Yazdi [29] used transaxial compression techniques to determine the SOS accurately for soft tissue in vitro. Nevertheless this method cannot be employed for the measurement of uncompressible material, such as bone tissue. Kuo et al. [30] developed a technique that can be used in either the reflection mode or the transmission mode to measure acoustic speed without the need to measure sample thickness. Their method required knowledge of the sound speed in a reference medium in which the specimen was placed, but this approach is not applicable to in vivo measurements. Hayashi et al. [31] measured the SOS in liver in vivo between a reflector and a transducer in reflection mode [31]. The measurement, however, depends on the qualitative judgement of image sharpness by the operator; therefore, it is not completely objective. Haumschild and Greenleaf [32] proposed a cross-beam method, so that the SOS could be predicted by calculating the center gravity of the energy scattered from the intersection of the crossed beam of transmitter/receiver pairs. Again, refraction, primarily by intervening bone structure, prevents or severely limits accurate SOS measurement elsewhere in the body.

The main purpose of this study is to validate a newly developed dual-transducer technique applying to the outpatients in our medical center. This technique utilizes two transducers placed on the same side of a test object, one used to transmit and receive, the other for receive only. The SOS is based on the information of the TOF from the signals received by both transducers and the separation distance between the transducer pair. The basic idea behind this approach is straightforward: the signals received from the two transducers provide the two variables needed to solve for acoustic speed without an assumption of object thickness. Acoustic speed measured from this technique will then be compared to the measurement of BMD obtained from DEXA at the same site on tibia shaft.

2. Material and methods

2.1. Theoretical derivation

The schematic diagram of the dual-transducer system employed to measure the SOS of bone tissue in reflection mode is shown in Fig. 1. The TOF is derived from the transmitting pulse trigger and the front and rear boundaries of bone tissue as detected by the transducer pair, Fig. 2. Transducer #1 transmits a broadband ultrasonic pulse that is normal to the test object

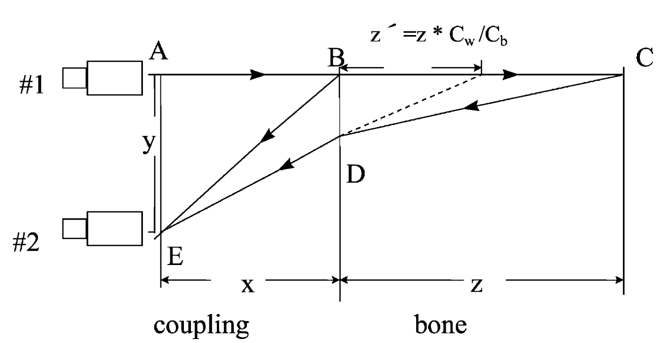

Fig. 1. The dual-transducer wave propagation path diagram.

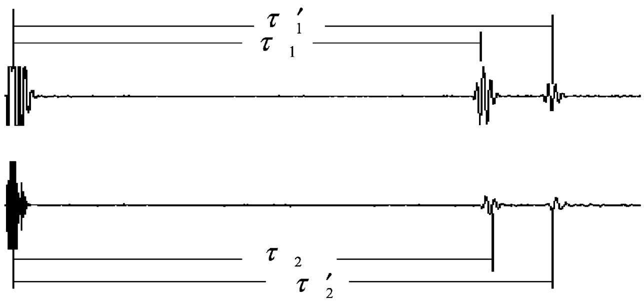

Fig. 2. Definition of TOF obtained from the transducer pair.

and receives the echo pulse. Transducer #2 is adjusted to receive echoes only after an external trigger. The corresponding equations can be derived straightforward from Fig. 1 and 2, as follows:

$$\tau_1 = \frac{2x}{C_w} \tag{1}$$

$$\tau_1' = \frac{2x}{C_w} + \frac{2z}{C_b} \tag{2}$$

$$\tau_2 = \frac{x}{C_w} + \frac{\overline{BE}}{C_w} \tag{3}$$

$$\tau_2' = \frac{x}{C_w} + \frac{z}{C_b} + \frac{\overline{CD}}{C_b} + \frac{\overline{DE}}{C_w} \tag{4}$$

Times τ_1 and τ_1' are the TOF's from the trigger of the transmitting pulse to the front and the rear echoes of bone tissue received by transducer #1. Times τ_2 and τ_2' are the TOF's measured from transducer #2. The variables $\overline{BE}$, $\overline{CD}$, and $\overline{DE}$ are the distances indicated in Fig. 1, x is the distance between transducer #1 and the test object, and z is the actual bone tissue thickness. According to the Snell's Law, z' is the effective distance when a pulse propagates into a boundary without refraction. C_w is the SOS in water and C_b is the SOS in bone tissue. From eqs. (1)–(4), C_b can be derived as [33]:

$$C_b = \frac{y \cdot (\Delta\tau_1)}{\tau_1' \cdot \sqrt{[(\Delta\tau_2 - K) - \Delta\tau_1] \cdot (\Delta\tau_2 - K)}} \tag{5}$$

where $\Delta\tau_1 = \tau_1' - \tau_1 Z$, $\Delta\tau_2 = \tau_2' - \tau_2$, and y is the separation distance of two transducers and

$$K = \sqrt{\frac{\tau_1^2}{4} + \frac{\tau_1^2 \cdot \tau_2 \cdot (\tau_2 - \tau_1)}{\tau_1' 2}} - (\tau_2 - \frac{\tau_1}{2}) \tag{6}$$

The variable C_b (SOS in bone tissue) can be evaluated using only the values of the TOF's $(\tau_1, \tau_1', \tau_2, \tau_2')$ obtained from the two echoes detected by the two transducers along with the separation distance y of the transducer pair.

2.2. Ultrasound system description

This study used two unfocused ultrasound transducers (Model #V303-SU, Panametrics Inc., Waltham, MA) both having a 1.0 MHz nominal center frequency and a 1/2 inch diameter. Transducer #1 was excited by a pulser/receiver (Panametrics 5058PR) to transmit ultrasound pulses and then to receive the echoes bouncing back from the front and the rear boundaries of the bone tissues. Transducer #2 was connected to another pulser/receiver (Panametrics 5052 PR) and set to receiver mode only. The transmitters and receivers were synchronized by an external trigger from a function generator (HP8111A). The received pulse echoes were amplified and then digitized by an A/D conversion board (GAGE CS250, 50 MHz sampling rate for each channel with 8-bit resolution). Data were then stored in a PC-type computer for further signal processing.

The dual-transducer module is shown in Fig. 3. Transducer #1 was fixed and positioned normal to the tibia shaft. Transducer #2 was adjustable to ensure that it receives the echo signals. Both transducers were packaged in a Plexiglas box filled with coupling medium. To provide a good contact surface with the tibia shaft, a thin polyethylene film was placed at the bottom of the test module.

2.3. Test subjects

Eighteen subjects were selected by one of the authors, Dr. Lin, from the Department of Orthopedics at the National Cheng-Kung University Hospital. Nine of 18 patients were outpatients suffering from low back pain, radiological evidence of osteoporosis and/or compression fracture of the vertebral body. The clinical impression was either of post-menopausal or senile

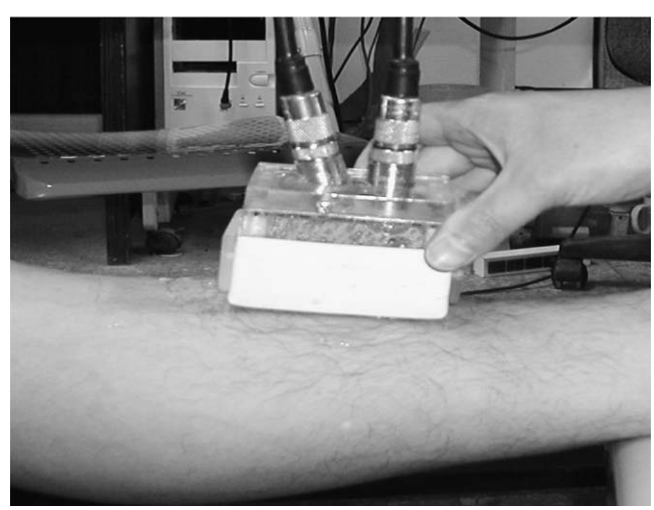

Fig. 3. The picture of dual-transducer module.

osteoporosis in patients. The nine patients included 5 males and 4 females, with an average age of 65 years (from 56 to 73). The other nine patients had been immobilized for more than 3 months after various orthopedic surgeries such as multiple fracture fixation and open/comminuted fracture intrameutatious of femur and pelvis. They averaged 52 years of age with the range from 21 to 72. The patients' SOS was measured at the site of the middle tibia shaft using the ultrasound technique described above and BMD by dual-energy X-ray absorptiometry (DEXA, LUNAR DPXL, USA). The averaged BMD in g/cm^2 was obtained over a region of interest (ROI) around 8×4 cm that encompassed the same ultrasonic test sites around the middle tibia shaft by Femur Mode provided by DEXA. The scanning speed was set in the slow mode.

3. Results

The reproducibility with the new dual-transducer system was assessed using a Plexiglas phantom with a known SOS (2748.5 m/s) determined using the traditional substitutive method. The SOS obtained from 10 different measurements with this technique, without using Plexiglas thickness, was 2801.1 ± 105.9 m/s. The CV (coefficient of variation) was 3.52%, and the accuracy was quite high at 98.1%. The results shown in Table 1 for 18 subjects are the average of 10 measurements for each subject. Each measurement was performed at slightly different positions at the site of the midpoint of the tibia shaft. The BMD was measured by dual-energy X-ray absorptiometry (DEXA) at the National Cheng Kung University Hospital. The BMD measurements ranged from 0.996 to 1.240 as also shown in Table 1. To obtain the regression between acoustic speed measured from our new method and BMD measured by DEXA, we plot the acoustic speed vs. BMD in Fig. 4. There was significant linear correlation coefficient ($r = 0.93$) between SOS and BMD.

Table 1
The results of BMD and SOS measurements for 18 subjects

Subject	BMD (g/cm^2)	SOS (m/s)Mean ± SD	CV%
No.01	1.240	4257.4±113.5	2.67
No.02	1.230	4260.9±143.0	3.36
No.03	1.111	3208.4±99.2	3.09
No.04	1.123	3363.3±62.2	1.85
No.05	1.054	3025.4±108.0	3.57
No.06	1.129	3449.1±77.2	2.24
No.07	1.055	3051.5±135.0	4.42
No.08	1.117	3269.4±71.0	2.17
No.09	1.127	3892.3±66.8	1.72
No.10	1.197	3873.4±145.4	3.75
No.11	1.070	3258.9±163.1	5.00
No.12	1.111	3192.5±27.8	0.87
No.13	1.157	3719.4±106.7	2.87
No.14	0.996	2850.6±256.9	9.01
No.15	1.187	3683.8±145.4	3.95
No.16	1.211	4303.0±186.7	4.34
No.17	1.216	4350.5±110.2	2.53
No.18	1.094	3116.4±18.9	0.61

4. Discussion and conclusion

The dual-transducer technique proposed here is a fairly simple and straightforward method and has the potential to be used in the clinical environment. The major advantage of this ultrasonic method is that it acquires measurements of SOS in bone without bone thickness information, which is often not available in in vivo measurements. The test site, the tibia shaft, has a flat surface and is superficial to the skin, making it suitable for this in vivo approach. The acoustic speed obtained from our approach is highly correlated with the BMD from DEXA measurement ($r = 0.93$). Simkin [28] reported that the acoustic speed measured from the SoundScan 2000 correlated only moderately with BMD values ($r = 0.56$). The acoustic speed measured by the SoundScan 2000 system is obtained from the ultrasonic wave propagation speed along only the cortical layer of the tibia shaft. To overcome this disadvantage, the acoustic speed measured by our technique uses the mean velocity of the ultrasonic wave through both the cortical layer and the cancellous layer of the tibia shaft just as the BMD from DEXA measurements also includes information form the whole tibia shaft (cortical and cancellous bone). In such a way, we are able to demonstrate that the acoustic speed measured by

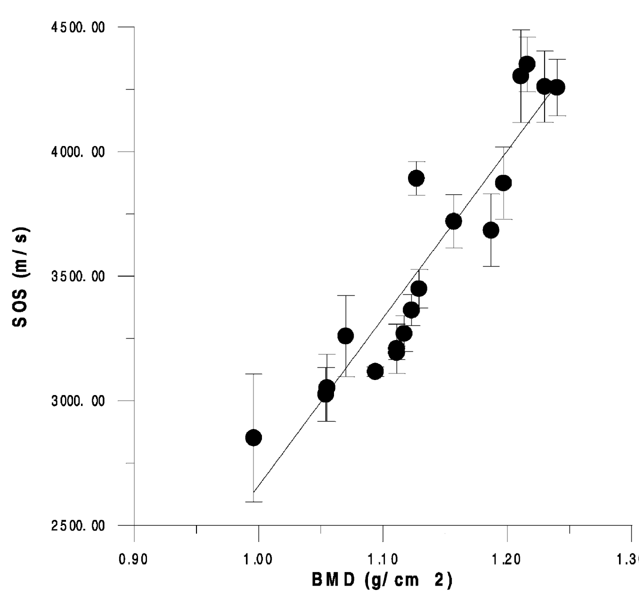

Fig. 4. Regression of BMD with acoustic speed on tibia shaft.

our technique has higher correlation with BMD than that measured by the SoundScan 2000 system

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