A Portable Ultrasonic Bone Densitometer For The Measurement Of Multiple Sites

YANG XU, ZENGFAN DING, WEI CHEN, YUBING XU, YANYAN CHEN, ZUCHANG MA and YINING SUN

ABSTRACT

The purpose of this study was to develop a new ultrasound device to estimate bone mineral density (BMD) at the multiple sites (radius and tibia). The device is entirely portable and handheld and permits evaluation of the BMD by computing a parameter known as speed of sound of first arriving signal (SOS_{FAS}). The SOS_{FAS} was achieved by the so-called time of flight (TOF) of ultrasonic propagation. Two parameters called SOS_{FAS-radius} and SOS_{FAS-tibia} were measured by temperature correction and be evaluated the correlation with the lumbar spine BMD. The correlation coefficient of SOS_{FAS-radius} and SOS_{FAS-tibia} with BMD was r=0.68 (p<0.001), and r=0.77 (p<0.001), respectively. Although X-ray methods are effective in bone mass assessment, osteoporosis remains one of the largest undiagnosed and under-diagnosed diseases in the world today. The research described here, in conjunction with the fact that the devices are designed to be manufactured at low cost, should enable the significant expansion of diagnosis and monitoring of osteoporosis.

1. INTRODUCTION

The report on osteoporosis according to the China Health Promotion Foundation (CHPF) [1] provides compelling evidence that fractures caused by osteoporosis pose a major and growing threat to the health of the elderly population in Asia, especially in China. More than thirty million people over the age of 60 are affected by enhanced bone fragility and an increased risk of fracture. The cost of osteoporosis in Asian countries will rise widely in the next decades because fracture rates increase
with age and the elderly population is growing rapidly [1]. The financial implications of these huge increases in the number of osteoporotic fractures will have considerable impact on health care and social welfare systems [1]. Prevention of osteoporosis has now been recognized as a major priority in research and health promotion.

Currently, dual-energy X-ray absorptiometry (DEXA) is the most commonly used technique for assessment of bone status and is considered the “gold standard” reference for measuring bone mineral density (BMD, g/cm²) [2, 3]. However, DEXA cannot be employed for population mass screenings due to its high cost, inconvenience, and reticence among patients concerning X-ray exposure[4]. This has led to increasing interest in the research of quantitative ultrasound (QUS) methods for evaluating bone status purposes [5-7]. QUS was considered to reduce the medical and economic burden of this disease, provided that cost-effective strategies for identifying patients at high risk for fracture. In addition, QUS seems to provide information not only about BMD but also about the microarchitecture and elasticity of bone[8, 9], so it becomes a promising method of bone status assessment.

At present, in commercial devices, QUS methods are usually categorized into two classes of methods: (a) through-transmission techniques in which the ultrasound wave passes through bone, e.g. heel bone, and the (b) axial-transmission techniques in which the ultrasound wave propagates along the long axis of bone, such as the radius or the tibia [10-12]. The parameters of ultrasonic measurement are: (a) through-transmission: broadband ultrasonic attenuation (BUA) and speed of sound at the calcaneus (SOS), (b) axial-transmission: speed of sound of the first arriving signal (SOS_{FAS}) [10]. Clinical results have shown that QUS parameters (BUA, SOS, and SOS_{FAS}) have a strong correlation with the lumbar spine BMD [5, 13, 14], and the measurement of QUS parameters affected by temperature significantly [15, 16]. In order to eliminate the effects of temperature, the producer installed a thermostat control system for the through-transmission devices, which allows for high-cost and poor portability. But for the axial-transmission devices, it is not suitable to add a thermostat control system. According to the relationship of SOS and temperature, we proposed to measure the skin temperature by a temperature sensor and then to amend the SOS using the temperature.

Based on the above consideration, in this paper, we designed a portable and low-cost ultrasonic bone densitometer for the measurement of multiple sites (radius and tibia), and amended ultrasonic characteristic parameter SOS_{FAS} using the measured temperature of multiple sites (radius and tibia). Meanwhile, we compared the value of SOS obtained in a clinical study with DEXA measurements to determine the validity of the new device.
2. MATERIALS AND METHODS

2.1 Device and Clinical Ultrasound Measurement

A new device for quantitative bone assessment that is portable, low-cost, and powered by DC power supply (12V 2A) has been constructed. It process ultrasound signals after propagating through the soft tissue contains a portion bone. The system consisted of a probe with two pairs of transducers [17] operating at a central frequency equal to 1.15 MHz, one pair acted as emitters (see Fig. 1 1 and 2) and the other pair as receivers (see Fig. 1 3 and 4). The transducers (U1000, Lanhui ultrasonic device Wuxi, China) produced a 150 V, 500 ns pulse to excite the emitters.

It was the same case with most applied QUS devices which measured $\text{SOS}_{\text{FAS}}$ at the radius and tibia. Signals from the receiving transducers were amplified by AD8627 and then captured by a 12-bit analog to digital converter (AD9235BRU-65M) that sampled the ultrasound signal at 60MHz. Two fast first input first output memory (FIFO, IDT72V251J10) were used to cache the results of ADC. After a measurement was completed, the FIFO data were sent to the microcontroller unit (STM32F103R8T6) for further analysis. Finally, the LCD monitor showed the results of the measurement, such as waveform, $\text{SOS}_{\text{FAS}}$, T-score and so on.

![Figure 1](image.png)

Figure 1. The probe contains two emitters (1 and 2) and two receivers (3 and 4) and a temperature sensor (5). Four paths of axial transmission: the ultrasound wave travels through coupling medium (ultrasound gel) and the soft tissue. The part of the wave which impinges the bone under the critical angle ($\theta_1 = 23^\circ$) travels along its surface and at each point part of the energy is reemitted at the same angle. $\theta_2$ is the inclination between the probe and the bone surface.
Currently, the preferred anatomic sites for multisite axial transmission are the distal one-third radius (Fig. 3a) and the middle of tibia (Fig. 3b). In operation, the probe is placed on region of interest of tibia or radius (Fig. 3c). The probe containing four transducers were used to excite and receive the waves that propagate along the cortical bone layer parallel to its long axis. The unprocessed waves (digital signals) were filtered and smoothed by the method of five-point cubic spline interpolation[18]. After smoothing, the whole signals were obtained and showed on the LCD (Fig. 3d). In this new device, the time of flight (TOF) of the first arriving signal is measured and used to calculate $S_{0AS}$, which are described in the next section. In addition, the skin surface temperature was measured for amending the
SOS as the ultrasound measurements. Specifically speaking, the chosen temperature coefficient is -3m/s/℃ in the range of 23±10 ℃.

A clinical study was carried out using the ultrasound device. Twenty five subjects aged 24-67 (mean age ± SD: 47±13 y) were recruited for this study under an institutional review board-approved protocol. All study subjects were interviewed and given written informed consent before the study. Subjects were excluded only if they may have been, or were pregnant. Each subject was measured three times at the radius and tibia with the ultrasound device respectively. Ultrasound coupling gel was used to ensure good acoustic conduction between the transducers and skin. For comparison, the average ultrasound velocity (SOS\textsubscript{FAS}) of each subject was measured, and a bone density (BMD) at the lumbar spine (the vertebral levels L1–L4) was measured using GE Prodigy DEXA scanner at Anhui Provincial Hospital.

2.2 The Measurement of SOS\textsubscript{FAS}

Two emitters and two receivers allow several acoustic pathways involving soft tissue path portions of the same length and variable bone path length, involving four travel times (the TOF of the FAS) (see Fig. 4a) from the four travel paths, which defined as TOF\textsubscript{1-3}, TOF\textsubscript{1-4}, TOF\textsubscript{2-3}, TOF\textsubscript{2-4} respectively.

The determination of the TOF was achieved using a parabolic interpolation of the signal using 5 points around the extremum, yielding a precision better than 5 nanoseconds[14]. The SOS\textsubscript{FAS} was obtained through the following iterative procedure:

A. Acquisition of time parameters of TOF\textsubscript{1-3}, TOF\textsubscript{1-4}, respectively.

B. Judgement of time difference between TOF\textsubscript{1-3} and TOF\textsubscript{2-4}:

If |TOF\textsubscript{2-4}-TOF\textsubscript{1-3}| > 0.01us (θ\textsubscript{2}≠0, L\textsubscript{1-3}≠L\textsubscript{2-4}) (Fig. 4b) then movement of the probe and the changes of inclination between the transducer surface with the bone surface, and then go to A, or else |TOF\textsubscript{2-4}-TOF\textsubscript{1-3}| ≤ 0.01us (θ\textsubscript{2}≈0, L\textsubscript{1-3}≈L\textsubscript{2-4}) (Fig. 4c), and then go to C.

C. Acquisition of time parameter of TOF\textsubscript{1-4} when the transducer surface is parallel with the bone surface as the θ\textsubscript{2}≈0.

D. Calculation of time difference between TOF\textsubscript{1-4} and TOF\textsubscript{2-3}, the difference denoted as ΔTOF in s.

\[ \Delta \text{TOF} = \text{TOF}_{1-4} - \text{TOF}_{2-3} \]  \hspace{1cm} (1)

E. Calculation of SOS via the formula:

\[ \text{SOS}_{\text{FAS}} = \frac{ΔL}{Δ \text{TOF}} \]  \hspace{1cm} (2)

Where ΔL is the difference between L\textsubscript{1-4} and L\textsubscript{2-3}, and calculated by the following equations (see Fig. 4b):
\[ \Delta L = L_{1-4} - L_{2-3} = L_{abcdef} - L_{gcdh} = \Delta L_1 + \Delta L_2 + \Delta L_3 - \Delta L_4 \]  

because the \( \theta_2 \approx 0 \), then (see Fig. 4c)

\[ \Delta L_1 = 0, \ \Delta L_4 = 0, \]  

\[ \Delta L = \Delta L_2 + \Delta L_3 = \Delta r + \Delta r = 2\Delta r \]  

The Eq. 2 was simplified as follow:

\[ \text{SOS}_{FAS} = \frac{2\Delta r}{\Delta \text{TOF}} \]  

Where \( \Delta r \) is the horizontal distance between the two receivers or the two emitters, and which is a constant determined by physical dimensions of the probe.

2.2 Data Analysis

Pearson’s correlation coefficient and probability p-value, which describe the significance of the correlation, were used to assess the relationships between ultrasonic bone status indicators and BMD. A p value of < 0.05 was considered to be statistically significant. All the indicators were reported as the mean±standard deviation (SD) and statistical analysis was conducted using SPSS19.0.
3. RESULTS AND CONCLUSION

The ultrasonic results and DEXA results are showed in Table 1. The correlations between SOS\textsuperscript{FAS-radius}, SOS\textsuperscript{FAS-tibia} and BMD are showed in Table 2. The SOS at the radius and tibia, and BMD at the lumber spine were significantly (p<0.001) correlated (Table 2). These correlations are similar to those reported when comparing DEXA-based BMD measurements at lumbar spine with radius and tibia (r=0.6-0.8 for SOS\textsuperscript{FAS-radius}, r=0.5-0.8 for SOS\textsuperscript{FAS-tibia}) [19-22]. The results indicated that this device might be applied for assessment of bone density and osteoporosis screening purposes.

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<tr>
<th>Table I. THE RESULTS OF QUS AND DEXA MEASUREMENTS (N=25).</th>
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<tr>
<td><strong>Mean±SD (range)</strong></td>
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<tr>
<td>SOS\textsuperscript{FAS-radius} (m/s)</td>
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<tr>
<td>3956±63 (3799-4047)</td>
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<tr>
<td>SOS\textsuperscript{FAS-tibia} (m/s)</td>
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<tr>
<td>3758±64 (3611-3833)</td>
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<tr>
<td>BMD (g/cm\textsuperscript{2})</td>
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<td>1.0±0.18 (0.70-1.39)</td>
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<tr>
<th>Table II. CORRELATIONS OF QUS AND DEXA MEASUREMENTS (N=25).</th>
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<tr>
<td><strong>Coefficient of correlation</strong></td>
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<tr>
<td><strong>p-value</strong></td>
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<tr>
<td>BMD vs. SOS\textsuperscript{FAS-radius}</td>
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<tr>
<td>0.68</td>
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<tr>
<td>p&lt; 0.001</td>
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<tr>
<td>BMD vs. SOS\textsuperscript{FAS-tibia}</td>
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<tr>
<td>0.77</td>
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<td>p&lt; 0.001</td>
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Although X-ray methods are effective in bone mass assessment, osteoporosis remains one of the largest undiagnosed and under-diagnosed diseases in the world today. CHPF 2013 reported that about four-fifths osteoporosis population under-diagnosed in china because of expensive and scarce diagnostic equipment[1]. The research described here, in conjunction with the fact that the devices are designed to be manufactured at very low cost ($450 USD) and portable (<1.5Kg), should enable the significant expansion of diagnosis and monitoring of osteoporosis. That is to say, this portable ultrasonic bone densitometer with temperature correction is convenient to enter the community health care institutions or even ordinary families in the future. Thus, improved the screening rate of osteoporosis in the elderly, and ensured early diagnosis and early prevention will be possible.

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REFERENCES
