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Ultrasound Transmission Measurements Through the Os Calcis

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Summary. A method of measuring ultrasonic propagation in the os calcis was devised for assessing bone properties in humans. Speed-of-sound (SOS) and broadband ultrasound attenuation (BUA) were measured using broadband acoustic pulses transmitted and received by a pair of focused transducers. The transducers are mounted coaxially in a water tank with the subject's heel in between. Reproducibility of results in an adult male was 10% for the BUA and 1.2% for the SOS. Both SOS and BUA changed when the transmission path through the os calcis was varied. For a population of normal male subjects, SOS and BUA were correlated with densitometry results on the os calcis, but less well correlated to area density at remote sites.

Key words: Ultrasound attenuation – Speed-of-sound – Bone – Osteoporosis.

Osteoporosis detection and its cure or prevention have increasingly become areas of medical concern. As the mean age of the human population increases, a greater number of both men and women are developing complications due to bone loss. Thus, methods for routine assessments of bone are needed. At the present time, radiography and photon absorptiometry are the most widely used methods for skeletal evaluation [1]. However, routine assessments, especially of asymptomatic subjects, are considered impractical with these techniques because of cost constraints and exposure to ionizing radiation.

Two techniques involving transmission of ultrasound, speed-of-sound (SOS), and broadband ultrasound attenuation (BUA) may allow detection of bone changes accompanying osteopenia. For example, Andre et al. [2] measured the SOS in the cortex of the human femur using a combined pulse-echo technique and an X-ray image. They found slightly lower speeds in patients who were at risk for fracture. Jeffcott and McCartney [3] measured SOS in race horses, and Rubin et al. [4] investigated SOS in sheep. Heaney et al. [5] reported application of SOS in normal subjects and osteoporotic patients. Several groups have used the BUA method in the os calcis [6–10]. Normal women had significantly higher BUA in the os calcis than women with femoral fractures. Poll et al. [9] found that BUA in the os calcis correlated well ($r = 0.8$) with single-photon absorptiometry in the distal forearm. Baran et al. [10] reported a significantly lower BUA in osteoporotic patients with hip fracture.

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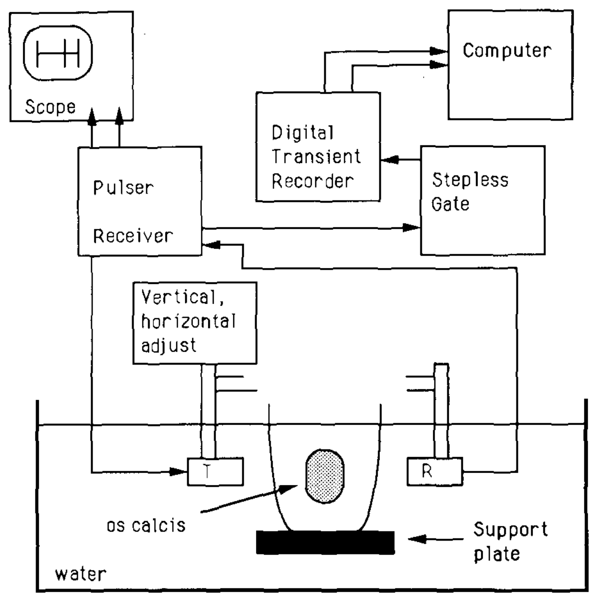

Fig. 1. Experimental apparatus. (Note, the drawing shows an AP view through the os calcis.)

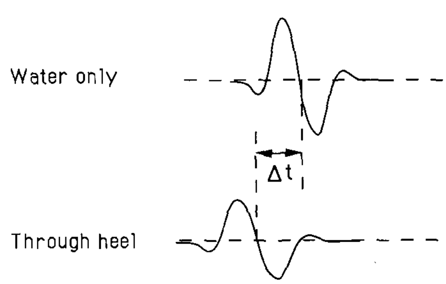

Fig. 2. Signal waveforms for transmission through water only (top) and through the heel (bottom), illustrating determination of Δt, the difference in pulse propagation times. Each waveform represents the signal at the receiver transducer versus time.

We investigated both SOS and BUA measurements for bone assessment. Our method for BUA is similar to that of Langton et al. [6] except for two features. First, we measured at a lower range of frequency. Our transducers have a larger fraction of their pulse bandwidth in 0.1–0.6 MHz range, where significant energy is detected after transmission through the os calcis. Second, we used focused transducers in order to allow finer localization. In addition, we combined SOS and BUA measurements at the same locations.

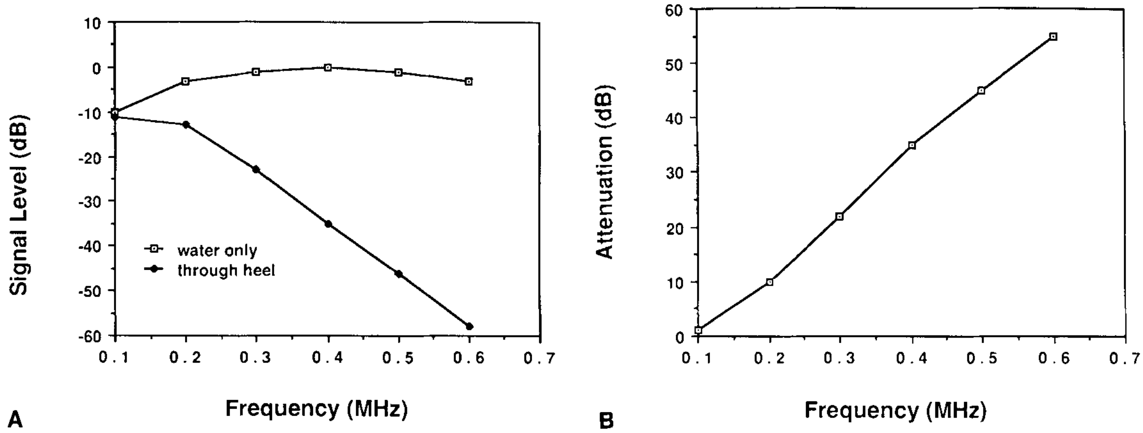

Fig. 3. (**A**) Reference (water only) signal spectrum and signal spectrum after propagation through the heel. (**B**) Reference signal spectrum-attenuated signal spectrum.

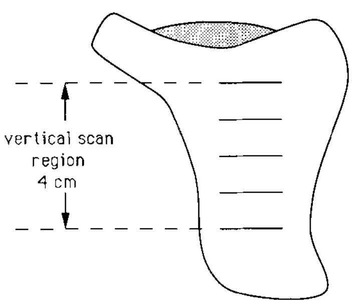

Fig. 4. Schematic diagram of multiple measurement sites. This is a lateral view of the os calcis, and measurements were done over a 4 cm path.

This report outlines our measurement methods; the precision of BUA and SOS is examined along with their correlation to bone densitometry in a group of normal males.

Materials and Methods

Ultrasound

SOS and BUA were measured in the os calcis using the experimental setup shown in Figure 1 [11, 12]. A pair of 500 kHz center frequency transducers were mounted coaxially in a water tank, separated by approximately 8 cm. The temperature of the water was maintained at 35°C. The transducers were 2.5 cm in diameter and were focused to a depth of about 4 cm. One served as an ultrasonic pulse transmitter and the other as a receiver. The transducers were mounted on an assembly that allowed vertical and horizontal manipulation of the beam axes relative to a subject's foot.

The pair of transducers were connected to a Panametrics 5055 PR pulser-receiver, operating in a through-transmission mode. The amplified receiver signal was sent into a stepless gate (Panametrics 5052 G) to isolate the portion of the signal of interest. Measurements were done by digitizing the gated signals using a Biomation 8100 (Gould) transient recorder, and analyzing signals in a PDP 11/23 computer. The transient recorder digitized with 8-bit precision, was operated at 20 MHz, and contained a 200 word buffer-memory to store waveforms. These waveforms were transferred to the computer for computations of the SOS and BUA.

During the experiment, the subject's heel was positioned on the foot support plate (Fig. 1) and strapped in place. The heel and foot support were then positioned between the transducers, with the ultrasound beam from the transmitter transducer propagating laterally through the center of the os calcis. Correct positioning was accomplished by palpating the heel and locating the sides of the os calcis. This location was then visually positioned along the axes of the transducers. A calibrated attenuator on the receiver amplifier was adjusted until the amplitude of the received signal was approximately equal to that of the signal when the beam passed through water alone. The difference in the attenuator settings was noted.

The average SOS through the heel (C_m) was determined using a substitution technique, where the *difference* between the times for the received pulse arrival, with and without the heel in the path of the ultrasound beam, was determined. The arrival time of the pulse was measured from the zero-crossing of the first negative slope of the received signal trace (Fig. 2). The SOS was then found using:

$$C_m = \frac{C_w}{1 - (C_w \Delta t/d_m)} \tag{1}$$

where Δt is the difference in the pulse arrival times, d_m is the heel thickness, and C_w is the SOS in water. The latter is known precisely provided the temperature is known [13]. In equation 1, Δt is positive if the arrival time is shorter with the heel in place than when transmitting through water. For single point measurements, the heel thickness, d_m, was determined using a skinfold caliper. When multiple measurements were done, d_m was determined for each measurement site using two pulse-echo transducers positioned with their sound beams coaxially with those of the transmitter and receiver transducers. The echo transit time from each pulse-echo probe to the skin surface was used to determine the probe to skin distance on both sides of the heel; from the known separation of these probes, the heel thickness could then be determined.

Attenuation of frequency components of the ultrasound pulse resulting from propagation through the heel also was determined using a substitution technique. BUA was measured by first determining the relative signal levels of frequency components in the waveform between 0.1 and 0.6 MHz with no heel in the beam path; this was done by taking a Fourier transform of the received signal. Signal amplitudes at the same frequencies were then determined after propagation through the heel (Fig. 3A). The difference between amplitudes for each frequency of interest was calculated and recorded in decibels after correcting for the difference between electronic attenuator settings when the two waveforms were recorded. The attenuation through the heel was then calculated and plotted versus frequency (Fig. 3B), and the slope of linear regression was determined. This BUA determination conforms with the approach of previous investigators.

Absorptiometry

Single photon absorptiometry (SPA) was used to measure the bone mineral density (BMD) of the radius shaft [1]. The BMD is an "area

Table 1. Speed-of-sound (SOS in m/seconds) and ultrasound attenuation slope (BUA in dB/MHz) for 1 individual measured seven times

	Measurement site									
	+10 mm		+5 mm		0		−5 mm		−10 mm	
Occasion	BUA	SOS	BUA	SOS	BUA	SOS	BUA	SOS	BUA	SOS
1	84.0	1703	80.8	1598	83.8	1588	88.5	1616	—	—
2	94.6	1674	84.3	1613	91.5	1538	90.1	1538	—	—
3	89.6	1599	88.8	1573	99.5	1550	97.6	1547	—	—
4	99.9	1575	100.4	1552	105.6	1537	109.3	1534	85.3	1539
5	110.6	1587	97.7	1561	85.7	1547	96.3	1542	63.0	1543
6	85.5	1604	95.4	1562	90.5	1547	117.5	1542	91.6	1513
7	82.5	1608	108.5	1573	110.6	1571	75.9	1564	71.6	1533

The "0 position" is the best estimate for the middle of the os calcis. During each session, results also were obtained from locations 5 and 10 mm superior to and inferior to the middle of the os calcis.

Table 2. Results (X ± SD) of ultrasonic data taken from male subjects

	SOS (m/sec) BUA		
Heel		Estimation at 0.350 MHz (dB)	Slope (dB/MHz)
Right	1569 ± 38	33.1 ± 6.9	89.5 ± 12.7
Left	1572 ± 38	32.9 ± 6.6	89.3 ± 12.6
Both	1571 ± 36	33.0 ± 7.0	89.4 ± 11.6

Measurement position was in the center of the os calcis as determined by the operator.

Table 3. BMDs (g/cm²) at various sites in male study population

Site	Minimum	X ± SD	Maximum
Spine	1.006	1.32 ± 0.166	1.723
1/3 Radius	0.636	0.793 ± 0.054	0.894
Distal radius	0.317	0.445 ± 0.56	0.554
Femur neck	0.83	1.093 ± 0.148	1.4

Table 4. Speed of sound and attenuation slope for all subjects

Position	SOS (m/s)	BUA attenuation slope (dB/MHz)
1	1579 ± 34	90.1 ± 13.1
2	1559 ± 32	94.5 ± 11.3
3	1542 ± 26	91.8 ± 7.0
4	1533 ± 21	87.8 ± 8.5
5	1533 ± 20	87.3 ± 9.7

Pos. #1 is the superior measuring spot, Pos. #2 is 5 mm lower, etc.

density" representing the mass of bone in the projection of a region and not a true volumetric density. Scans were made on a standard site one-third of the forearm length proximal to the ulna styloid with a rectilinear scanner using a ^{125}I source (Lunar Radiation SP2). Dual photon absorptiometry (DPA) was used to measure the lumbar spine and the proximal femur following the manufacturers instructions. Version 8C software was used to minimize the small effect of source activity on spine scans [8]. A standard rectilinear scanner using a ^{153}Gd source was used (Lunar Radiation DP3). The femur scan program was used to scan the left heel in the air with the subjects lying on their side. The rectilinear scan of the heel in lateral projection proceeded at 3 mm intervals over the entire heel region. The posterior region was taken for analysis using a manual region-of-interest. Precision of spine and femur BMD determinations *in vivo* are about 2% in our laboratory. For both SPA and DPA the BMD should be recognized as an area density rather than a physical volumetric density.

Subjects

Reproducibility was investigated by measuring SOS and BUA on the right heel of a 42-year-old adult male; seven sets of measurements were made over 3 weeks. During each set, measurements were done at four and if possible, five different paths through the heel of the subject. One path was the experimenter's best estimate of the center of the os calcis, similar to the location used by Rossman et al. [11] in a population of female subjects. In addition, measurements were obtained with the axis of the transmitting transducer 5 and 10 mm above the center position, as well as 5 mm, and whenever possible, 10 mm below this spot.

BUA and SOS measurements were also performed on a population of normal white males (n = 42) ranging in age from 20 to 47 years (mean = 30 years). All had normal spine BMD (x = 1.32 ± 0.17 g/cm²), as determined by DPA. Five measurements were made at a single position on each heel.

Measurements also were done at multiple sites on this group of subjects. The beam axis was first positioned near the top of the os calcis, as determined by palpation. Subsequent measurements were done at sites 5, 10, 15, and 20 mm lower (Fig. 4).

Results

Table 1 presents the results of the reproducibility study where the BUA and the SOS are listed for each measurement period. As mentioned above, four or five measurements, each from a slightly different position, were taken each day on this subject. At the central position, both BUA and SOS varied from one measurement period to another. The SD of the BUA results was about 10% of the mean value, whereas the SD of SOS was relatively constant (19 m/second or 1.2%) at the central position.

Some of the variability appeared to be related to the placement of the focused transducer, evident from the results obtained with the transducer above and below the estimated middle position. Table 1 shows that for each set of measurements, SOS gradually increased, and BUA gradually decreased as the transducer placement was elevated. This may be a result of increased amounts of compact bone and decreased amounts of trabecular bone as the measurement site was elevated.

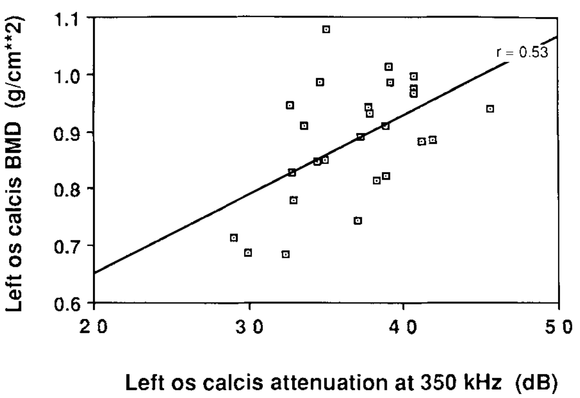

Fig. 5. Left os calcis BMD versus mean sonic attenuation at 350 kHz in the same heel. The mean was determined for all five transmission paths for each subject.

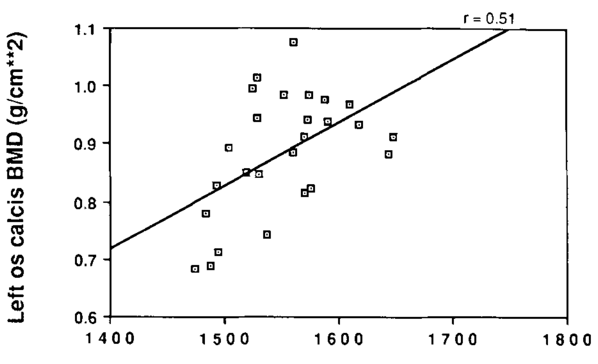

Fig. 6. Left os calcis BMD versus mean os calcis SOS in the same heel. The mean was determined for all transducer positions for each male subject.

Ultrasound measurements were made on the right and left heels of each male subject; the values are given in Table 2. The correlation between the left and right heel measurement was 0.89 for SOS and 0.68 for BUA; the SEE in predicting one heel from another was 17 m/second for SOS and 9 dB/MHz for BUA. The systematic difference between the two heels averaged 3 m/second for SOS and 0.26 dB/MHz for BUA, indicating that either heel could be used for comparison between ultrasound and BMD.

Table 3 lists the BMD values at each of the sites studied in this group of subjects. Table 4 shows SOS and BUA at each transducer position on the os calcis, with position 1 the superior monitoring site. The data were averaged for all subjects. SOS decreased significantly and BUA showed a tendency to drop as the area monitored was lowered.

To study correlations, the ultrasound measurements from all 10 sites were averaged for each subject. The BMD of the posterior half of the left os calcis was moderately correlated with BUA ($r = 0.53$) and SOS ($r = 0.51$) of the same heel (Figs. 5 and 6). Part of the reason for lack of a high correlation was due to variation in BMD across the os calcis. Our BUA and SOS measure only a limited area whereas the rectilinear scanner integrates density across the entire heel. The BMD in the low density region-of-interest measured by BUA and SOS was isolated from the DPA scans; the correlation of BMD to ultrasound in this zone was higher, 0.72 for SOS (see Fig. 7) and 0.56 for BUA. The correlations of SOS and BUA with BMD at other sites (spine, femur, radius) were lower (0.3–0.4) partly because of the limited variation in BMD in normal males.

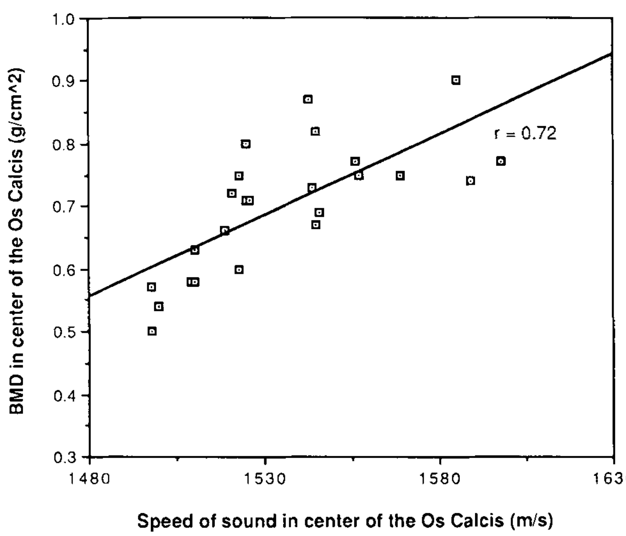

Fig. 7. BMD in the center of the left os calcis versus SOS at the same approximate position.

Discussion

Day-to-day reproducibility in 1 subject was about ±10% for BUA slope and 1.2% for SOS. In order for these ultrasound measurements to be useful, in patient screening for example, it is necessary to reduce these variations. A major source of variability is probably associated with variations in the exact path through which the sound beam travels. This is suggested by data in Tables 1 and 4, indicating that the SOS and attenuation depend on the location in the os calcis. To overcome this problem it may be necessary to (1) use unfocused transducers, as is done by other investigators, to provide spatial averaging; or (2) utilize multiple measuring sites with selection of an optimum region. We are currently exploring both these approaches.

Both SOS and BUA were correlated with BMD at the same site on the os calcis of normal males, but less well correlated to density at remote sites. Other investigators, including our own group, have seen higher correlations in females where the range of BMD values has been larger then in males [9, 11]. Further investigations are needed over a wider range of variation to assess these associations.

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