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Broadband Ultrasonic Attenuation Imaging: A New Imaging Technique of the Os Calcis

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Abstract. Ultrasound transmission measurement through the os calcis is an emerging technique and a promising clinical tool for early assessment of osteoporosis. However, several previous studies showed that broadband ultrasonic attenuation (BUA) is sensitive to small variations in bone mass or structure. The os calcis is an inhomogeneous bone and therefore, the attenuation depends on the location in the os calcis. BUA distribution within the os calcis can be measured by rectilinear scanning over the entire bone. We used a mechanical scanning device with both unfocused and focused transducers. The spatial resolution of these was about 25 mm and 4 mm, respectively. There was good agreement ($r = 0.97$) between the results with unfocused and focused transducers. In addition, imaging the variations of BUA is possible with the focused transducers, and high quality images are obtained. These images permit the selection of optimal regions of interest for ultrasound attenuation measurement.

Key words: Ultrasound attenuation — Bone — Osteoporosis

Among the considerable advances in bone densitometry techniques and their clinical applications, ultrasound is currently considered with great interest by scientists and clinicians and is now commercially available from several sources. This is supported by the fact that the strength of cancellous bone is determined not only by its density but also by its structure. Now, it has been proved that ultrasound attenuation depends also on both bone mass and structure [1–3]. The basis of the measurement of broadband ultrasonic attenuation (BUA) in transmission through the os calcis was established by Langton et al. [4] The authors have shown that women with recent fractured hip could be differentiated from normal women by measuring BUA. Then, several studies were published comparing BUA in the os calcis with bone mineral density at various skeletal sites measured by different techniques [single photon absorptiometry (SPA), dual photon absorptiometry (DPA), or quantitative computed tomography (QCT)] for osteoporotic and normal women [5–20]. The os calcis has been chosen as a site for the measurement because it is easily accessible, mainly composed of cancellous bone and surrounded by a fairly thin layer of soft tissues.

Nevertheless, one of the main problems encountered by the technique is related to the inhomogeneity of the os calcis [21] and to the sensitivity of the BUA to small changes in density and structure. So, a high variability of the measurements is related to the transducers positioning [22]. The positioning of the heel *in vivo* becomes important for two reasons. First, if the os calcis is highly inhomogeneous, the BUA will be sensitive to the site chosen for the measurement. One of the most critical steps with commercial devices measuring BUA is correct foot positioning on the foot support. But even then, the exact position of the transducers is unknown and cannot be controlled. Due to interindividual anatomical variations and variable amount of soft tissue below and behind the heel, the site of measurement may vary from one subject to the other. This might be one of the factors for the observed interindividual variability and should be definitely controlled to make the comparison more conclusive. Second, the positioning is also important for repeat measurements on individuals over a period of time to monitor the progression of bone loss or response to therapy. The *in vivo* reproducibility of the BUA technique is found to be of the order of 3 or 4%. This should be improved for the longitudinal studies. To overcome these problems we investigated the possibility of generating images of the BUA parameter by scanning the entire os calcis. Comparison has been made with unfocused transducers and focused transducers.

Materials and Methods

Measurements were performed on 12 os calces removed from fresh female cadavers (age range 70–85), all of them being pairs. The bones were stored at 4°C until measured, when they were brought up to room temperature.

Our method for BUA was similar to that of Langton et al. [4], but like Rossman et al. [9] we also used focused transducers. Our experimental setup is shown in Figure 1. A pair of transducers were mounted coaxially in a water tank, at room temperature. The distance between the unfocused transducers (Panametrics, 25 mm diameter, central frequency 500 kHz) was twice the Fresnel-Fraunhoffer length (approximately 100 mm). The focused transduc-

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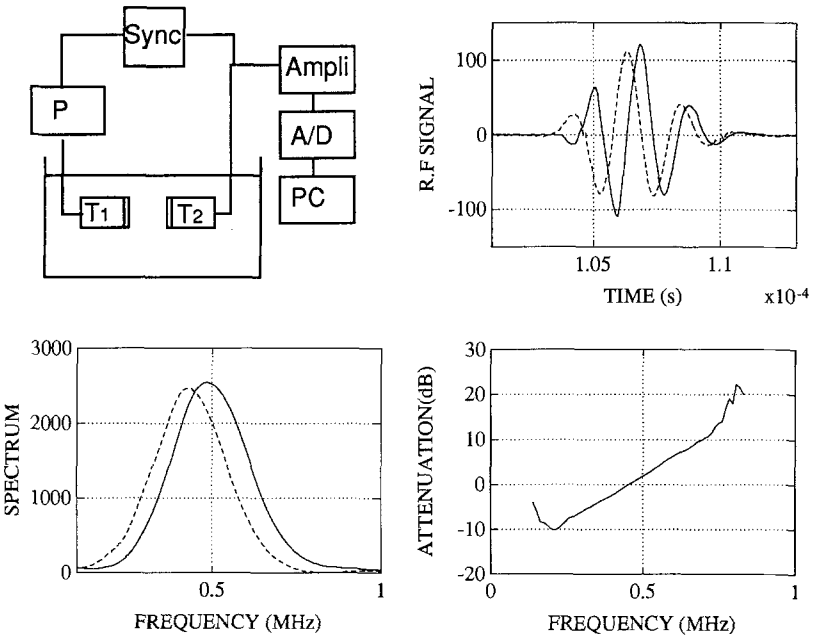

Fig. 1. (a) Experimental setup: T1, transmitter; T2, receiver; P, pulse generator; Ampli, amplifier; A/D, digitizer; PC, computer; Sync, synchronization. Basis of BUA measurement: (b) ultrasound pulses (continuous line, reference signal; dashed line, signal transmitted through bone); (c) amplitude spectra of the reference signal (continuous line) and of the signal transmitted through bone (dashed line); (d) attenuation as a function of the frequency. BUA is the slope of the linear fit of the curve.

ers (Panametrics, 29 mm diameter, central frequency 500 kHz, 35 mm focal length) were separated by a distance of approximately 70 mm (twice the focal length).

One of the transducers is the ultrasonic transmitter and the other one acts as the receiver. Both are connected to an ultrasonic pulse receiver, amplifier, digitizer system (Contrôle US, Orsay, France). The received signal is digitized at a rate of 12 MHz and then transferred to an IBM PC for further processing. The attenuation was obtained using a substitution method. An ultrasound pulse composed of various frequencies ranging from 200 to 600 kHz is received first without and then with the bone interposed between the transducers. Then the signal was gated and Fourier transformed into the frequency domain. The attenuation as a function of frequency is derived from the difference of the logarithm of the spectra of the signal without and with bone. The attenuation displays a nearly linear dependency with frequency. A linear least squares fit was performed to the data over the frequency range. The slope of the fit is the BUA in decibel/megaHertz (dB/MHz).

The sample was submerged in water between the two transducers and was suspended by a pliers at its distal extremity. The bone samples were located centered between the transducers, in the narrowest part of the ultrasonic beam. The transducers were driven by stepper motors to allow alignment. The bone could also be moved by stepper motors (finer step 1/100 mm) in two perpendicular directions x and y so that complete ultrasonic scanning could be performed. Figure 2 shows a schematic view of the os calcis to explain the positioning considerations. The os calcis was positioned so that its long axis was vertical and perpendicular to the path of the ultrasonic beam. The external side of the bone was facing the transmitter. The x axis was oriented along the vertical axis of the os calcis and the y axis was parallel to the long axis of the bone going from the back of the heel towards the toe of the foot.

The bones were examined extensively by scanning both the x and y directions in 1-mm intervals until the extremity of the pliers appeared in the ultrasound field. The size of a scan was typically 70 × 70 mm. A value of BUA was obtained for each position and an image of the parameter of 70 × 70 pixels could be processed. Then a small square region of interest (ROI) of approximately 1 cm^2 was selected in the middle of the posterior part of the os calcis. The average value of BUA over the 100 readings of BUA for the ROI was calculated. In the following sections, local BUA refers to the measurement at a single position, whereas average BUA is measured within a ROI.

The precision or the reproducibility of the present technique *in vitro* was assessed in two ways. First it was determined by taking 10 daily measurements on one os calcis over an interval of 2 days at the same site by accurately positioning the bone before each measurement. BUA was measured for a single position of the transducers. Second, 10 measurements of the average value of BUA over the ROIs previously defined were performed. Between each measurement, the bone remained attached to its support in the water tank and was simply removed from the ultrasonic beam by using the motors. Accurate repositioning is possible due to the high precision (1/100 mm) of the motors. Linear regression analysis (least square) was used to compare BUA measured with the pairs of unfocused and focused transducers.

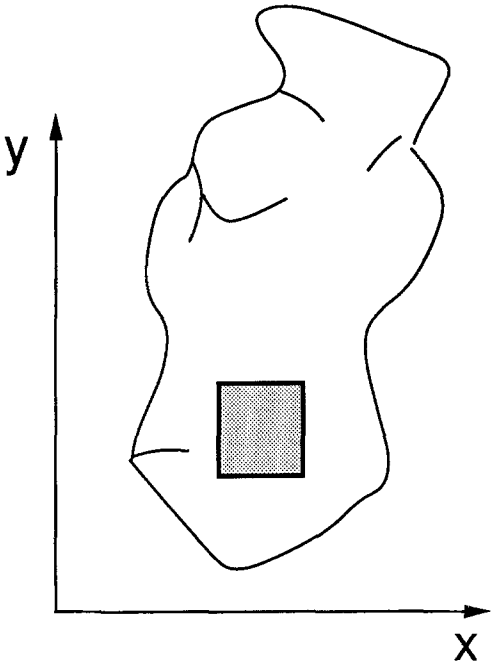

Fig. 2. Schematic view of the os calcis in position for BUA scanning. On a lateral view of the bone it shows the directions of scanning and the ROI selected for averaging BUA values.

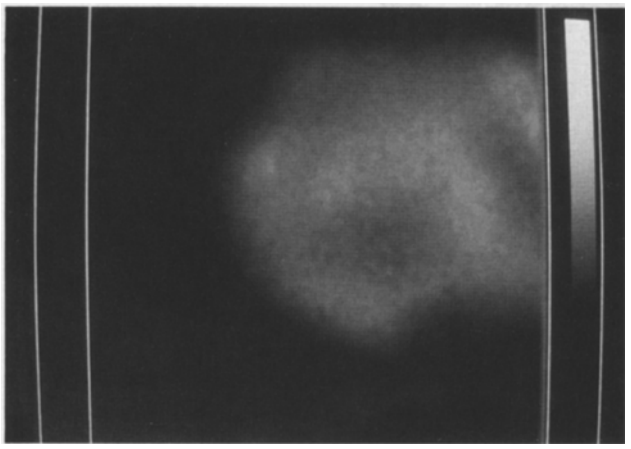

Fig. 3. BUA images of the os calcis for a pair of unfocused transducers.

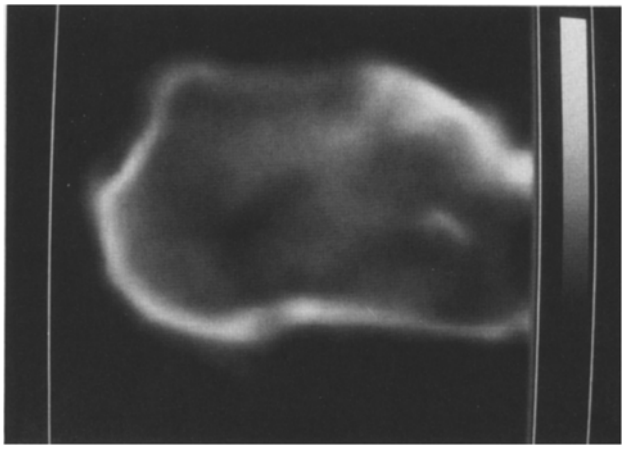

Fig. 4. BUA images of the os calcis for a pair of focused transducers.

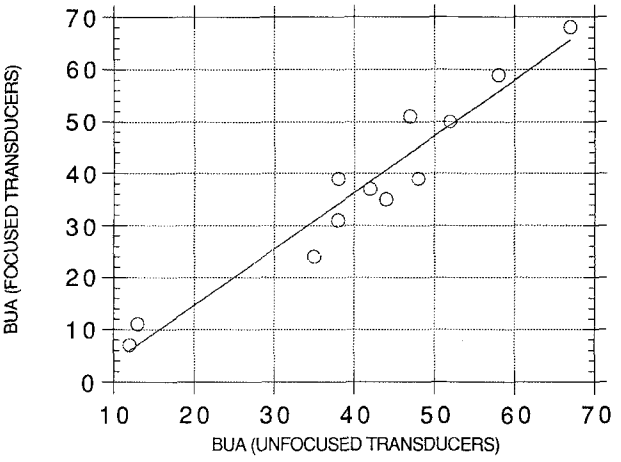

Fig. 5. BUA for focused transducers against BUA for unfocused transducers.

Table 1. Results of BUA for unfocused and focused transducers

Os calcis	Unfocused transducers × (SD)	Focused transducers × SD
1 (r)	42 (8)	37 (6)
1 (l)	48 (7)	39 (7)
2 (r)	52 (4)	50 (11)
2 (l)	47 (6)	51 (6)
3 (r)	67 (8)	68 (14)
3 (l)	58 (5)	59 (7)
4 (r)	44 (4)	35 (6)
4 (l)	38 (4)	39 (5)
5 (r)	13 (2)	11 (1)
5 (l)	12 (2)	7 (2)
6 (r)	38 (2)	31 (3)
6 (l)	35 (4)	24 (3)

r: right foot; l: left foot

Results

Figures 3 and 4 show the comparison between the typical ultrasonic images of BUA for a pair of unfocused and focused transducers. The grayscale for both images is black (0 dB/MHz) to white (100 dB/MHz). In Figure 5, average BUA values measured with focused transducers are plotted against average BUA values measured with unfocused transducers and the data are summarized in Table 1 (average BUA and SD). Data fall on a line of slope 1.08 and intercept −7.07 dB/Mz. Highly significant correlation is found ($r = 0.97, P < 0.001$). The intra-ROI variability of BUA is defined as the mean value of the following ratio: SD divided by average BUA. The variability is 12% for the unfocused transducer and 16% for the focused one. The precision is 0.6% for the local BUA and 0.1% for the average BUA.

Discussion

As accurate positioning of the bone was possible, our precision is related to intrasystem error only, which is the minor cause of error. In this respect, it is similar to the one measured in by Langton et al. [22]. It is better than the usual measured value *in vivo*. The predominant factor of error is due to the difficulty to define a specific zone for the measurement and then to find it again for further measurements [1]. Averaging the BUA over a ROI yields a low intrasystem error.

The complete assessment of the BUA distribution within the os calcis is possible by scanning over the whole bone. To date, we present the first images of BUA of the os calcis. Images of the os calcis with focused transducers are superior to those with unfocused transducers. Indeed, the focused transducers measure a narrow path across the os calcis, approximately 4 mm in the focal zone, whereas unfocused transducers measure a wider path of 25 mm. When using unfocused transducers, the local BUA at two adjacent pixels are strongly correlated and that explains the blurry aspect of the image in that case.

There is an excellent correlation between the average BUA measured with unfocused or focused transducers. The small dispersion of data around the regression line might be accounted for by the fact that between the measurements with both pairs of transducers the sample had to be removed from the water tank. When positioning the bone again for the next measurement, exactly the same orientation in the ultrasonic beam could hardly be obtained. For the focused transducers, the average BUA values are somewhat lower than those for unfocused transducers; this is supported by the

negative intercept (−7.07) of the linear fit of data. Rossman et al. [9], comparing their data *in vivo* for focused transducers with data from literature generally measured with unfocused transducers reported a similar observation. They argued that it was probably due to the fact that using unfocused transducer, with larger ultrasonic beam, average out some of the local fluctuations in BUA. However, in our opinion, this argument cannot account for the lower BUA measured with focused transducer. A possible but yet unclear explanation for that observation might be related to the diffraction effect which is different for unfocused or focused transducers. From our data, direct evidence for the averaging effect caused by unfocused transducers is given by the comparison of the variability of local BUA in the ROI. The variability is greater with focused transducers than with unfocused ones. Large variability of the local BUA within the ROI, similar to the one reported by Zagzebski et al. [15] and Glüer et al. [19], indicate that local BUA is strongly dependent on the location in the os calcis. Using unfocused transducers, as is done by other investigators, is relevant when BUA is measured locally for a single position because it provides a kind of spatial averaging, however, focused transducers are required for imaging BUA variations in the os calcis. The major progress introduced here consists of scanning the entire bone which leads to a greater amount of information. The spatial distribution of the BUA can be measured. Focused transducers must be used if the BUA distribution is to be measured with an acceptable spatial resolution. The actual spatial resolution of our imaging device is about 4 mm, and this is the limit for measuring the local BUA. The image represents the support for correct relocation of ROI and for selection of the optimal site of measurement. The placement of the ROI is not dependent on the spatial resolution, as it is always possible to relocate the ROI according to predefined criteria such as distances from the edges, or by image superposing. As for dual X-ray absorptiometry (DXA) or quantitative computed tomography (QCT), it makes it possible to control the location, size, and shape of the ROI and to use multiple measurement sites.

Current studies are conducted in our group to assess the technique *in vivo*. At this time, it is not known if the measurement is significantly affected by soft tissues surrounding the heel even though high concordance between values of BUA *in vivo* and that in three fully dissected os calces was reported in [23].

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References

1. Langton CM (1987) Critical analysis of the ultrasonic interrogation of bone and future developments. In: Palmer SB, Langton CM (eds) Ultrasonic studies of bone. IOP, Bristol, p 73
2. McKelvie ML, Palmer SB (1991) The interaction of ultrasound with cancellous bone. Phys Med Biol 36:1331–1340
3. Tavakoli MB, Evans JA (1992) The effect of bone structure on ultrasonic attenuation and velocity. Ultrasonics 30:389–395
4. Langton CM, Palmer SB, Porter RW (1984) The measurement of broadband ultrasonic attenuation in cancellous bone. Eng Med 13:89–91
5. Poll V, Cooper C, Cawley MID (1986) Broadband ultrasonic attenuation in the os calcis and single photon absorptiometry in the distal forearm: a comparative study. Clin Phys Physiol Meas 7:375–379
6. Evans WD, Crawley EO, Compson JE, Evans C, Owen GM (1987) A comparison of broadband ultrasonic attenuation with single photon absorptiometry and quantitative computed tomography for measurement of bone mineral content. In: Palmer SB, Langton CM (eds) Ultrasonic studies of bone. IOP, Bristol, p 27
7. Hosie CJ, Smith DA, Deacon AD, Langton CM (1987) Comparison of broadband ultrasonic attenuation of the os calcis and quantitative computed tomography of the distal radius. Clin Phys Physiol Meas 8:303–308
8. Baran DT, Kelly AM, Karellas A, Gionet M, Price M, Leahey D, Steuterman S, McSherry B, Roche J (1988) Ultrasound attenuation of the os calcis in women with osteoporosis and hip fractures. Calcif Tissue Int 43:138–142
9. Rossman P, Zagzebski J, Mesina C, Sorenson J, Mazess R (1989) Comparison of speed of sound and ultrasound attenuation in the os calcis to bone density of the radius, femur and lumbar spine. Clin Phys Physiol Meas 10:353–360
10. McCloskey EV, Murray AS, Miller C, Charlesworth D, Tindale W, Odorherty DP, Bickerstaff DR, Hamdy NAT, Kanis JA (1990) Broadband ultrasound attenuation in the os calcis: relationship to bone mineral at other skeletal sites. Clin Sci 78:227–233
11. Porter RW, Miller CG, Grainger D, Palmer SB (1990) Prediction of hip fracture in elderly women: a prospective study. Br Med 7:638–641
12. Resch H, Pietschmann P, Bernecker P, Krexner E, Wilvonseder R (1990) Broadband ultrasound attenuation: a new diagnostic method in osteoporosis. AJR 155:825–828
13. Agren M, Karellas A, Leahey D, Marks S, Baran D (1991) Ultrasound attenuation of the os calcis: a sensitive and specific screening test for osteopenia in postmenopausal women. Calcif Tissue Int 48:240–244
14. Baran DT, McCarthy CK, Leahey D, Lew R (1991) Broadband ultrasound attenuation of the os calcis predicts lumbar and femoral neck density in caucasian women: a preliminary study. Osteoporosis Int 1:110–113
15. Zagzebski J, Rossman P, Mesina C, Mazess R, Madsen E (1991) Ultrasound transmission measurements through the os calcis. Calcif Tissue Int 49:107–111
16. Damikalis JE, Drekatis E, Gourtsoyiannis NC (1992) Ultrasound attenuation of the calcaneus in female population: normative data. Calcif Tissue Int 51:180–183
17. Truscott JG, Simpson M, Stewart SP, et al. (1992) Bone ultrasonic attenuation in women: reproducibility, normal variation and comparison with photon absorptiometry. Clin Phys Physiol Meas 13:29–36
18. Herd RJ, Ramalingham T, Ryan PJ, Fogelman I, Blake GM (1992) Measurements of broadband ultrasonic attenuation in the calcaneus in premenopausal and postmenopausal women. Osteoporosis Int 2:247–251
19. Glüer CC, Vhlensiek M, Faulkner KG, Engelke K, Black D, Genant HK (1992) Site-matched calcaneal measurements of broad-band ultrasound attenuation and single X-ray absorptiometry: Do they measure different skeletal properties? J Bone Miner Res 7:1071–1079
20. Waud CE, Lew R, Baran DT (1992) The relationship between ultrasound and densitometric measurements of bone mass at the calcaneus in women. Calcif Tissue Int 51:415–418
21. Shukla SS, Leu MY, Tighe T, Krutoff B, Craven JD, Greenfield MA (1987) A study of the inhomogeneity of the trabecular bone mineral density in the calcaneus. Med Phys 14:687–690
22. Langton CM, Ali AV, Riggs CM, Evans GP, Bonfield W (1990) A contact method for the assessment of ultrasonic velocity and broadband attenuation in cortical and cancellous bone. Clin Phys Physiol Meas 11:243–249
23. McCloskey E, Murray S, Charlesworth D, Miller C, Fordham J, Clifford K, Atkins R, Kanis J (1990) Assessment of broadband ultrasound attenuation in the os calcis in vitro. Clin Sci 78:221–225