A Comparison of Ultrasound and Computed Tomography in Evaluating the Mechanical Properties of Trabecular Bone

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This study compared ultrasound parameters and bone mineral density (BMD) in the assessment of the mechanical properties of trabecular bone. The BMD of bovine tibial trabecular bone specimens was measured by CT scanning each specimen in all three orthogonal directions. Similarly, ultrasound velocity and attenuation measurements were also made in these directions. Specimens were then divided into three groups for mechanical testing. The ultimate strength, Young's modulus and energy absorption were measured for each specimen. It was found that BMD was independent of trabecular orientation while ultrasound velocity and attenuation values were significantly higher in the superior/inferior (SI) direction corresponding to the load-bearing axis at stance. All mechanical properties were also significantly higher in the SI direction. The linear correlation demonstrated that ultrasound parameters, particularly ultrasound velocity, were better than BMD as predictors of compressive mechanical properties.

Key Words: BMD, Ultrasound Velocity, Ultrasound Attenuation, Trabecular Bone, Strength

1. Introduction

Osteoporosis is the reduction in bone mineral density due to the thinning and destruction of trabeculae, accompanied by decreased bone strength and increased fragility (Kleerekoper et al. 1985, Aaron et al. 1989). This disease affects an increasing number of the aged population, especially postmenopausal women. Detection and management of osteoporosis have increasingly become areas of concern. In an effort to evaluate bone status, a variety of diagnostic tools, mainly non-invasive densitometric techniques, have been developed. These include single/dual photon absorptiometry (SPA/DPA), dual energy X-ray absorptiometry (DEXA), and quantitative computed tomography (QCT). All of these methods are relatively expensive, require the use of ionizing radiation, and can only measure bone mineral density or content. Since the reduction in BMD due to osteoporosis causes a corresponding structural change in trabecular bone, the other qualitative factors of bone fragility should also be considered for proper assessment of fracture risk.

Recently, ultrasound technique has been introduced as a promising clinical tool for evaluating the condition of bone as it is inexpensive and radiation free, utilizes portable equipment, and provides information on trabecular bone morphology. The ultrasound velocity is related to the density and elastic modulus of material (Krautkramer et al. 1990, Langton and Evans 1991, Han 1998), while attenuation is dependent upon the structural parameters, including trabecular connectivity, separation and mean intercept length (Gluer et al. 1994; Han and Rho 1995). Many previous studies (McKelvie et al. 1989; McCloskey et al. 1990; Gluer et al. 1992; Massie et al. 1992) have often correlated ultrasound parameters with BMD acquired through the above traditional measurements. Trabecular bone is highly anisotropic and heterogeneous ; its strength in the SI direction where highly organized trabecular structures dominate is higher than in other directions. However, BMD is not able to reflect directional variation of bone prop-

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erties. On the other hand, ultrasound velocity and attenuation are influenced both by bone mass and by morphology (Gluer et al. 1994). It is, therefore, believed that application of ultrasound reflecting the trabecular structural properties might directly provide better assessment of bone fracture.

This study was undertaken to compare ultrasound parameters and bone mineral density by QCT in the assessment of various mechanical properties of trabecular bone. This would indicate whether ultrasound parameter provides its superiority to BMD by QCT in the prediction of bone fracture.

2. Materials and Methods

Forty-seven 8 mm cubic specimens were obtained from fresh bovine proximal tibiae. After the proximal subchondral bone plate was removed, three additional cuts were made using a band saw. The cubic specimens were then cut from these sections of 11 mm each. Three orthogonal axes of these specimens were aligned in superior/inferior (SI), medial/lateral (ML), and anterior/posterior (AP) directions.

The BMD of cubic specimens was measured by QCT. Prior to CT measurements, specimens were degassed under vacuum to remove air bubbles, and placed in water-filled Plexiglas® containers. Each specimen was scanned with 1.5 mm slices taken at 1.5 mm intervals at 120 kVp, 120 mA. The CT images were transferred to a Sun Sparc station 10 and analyzed using image analysis software (C-MED, Virtual Vision, Cupertino, CA). The raw CT values were then converted into Hounsfield units (HU). Each specimen was scanned three times by directing the beam into all three orthogonal directions in order to examine the directional effect on BMD measurement.

The ultrasound velocity was measured in a manner similar to that used in previous work by a pulse transit time approach (Lin et al. 1994). A pair of contact transducers with a center frequency of 0.5 MHz (Panametrics V101, Waltham, MA) was placed at opposite ends of the specimens (Fig. 1). The sonic velocities of each specimen were calculated from the thickness of specimen divided by the time delay of wave propagation measured directly from a digital storage oscilloscope (Tektronix 2232, Beaverton, OR).

In a measurement of ultrasound attenuation, a pulse transmission technique was used with a pair of broadband ultrasound immersion transducers having 0.5 MHz nominal center frequency (Panametrics V301). Identical transmitting and receiving transducers were mounted coaxially on opposite sides of a water-filled Plexiglas® tank and remained fixed (Fig. 2). In order to exclude the unattenuated signals passing alongside a spec-

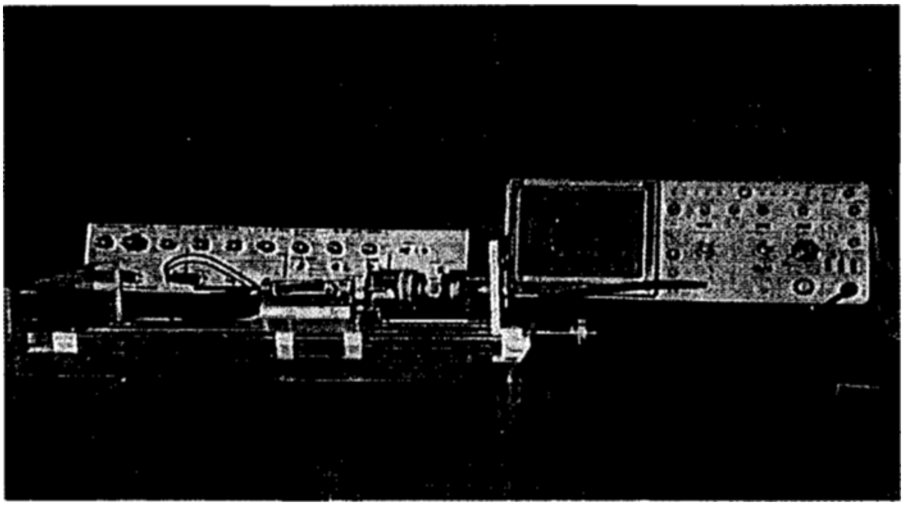

Fig. 1 Photograph of ultrasound velocity measurement apparatus.

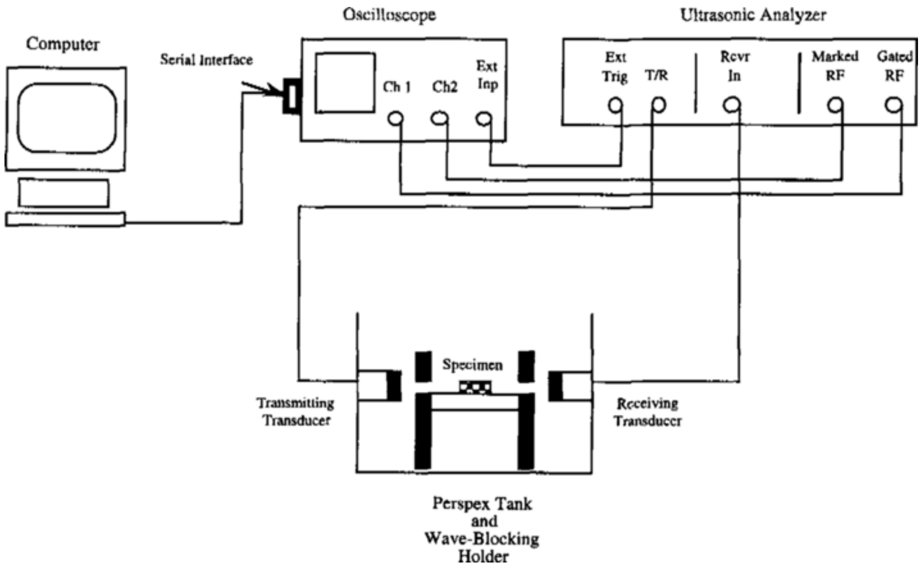

Fig. 2 Schematic diagram of the system for measurement of ultrasound attenuation.

imen, the wave-blocking holder with holes slightly smaller than the specimen was used, allowing the ultrasound propagation to pass through only two sides of the specimen, transmitter and receiver. Time-based signals captured by a oscilloscope were converted to the frequency domain using fast Fourier transformation (FFT). A spectrum obtained with a specimen in place was subtracted from a spectrum through water only and this difference in dB was plotted vs. frequency. Data were acquired via RS232C serial board interfacing with a micro computer (Macintosh IIci), and signal acquisition, plotting, and analysis were performed using a custom program written in LabVIEW (National Instruments, Austin, TX). The attenuation of ultrasound of each specimen was measured at the center frequency of transducers (0.5 MHz) and normalized by thickness of the specimen, which was found using a digital caliper. Measurements of ultrasound velocity and attenuation for each specimen were made in the three orthogonal directions.

Each specimen was loaded in uniaxial compression on an axial testing machine (MTS T22K) at a constant crosshead rate of 0.5 mm/min. Mechanical compressive load was applied to cubic specimen on self-leveling platens, which were used to minimize stress concentrations or bending in case the surfaces perpendicular to the loading direction were not perfectly parallel. Forty-seven specimens were divided into three groups : 16 for the first group, 15 for the second group, and 16 for the third group. The ultimate strength, Young's modulus, and absorbed energy were determined in the SI direction for the first group, in the ML direction for the second group, and in the AP direction for the third group. The energy absorbed by each bone specimen during mechanical loading to fracture was measured by digitizing the area under the stress-strain curve to the point of the maximum load using SIGMASCAN™ software (Jandel Scientific Corporation).

The various mechanical compressive properties were compared with ultrasound velocity and attenuation, as well as BMD. The relation in each of the three groups and for all specimens without grouping was respectively examined with linear regression analysis.

3. Results

The experimental data for BMD, ultrasound parameters, and mechanical properties are summarized in Table 1. The three directional BMD values of each cubic specimen, obtained in each of

Table 1 Summary of experimental results for BMD, ultrasound parameters and mechanical properties.

	Minimum	Maximum	Mean
BMD (HU)			
AP	316	880	484
ML	326	850	480
SI	320	901	477
Velocity (m/sec)			
AP	1864	2223	2066
ML	1849	2245	2068
SI	2327	3312	2853
Attenuation (dB/cm)			
AP	7.3	17.1	12.9
ML	8.9	15.9	11.4
SI	13.8	30.9	21.7
Strength (MPa)			
AP	2.0	9.4	6.2
ML	3.4	11.0	7.6
SI	5.5	38.3	21.0
Modulus (GPa)			
AP	0.11	0.67	0.33
ML	0.21	0.66	0.45
SI	0.28	2.85	1.46
Energy (KJ/m^3)			
AP	38	232	152
ML	80	349	198
SI	70	553	305

the AP, ML, and SI directions, showed that average BMD variation within specimen was 3.37% of mean BMD.

The ultrasound velocity of cubic specimens in the SI direction was higher than in the AP direction and in the ML direction. Similarly, the ultrasound attenuation in the SI direction was also higher than in the AP direction and in the ML direction.

The ultimate strength in the AP direction was somewhat less than that in the ML direction. However, bone strength in the SI direction was significantly higher than in the AP and ML directions. Similarly, the elastic modulus and energy absorption capacity in the SI direction were also higher than those in the AP direction and the ML direction.

To compare QCT and ultrasound in assessing mechanical properties of trabecular bone, BMD and ultrasound parameters were associated with Young's modulus and ultimate strength as well as energy absorbed. The correlation coefficients are shown in Table 2. All mechanical compressive properties were best correlated with ultrasound velocity and attenuation in the SI direction where a dominant structure exists. Ultrasound velocity was best in the predictability of ultimate strength and Young's modulus in the SI direction. The

Table 2 Coefficients of determination (r) from linear regression analysis applied between mechanical properties and ultrasound parameters plus BMD. "a"=$p<0.0001$, "b"=$p<0.05$, and "$*$"=$p>0.05$

	Direction	Number	BMD Via QCT	Ultrasound Velocity	Ultrasound Attenuation
Young's Modulus	AP	16	.471*	.501*	.349*
	ML	15	.464*	.346*	.423*
	SI	16	.878^{a}	.946^{a}	.783^{a}
	All	47	.706^{b}	.911^{a}	.847^{a}
Ultimate Strength	AP	16	.640^{b}	.611^{b}	.448^{b}
	ML	15	.633^{b}	.823^{b}	.501^{b}
	SI	16	.893^{a}	.932^{a}	.848^{a}
	All	47	.738^{b}	.910^{a}	.871^{a}
Absorbed Energy	AP	16	.486*	.449*	.250*
	ML	15	.387*	.747^{b}	.326*
	SI	16	.661^{b}	.716^{b}	.690^{b}
	All	47	.637^{b}	.727^{b}	.685^{b}

predictability of mechanical properties by ultrasound attenuation was not particularly better than that by BMD for any group. Nevertheless, attenuation was appreciably better correlated with Young's modulus and ultimate strength than BMD when all specimens were analyzed without grouping. Ultrasound velocity had the highest association with all mechanical properties when specimens were not grouped.

4. Discussion

The results showed the 3.37% average maximum BMD variation within a specimen, confirming that BMD measurements by QCT were independent of trabecular bone direction. This was consistent with the previous study where the measure of density contained no information concerning structural anisotropy (Gluer et al. 1994). On the other hand, the fact that ultrasound velocity and attenuation values were generally higher in the SI direction than in other directions was a strong indication that ultrasound could reflect structural properties. Gluer *et al.* (1994) evaluated BMD and ultrasound parameters in relation to bone structural parameters, trabecular thickness, connectivity, separation, and mean intercept length. In that study, BMD did not demonstrate any anisotropy, while structural parameters were explained by ultrasound velocity and attenuation. In fact, despite ultrasound parameters providing valuable information independent of BMD, many previous studies (Gluer et al. 1992; Massie et al. 1992; Lees and Stevenson 1993; Lin et al. 1994; Poet et al. 1994) in the field of osteoporosis have focused on obtaining a close relationship between ultrasound parameters and BMD. The results in this study showed that ultrasound velocity surpassed BMD in assessing all mechanical properties in the SI direction. However, although ultrasound attenuation has been known to reflect structural anisotropy of trabecular bone (Gluer et al. 1994), its ability to predict mechanical properties has been rather disappointing. This was probably due to the fact that the present wavelength was irrelevant in assessing trabecular bone property in relatively dense cancellous bone being examined (Serpe and Rho 1995). In general, two mechanisms can induce attenuation : scattering and absorption. In scattering, the amplitude of the propagating wave is diminished because some of the energy has been redirected. Scattering depends on the wavelength of the ultrasound signal and the acoustic properties of the medium. When sound waves pass from one medium into another, a certain amount of backscattering occurs in which some of the propagating wave is reflected back to the source. The more complex (i. e. acoustically heterogeneous) the material is, the more scattering there will be. Trabecular bone is a complex, heterogeneous material because it is composed of a trabecular framework and a liquid-like interior (i. e. bone marrow). Therefore, scattering and backscattering are highly active when an ultrasound wave propagates through it. An ultrasound wave undergoes absorption when a portion of the propagating wave's energy is converted to heat. The molecular composition of the material and the frequency of the ultrasound wave determine the level of absorption. Generally, the higher the wave frequency, the greater the absorption. In dense cancellous bone, the scattering effect of ultrasound waves on attenuation may be highly pronounced as a result of increased interaction of the sound waves with the trabecular structure. Thus, both bone mass and architecture govern ultrasound attenuation in a complicated way with the combined effect of absorption and scattering. Nevertheless, ultrasound attenuation was appreciably better than BMD in the prediction of mechanical properties when all specimens were analyzed without grouping. A better predictability of mechanical properties by ultrasound attenuation might be due to the fact that all specimens without grouping have more structural orientations than those in each of AP, ML and SI groups. In fact, it is meaningful that ultrasound parameters could discriminate the directional variation, which BMD was not able to do. This advantage of ultrasound motivated researchers to develop its technique for clinical application. Nevertheless, this study has inevitable drawbacks. Unlike bone *in vivo, in vitro* specimens contain damage of peripheral trabeculae due to machining even though extreme care was taken. This might lead to experimental errors in mechanical testing results. In addition, mechanical tests of bone strength might be affected by friction at the interface between the specimen and the platens (Keaveny *et al.*, 1993). Errors due to non parallel specimen faces were minimized by using swiveling platens.

The superior ability of ultrasound parameters to incorporate the trabecular architectural property should be considered in in vivo bone assessment. Current ultrasound techniques, however, limit direct measurements at the wrist, vertebrae, and femoral neck, which are frequently involved in osteoporotic fractures. Eventually, ultrasound techniques should be developed which can directly measure these bones by placing the probes at the sites of interest. Future studies also need to develop measurement technique in the load-bearing direction in vivo.

References

Aaron J., Johnson D., Paxton. S and Kanis J., 1989, "Secondary Osteoporosis and the Microanatomy of Trabecular Bone," *Clinical Rheumatology* Vol. 8, (S2) ; 84~88.

Gluer C., Vahlensieck M., Faulkner K., Engelke K., Black D. and Genant H., 1992, "Site-Matched Calcaneal Measurements of Broadband Ultrasound Attenuation and Single X-Ray Absorptiomerty." Do they Measure Different Skeletal Properties? J Bone and Min Res Vol. 72, 1071~1079.

Gluer C., Wu C. and Genant H. 1993, "Broadband Ultrasound Attenuation Signals Depend on Trabecular Orientation." An in Vitro Study. Osteoporosis Int Vol. 3, 185~91.

Gluer C., Wu C., Jergas M., Goldstein S. and Genant H. 1994, "Three Quantitative Ultrasound Parameters Reflect Bone Structure." Calcified Tissue Int Vol. 55, 46~52.

Grimm M. and Williams J. 1993, "Prediction of Young's Modulus in Trabecular bone with a Combination of Ultrasound Velocity and Attenuation Measurements." ASME Bioengineering Conference Vol. 24, 608~609.

Han S. and Kim M. 1998, "Ultrasound Attenuation in the Assessment of bone Mineral Density and Elastic Modulus of human Trabecular bone." J. of KOSOMBE Vol. 19(2), 171~176.

Han S. and Rho J. 1995, "Characteristics of Ultrasound Attenuation in the Assessment of Trabecular bone Property." 41th Annual Meeting ORS Orlando, Florida.

Kleerekoper M., Villanueva A., Stanciu J., Sudhaker Rao D. and Parfitt A. 1985, "The Role of Three-Dimensional Trabecular Microstructure in the Pathogenesis of Vertebral Compression Fractures." Calcified Tissue Int Vol. 37, 594~597.

Keaveny T., Borchers R., Gibson L. and Hayes W. 1993, "Theoretical Analysis of the Experimental Artifact in Trabecular bone Compressive Modulus." J Biomech Vol. 26(4/5), 599~607.

Krautkramer J. and Krautkramer H. 1990, "Ultrasonic Testing of Materials, 4th Ed, Springer Verlag, Berlin."

Langton C. and Evans G. 1991, "Dependence of Ultrasonic Velocity and Attenuation on the Material Properties of Cancellous Bone." Osteoporosis Int Vol. 1, 194.

Lees B. and Stevenson J. 1993, "Preliminary Evaluation of a new Ultrasound bone Densitometer." Calcified Tissue Int Vol. 53, 149~152.

Lin D., Ahmad H,. Xu W., Klein M., Siffert R. and Kaufman J. 1994, "Comparison of Ultrasonic Attenuation and Velocity for Estimating Vertebral Trabecular bone Density in Vitro." 40th Annual Meeting ORS, Vol. 438, New Orleans, Louisiana.

Massie A., Reid D. and Porter R. 1992, "Screening for Osteoporosis : Comparison Between Dual Energy X-ray Absorptiometry and BUA in 1000 Premenopausal Women." Osteoporosis Int Vol. 3, 107~110.

McCloskey E., Murray S., Miller C., Fordham J., Clifford K., Atkins R. and Kanis J. 1990, "Broadband Ultrasound Attenuation in the os Calcis : Relationship to bone Mineral at other Skeletal Sites." Clin Science Vol. 78, 221~225.

Mckelvie M., Fordham J., Clifford C. and Palmer S. 1989, "In Vitro Comparison of Quantitative Computed Tomography and Broadband Ultrasonic Attenuation of Trabecular bone." Bone Vol. 10, 101～104.

Poet J., Serabian I., Camboulives H., Dufour M. and Roux H. 1994, "Broadband Ultrasound Attenuation of the os Calcis : Preliminary study." *Clinical Rheumatology* Vol. 13 (2), 234～238.

Serpe L and Rho J., 1995, "The Nonlinear Dependence of Broadband Ultrasound Attenuation on Bone Mineral Density : An in vitro study." *41th Annual Meeting ORS*