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Ultrasonic Scattering from Cancellous Bone: A Review

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Abstract

This paper reviews theory, measurements, and computer simulations of scattering from cancellous bone reported by many laboratories. Three theoretical models (Binary Mixture, Faran Cylinder, and Weak Scattering) for scattering from cancellous bone have demonstrated some consistency with measurements of backscatter. Backscatter is moderately correlated with bone mineral density in human calcaneus *in vitro* ($r^2 = 0.66 - 0.68$). Backscatter varies approximately as frequency cubed and trabecular thickness cubed in human calcaneus and femur *in vitro*. Backscatter from human calcaneus and bovine tibia exhibits substantial anisotropy. So far, backscatter has demonstrated only modest clinical utility. Computer simulation models have helped to elucidate mechanisms underlying scattering from cancellous bones.

I. INTRODUCTION

Prospective [1–8] and retrospective [9–19] clinical trials have demonstrated that broadband ultrasound attenuation (BUA) (the slope of attenuation coefficient vs. frequency) and speed of sound (SOS) in calcaneus are very useful for diagnosis of osteoporosis. This clinical utility is supported by abundant pre-clinical data [20–57].

Ultrasonic scattering from bone has received less attention than BUA and SOS. However, the study of scattering is important for two reasons. First, it can elucidate mechanisms responsible for BUA, which is the combined result of absorption and scattering. (Scattering in general may include both longitudinal-to-longitudinal and longitudinal-to-transverse components.) Second, scattering measurements have shown diagnostic promise in their own right in studies *in vitro* [58–87] and *in vivo* [88–93]. Since measurement of backscatter may be performed with a single transducer in pulse-echo mode, it has the potential to be measured at sites other than the calcaneus, such as the hip and spine. Backscatter is known to provide information regarding size, shape, number density, and elastic properties of scatterers [94–99]. Cancellous bone contains many approximately cylindrically-shaped scatterers (trabeculae) and plate-like structures arrayed in a mesh. See Figure 1. The spaces between the trabeculae are filled with marrow (*in vivo*) or water (*in vitro*). Trabeculae are likely candidates for scattering sites due to the disparity in acoustic properties between mineralized trabeculae and the fluid filler. See Table I.

II. THEORETICAL MODELS

As shown in Figure 1, cancellous bone has an extremely complicated structure. Existing theoretical models of ultrasonic scattering from cancellous bone therefore rely on many simplistic assumptions in order to make the problem tractable. In spite of their simplicity, however, these models have shown considerable success in predicting aspects of scattering from cancellous bone. Scattering measurements from cancellous bone are often in the low ka regime where $k = 2\pi / \lambda$, λ = wavelength, a = radius = Tb.Th/2, and Tb.Th = trabecular thickness. For example, for interrogation of calcaneus (with mean Tb.Th of 0.127 mm [100]) at a typical diagnostic frequency of 500 kHz, $ka = 0.13$.

A. Binary Mixture Model

Strelitzki *et al.* proposed the Binary Mixture model in which the scattering coefficient is proportional to mean fluctuations in velocity and density [59, 65]. This approach has shown success in soft tissues [94]. Following the tradition of the application of the Binary Mixture model to soft tissues, Strelitzki *et al.* neglect density fluctuations. The predictions of the Binary Mixture model are consistent with the reported nonlinear dependence of BUA on porosity in cancellous bone [35]. The Binary Mixture model also predicts a quasi-linear dependence of attenuation due to scattering with frequency over a limited bandwidth for sufficiently small scatterers [65].

B. Faran Cylinder Model

Wear proposed the Faran Cylinder model, which regards trabeculae as solid cylinders embedded in fluid (marrow *in vivo* or water *in vitro*) [60]. See Figure 1. The cylinders (trabeculae) are assumed to be longer than the beam width. Faran's theory of scattering from cylinders is then used to predict scattering from trabeculae [95]. The model assumes that the trabeculae are positioned sufficiently randomly that the incoherent contribution to scattering dominates the coherent contribution. (In other words, the phase difference between scattered signals from pairs of cylinders is assumed to be uniformly distributed between 0 and 2π .) The model also ignores multiples scattering. When the cylinder diameter is much smaller than the wavelength, the Faran Cylinder model predicts that backscatter (and total scatter) should be approximately proportional to frequency cubed [60]. (The mean trabecular thickness in human calcaneus, about 127 microns [100], is much smaller than the wavelength at the typical diagnostic frequency of 500 kHz, about 3 mm, in the surrounding fluid.) The model also predicts that backscatter should be approximately proportional to trabecular thickness cubed [74].

C. Weak Scattering Model

Chaffai *et al.* and Jenson *et al.* proposed the Weak Scattering model, which is based on a random description of the scattering tissue [64]. Like the Binary Mixture model, the Weak Scattering model has shown much prior success in modeling scattering from soft tissues [96]. Structural autocorrelation functions may be measured from cancellous bone samples (e.g. using micro computed tomography, microCT) and used as inputs for the calculation of predicted backscatter coefficients. The weak scattering model requires small contrasts in acoustic properties (sound speed and density) between scatterers (i.e. trabeculae) and the

fluid filler (marrow *in vivo* or water *in vitro*) [97]. As with the Faran Cylinder model, the Weak Scattering model considers only the incoherent component of scattering [76]. Deligianni and Apostolopoulos extended the Weak Scattering model to a two-component form [98].

D. Comparison of Models

All three models are simplistic. All three ignore multiple and coherent scattering. It is instructive to consider the disadvantages and the advantages of the Faran Cylinder model compared with the other two. The main disadvantage of the Faran Cylinder model is that it assumes an idealized cylindrical geometry for cancellous bone. In reality, trabeculae can be somewhat jagged and curved, which means that they deviate from a true cylindrical shape. (However, as can be seen in Fig. 1, the extent of curvature is often minimal on the scale of an ultrasonic beam width—typically about 1 cm at 500 kHz.) In addition, cancellous bone can contain small plate-like structures and cross-struts between trabeculae. Scattering contributions from point-like (on the scale of an ultrasonic wavelength) plates and short cross-struts may explain measurements of backscatter coefficient that vary with frequency more rapidly than the cubic dependence predicted by the Faran Cylinder model (since scattering from structures small compared with the wavelength are proportional to frequency to the *fourth* power). The Binary Mixture and Weak Scattering models, with their statistical characterization of the cancellous bone, are more flexible in their ability to accommodate complex microstructure.

Advantages of the Faran Cylinder model include the following. 1) Unlike the Binary Mixture and Weak Scattering models, the Faran Cylinder model does not require that the acoustic properties (density and sound speed) within the two-component trabecular bone medium deviate only slightly from their mean values (spatial mean throughout the entire scattering volume). Although the true density and sound speed of trabeculae are not known with great certainty, they probably deviate substantially from density and sound speed of the fluid filler. See Table I, and note that the density and longitudinal sound speed of water and marrow are approximately 1 g/cm³ and 1480 m/s. Jenson *et al.* have acknowledged this limitation of the Weak Scattering model [76]. The Binary Mixture model actually neglects density fluctuations altogether. 2) Unlike the Binary Mixture and Weak Scattering models, the Faran Cylinder model allows for the propagation of shear waves within trabeculae. Shear wave propagation has been measured in cortical bone [99] and is therefore plausible within trabeculae. Simulation studies suggest, however, that shear waves within the trabecular network may play a negligible role in backscattering properties of cancellous bone [79]. 3) Unlike the Binary Mixture [59,65] and the Weak Scattering [76] models, the Faran Cylinder model does not require isotropy. Cancellous bone, particularly in weight-bearing bones like calcaneus, however, does exhibit some anisotropy (see Section III.E). Jenson *et al.* have also acknowledged this limitation of the Weak Scattering model [76].

III. EXPERIMENTAL RESULTS

A. Dependence of Backscatter on Bone Mineral Density

In the first investigation of ultrasonic backscatter from cancellous bone, Roberjot *et al.* found that integrated (average) backscatter coefficient exhibits a moderate correlation ($r^2 = 0.68$) with bone mineral density (BMD) *in vitro* (human calcaneus, 200 – 600 kHz) [58]. Subsequently, Wear and Armstrong found that that backscatter coefficient at 500 kHz exhibits a similar correlation *in vitro* ($r^2 = 0.66$) (human calcaneus) [62]. Hoffmeister *et al.* found apparent (not compensated for attenuation) integrated backscatter to decrease gradually (but with statistical significance) with BMD (bovine cancellous tibia, 1–3 MHz) [66]. The rate of decrease is even steeper at higher frequencies (bovine cancellous tibia, 2.5–7.5 MHz), resulting in higher magnitudes of correlation with BMD ($r^2 = 0.82$ in transverse orientation and $r^2 = 0.49$ in longitudinal orientation) [87].

B. Dependence of Backscatter on Frequency

Frequency-dependent backscatter may be measured by interrogating cancellous bone samples using broadband transducers. The average frequency-dependent backscatter coefficient, $\eta(f)$, may be fit to a power law form, $\eta(f) = Af^n$, and the exponent n (which is an index of frequency dependence) may be compared with theoretical models. The power law model for backscatter coefficient has intuitive appeal because the theoretical value for the exponent, n , is known in some simple limiting cases. For example, $n = 4$ for scatterers that are much smaller than a wavelength, and $n = 3$ for long cylinders that are much narrower than a wavelength (under some conditions). Generally speaking, n decreases as scatterer size increases (unless resonances complicate the situation).

Wear reported an average value of $n = 3.26 \pm 0.20$ (standard error) in human calcaneus (300–700 kHz), which is a little higher than the value of approximately 3 predicted by the Faran Cylinder model for thin cylinders over this frequency range [60, 73]. (As discussed in section V.A. and II.D., multiple scattering and scattering from small plates and cross-struts may explain this slightly elevated exponent). Subsequently, Chaffai *et al.* measured 3.38 ± 0.31 (standard error) in human calcaneus (0.4–1.2 MHz), which is close to the value of 3.48 predicted by the Weak Scattering model [64] for the samples in question over this frequency range. Padilla *et al.* measured 3.1 ± 1.09 (standard deviation) in human femur (0.4–1.2 MHz) [81], which is reasonably close to these values, given the accuracy and precision of the measurement. Deligianni and Apostolopoulos [98] achieved good agreement between theoretical predictions (based on a two-component Weak Scattering model) and experimental measurements of frequency-dependent backscatter in bovine cancellous bone but did not report their results in power-law form.

For the frequency ranges and mean trabecular thicknesses (Tb.Th) considered above, scattering may be considered to be primarily in the low ka regime where $k = 2\pi / \lambda$, λ = wavelength, and radius $a = \text{Tb.Th}/2$. Assuming a mean trabecular thickness of 0.127 mm in calcaneus [101], the frequency range from 300–700 kHz (λ in the surrounding fluid: 5.0 – 2.1 mm) corresponds to a ka range of 0.08 – 0.19 and the frequency range from 0.4 – 1.2 MHz (λ in the surrounding fluid: 3.8 – 1.3 mm) corresponds to a ka range of 0.11 – 0.32.

Assuming a mean trabecular thickness of 0.172 mm in femur [101], the frequency range from 0.4 – 1.2 MHz corresponds to a ka range of 0.14 – 0.43.

The measurements of backscattering power law exponent suggest that the Faran Cylinder and Weak Scattering models both predict the observed dependence of backscatter on frequency fairly well. (The Binary Mixture model has not been directly compared with experimental backscatter measurements). Because of 1) the limited accuracy and precision of experimental backscatter measurements (see Section III.F.), and 2) the uncertainty of the values for material properties of cancellous bone (see Table I), it is difficult, based on existing data, to conclude that either model performs superior to the other in this regard. Moreover, both models are sufficiently simplistic in their assumptions that neither one can be expected to model the physics extremely well. The accuracy and precision of experimental measurements are limited by many factors, including small sample size, inhomogeneous samples, speckle noise, phase cancellation, coherent effects, and multiple scattering. Therefore, the uncertainty of measurements of exponents in cancellous bone samples is probably at least a few tenths. The main conclusion to draw from the theory and data is that the true exponent for cancellous bone is probably near the 3.0 – 3.5 range. Both models are in reasonable agreement with this. Frequency-dependent backscatter coefficient model predictions and measurements for a human femoral cancellous bone sample (porosity = 94% and mean trabecular thickness = 134 microns, measured by microCT) are shown in Figure 2.

C. Dependence of Backscatter on Trabecular Thickness

The dependence of backscatter on trabecular thickness (Tb.Th) has potential diagnostic importance because a reduction in trabecular thickness would be expected to be associated with increased fracture risk and reduced backscatter coefficient. The backscatter coefficient at a particular frequency, $\eta(f_0, Tb.Th)$, may be fit to a power law form, $\eta(f_0, Tb.Th) = BTb.Th^m$, and the exponent m may be compared with theoretical models. The Faran cylinder model predicts the exponent m to be 2.9 [74]. Wear and Laib reported an average measurement of m of 2.80 (95% confidence interval: 1.7 – 3.9) (human calcaneus, 500 kHz) [74], where Tb.Th was assessed using microCT. The square of the correlation coefficient of a linear regression of log backscatter coefficient vs. log Tb.Th was 0.40, suggesting that 40% of variations in backscatter may be attributed to variations in Tb.Th [74].

The Weak Scattering model predicts scattering based on the autocorrelation function of the scattering medium. The width of the autocorrelation function is related to Tb.Th. Jenson *et al.* found the Weak Scattering model to yield good agreement between estimates of Tb.Th obtained directly from microCT ($130 \pm 6.5 \mu\text{m}$) and indirectly from ultrasound backscattering measurements ($138 \pm 6.5 \mu\text{m}$) (human calcaneus, 0.4–1.2 MHz) [76]. Subsequently, Padilla *et al.* found good agreement (microCT: $132 \pm 12 \mu\text{m}$; ultrasound: $134 \pm 15 \mu\text{m}$) (human femur, 0.4–1.2 MHz) [81, 86]. The square of the correlation coefficient of microCT-based and ultrasound-based estimates of Tb.Th was 0.44 [80, 84], a value very similar to that obtained in Faran-cylinder-model based study mentioned above (0.40) [74].

D. Dependence of Backscatter on Fluid Filler (Marrow or Water)

Most *in vitro* studies of the ultrasonic properties of cancellous bone involve defatted bone specimens immersed in water tanks. In these experiments, water *in vitro* substitutes for marrow *in vivo* as the fluid filler within the porous trabecular matrix. Nicholson and Bouxsein found a small but statistically significant 2.1 dB decrease in backscatter coefficient when water is substituted for marrow (water: -30.9 ± 6.3 dB; marrow: -28.8 ± 4.7 dB; human calcaneus, 600 kHz) [49]. (The statistical significance arose from the fact that 46 samples were measured in this study so that the standard errors were lower than the standard deviations by a factor of approximately seven.) Hoffmeister *et al.* found a small but statistically significant decrease of approximately 0.5 dB in apparent integrated backscatter when water is substituted for marrow (bovine tibia, 2.25 MHz) [71]. The magnitudes of these differences are fairly small, however, relative to the variations in backscatter associated with other factors such as BMD, frequency, and trabecular thickness. Therefore, experiments that substitute water for marrow are relevant to *in vivo* scattering.

E. Anisotropy of Backscatter

Although commercial bone sonometers interrogate calcaneus in the mediolateral (ML) orientation, calcaneus samples may be interrogated in multiple orientations *in vitro*. Wear found average backscatter coefficient to be 50% (1.8 dB) higher in the ML direction than in the anteroposterior (AP) direction (human calcaneus, 500 kHz) [61]. Backscatter coefficient in both orientations approximately conformed to a cubic dependence on frequency [61]. In the ML orientation, the ultrasound propagation direction is approximately perpendicular to the trabecular axes. In the AP orientation, a wide range of angles between the ultrasound propagation direction and trabecular axes is encountered. The higher backscatter in the ML direction may be due to the fact that the trabeculae are oriented in such a way to present the maximum cross sectional area available to intercept (and therefore, scatter) the incident ultrasound beam.

Hoffmeister found apparent integrated backscatter to be slightly higher in the ML direction (-33.9 dB) than in the AP (-34.3 dB) or superoinferior (SI) (-34.6 dB) directions (bovine tibia, 1–3 MHz) [66].

F. Precision of Backscatter Measurements

In order to appreciate the limitations of comparisons between theoretical predictions and experimental measurements of scattering from cancellous bone, it is important to understand measurement precision. Cancellous bone, like soft tissues, contains a complicated arrangement of densely-packed scatterers (trabeculae) that produce highly variable scattered signals, depending on the extent to which echoes from individual scatterers interfere constructively or destructively. The resulting interference pattern, which gives rise to speckle in medical ultrasound images, produces wide fluctuations in scattering measurements. For example, Chaffai *et al.* reported a wide variation of measurements of the exponent, n , of frequency dependence of power law fit (see Section III.B) from individual human calcaneus samples (ranging from 2.76 to 3.86) [64]. However, Chaffai *et al.* could not be certain whether the variation was attributable to micro-architectural variations or to random interference effects [64].

In order to investigate the relative roles of micro-architectural variations and random interference effects, Wear adapted a model developed by Lizzi *et al.* [108] to predict statistical fluctuations in midband backscatter coefficient and n in human calcaneus [67]. The model of Lizzi *et al.* is appropriate for scattering media (such as cancellous bone) that contain many scatterers per resolution cell. It accounts for the random interference of echoes (speckle) from individual scatterers (e.g. trabeculae) as they are summed at the receiver. Wear showed that while random interference effects only partially explain measured variations in the midband (or average) backscatter coefficient, they are virtually *entirely* responsible for observed variations in n (human calcaneus, 500 kHz) [67]. Consequently, measurements of n in individual human calcanea at diagnostic frequencies provide little or no diagnostic information. (In other words, it is far more difficult to estimate n from noisy backscatter measurements on individual calcanea than from average backscatter measurements obtained from large numbers of samples as discussed in Section III.B.)

G. Clinical Findings

Backscatter is interesting from a clinical standpoint because it can be measured with a single transducer and therefore may be potentially extended beyond the calcaneus to other sites in the skeleton such as the hip and spine. So far, only modest clinical success has been reported for backscatter, however. This may be due to high variability of backscatter measurements due to speckle noise [67] and the distorting effects of rough cortical bone surfaces.

Wear and Garra found a moderate correlation ($r^2 = 0.76$) between ultrasonic backscatter and bone mineral density (BMD) assessed using x-ray computed tomography (CT) (normal human volunteers, calcaneus, 2.25 MHz) [88, 91]. In the most definitive clinical investigation (the only one measuring fracture risk) involving backscatter, Roux *et al.* found broadband ultrasonic backscatter to be moderately predictive of fracture (odds ratio: 1.58; 95% CI: 1.14–2.19) (210 women, calcaneus, 200–600 kHz) [92]. Wear and Armstrong found modest correlations between average backscatter coefficient, BUA, SOS, and age (women, calcaneus, 1 MHz) [93]. Wear *et al.* reported a modest correlation ($r^2 = 0.37$) between the backscatter spectral centroid shift and BMD (human spine, 2.5 MHz) [72].

IV. SIMULATION RESULTS

Simulations have been useful for complementing theoretical and experimental approaches in the investigation of scattering of ultrasound by cancellous bone. Luo *et al.* implemented a 2D simulation of ultrasound propagation that solved the 2D visco-elastic wave equation [46]. In an extension of this work, Kaufman *et al.* [83]—using slices from digitized 3D micro-tomographs of a human cancellous calcaneus sample to represent the 2D distribution of material properties in a simulation—analyzed two cases for a through-transmission measurement over the range from 300 to 900 kHz: 1) with full accounting for viscous absorption losses, and 2) with all viscous loss terms set to zero. They found attenuation to be similar in both cases, and argued that scattering may therefore be the main source of attenuation for simple 2D situations.

Bossy *et al.* [79] subsequently implemented a finite-difference time-domain (FDTD) algorithm to compute a numerical solution for 3D linear elastic wave propagation through

cancellous bone specimens immersed in water. They used digitized 3D synchrotron microtomographs of cancellous bone samples (31 human femur specimens) to represent 3D distributions of material properties in their simulations. Their algorithm accounted for reflection, refraction, and mode conversion at bone interfaces. Although their algorithm did not take absorption into account, their simulations reproduced major phenomena consistent with widely-accepted experimental findings: 1) the quasi-linear variation of attenuation with frequency, 2) the monotonic increase of BUA and SOS with bone volume fraction, and 3) negative velocity dispersion [79]. Subsequent extensions of this work by Padilla *et al.* [84] and Haïat *et al.* [85] reinforced the initial findings of Bossy *et al.* [79]. In another recent extension, Bossy *et al.* provided evidence that for human cadaver femur cancellous bone specimens, absorption may be the primary source of attenuation at low frequencies (below approximately 600 kHz for average specimens) while scattering may be the primary source of attenuation at high frequencies (above approximately 600 kHz) [109]. This would suggest that absorption is the primary source of attenuation throughout most of the diagnostic range (300 – 700 kHz). They further argued that the importance of absorption may increase with volume fraction. Bossy *et al.* suggested that mode-conversion from longitudinal to shear could be a significant form of scattering in these simulations [79].

V. DISCUSSION

A. Multiple Scattering

Multiple scattering, if present, would have the effect of applying additional high-pass filtering to scattered waves (since scattering coefficient increases rapidly with frequency). This would increase the measured exponent (n) of frequency dependence of scattering. Since measurements of n only slightly exceed the single-scattering Faran Cylinder model prediction, multiple scattering does not seem to play a big role in typical scattering measurements [60]. The reasons for this may be as follows. The magnitude of the scattering coefficient from individual trabeculae and the number of trabeculae per unit volume may be sufficiently low to marginalize the importance of multiple scattering. In addition, multiple-scattered waves, if present, would experience greater attenuation than singly scattered waves because 1) attenuation coefficient is directly proportional to frequency and multiple-scattered wave spectra tend to have higher frequency content (due to having experienced multiple high-pass filters) than single-scattered waves, and 2) attenuation increases with path length and multiple-scattered waves tend to traverse longer paths than single-scattered waves [60]. Chaffai *et al.* [64] and Jenson *et al.* [75], based on their Weak Scattering theory and experimental data, agreed that multiple-scattered waves are probably negligible in typical scattering measurements. Recent work by Haïat *et al.*, however, suggests that multiple scattering effects can help explain negative velocity dispersion in cancellous bone [110].

B. Absorption and Scattering

Attenuation is the combined result of absorption and scattering. While attenuation in cancellous bone is approximately proportional to frequency to the *first* power [20–56], backscatter coefficient is approximately proportional to frequency to the *third* power (in the diagnostic frequency range, 300 – 700 kHz) [60]. Moreover, the Faran Cylinder model predicts that *total scatter*, not just *backscatter*, should be approximately proportional to

frequency to the *third* power [60]. Even without the Faran Cylinder model, it is difficult to imagine a circumstance that would lead to *cubic* backscatter (scattering at 180 degrees) and *linear* total scatter (the integral of scattering coefficient over all solid angles). This inconsistency of frequency dependencies for attenuation and scattering led Wear to suggest that scattering may be only a minor contribution to attenuation at diagnostic frequencies [60]. Chaffai *et al.* subsequently agreed with this [64]. Wear further suggested [60] (and Chaffai *et al.* agreed [64]) that this inconsistency of frequency dependencies implied that absorption may be the primary source of attenuation. Padilla and Laugier subsequently proposed a weak scattering / poroelasticity model that also suggested that absorption was the primary source of attenuation [68]. However, since scattering measurements were limited to *longitudinal-to-longitudinal* scattering, this conclusion may have been somewhat premature since the relative importance of *longitudinal-to-shear* conversion was not fully appreciated at that time. Recent simulation work has suggested that the conversion of incident longitudinal waves into scattered shear waves may be significant [79, 84, 85, 109], but would only exceed absorption loss at high frequencies (above approximately 600 kHz) [109] (see Section IV), which are at the high end of the diagnostic range (300 to 700 kHz). Measurements of attenuation from 1 to 10 MHz in phantoms consisting of graphite fibers suspended in gelatin have shown the combined result of classical viscous loss within the gelatin and scattered evanescent shear waves to produce an approximately linear frequency dependence of attenuation [111] (consistent with theoretical predications [112]) *parallel* to the fibers and a somewhat higher than linear frequency dependence of attenuation *perpendicular* to the fibers (which is orientation in which scattering measurements on cancellous bone have been performed). See Ref. [111], Figure 8.

Recent simulations [79, 83–85, 109] modeled through-transmission experiments and did not explore the immediate fate of shear wave energy scattered from trabeculae. Regardless of whether the redirected shear wave energy persists as an ultrasound wave or is absorbed by the cancellous bone medium, it would elude the receiving transducer in simulated through-transmission experiments. Although shear waves may arise from mode conversion at trabecular interfaces, they may be extremely transient. For example, Hosokawa estimated shear attenuation coefficients in bovine cancellous bone to be approximately 17 dB/mm (at 1 MHz) [113], implying that shear wave power is reduced by approximately 98% for each mm of propagation. Similarly, Mottley and Miller described shear waves generated from graphite particles suspended in gelatin as “evanescent” [111]. Like the multiple-scattered wave discussed above, the mode-converted shear wave may have transient significance in the immediate proximity of the scatterer, but due to high attenuation it is rapidly extinguished. If longitudinal-to-shear mode conversion is significant, then the relative roles of absorption and scattering in cancellous bone (even at high frequencies, above 600 kHz) will depend somewhat on the relative roles of absorption and scattering of mode-converted shear waves. If the rapid attenuation of mode-converted shear waves is primarily due to absorption, then absorption would be the dominant loss mechanism even at high frequencies, albeit with the caveat that the ultrasonic energy briefly takes the form of a very short-lived shear wave prior to absorption. More research is needed in this area.

VI. CONCLUSION

Pulse-echo data has been acquired from cancellous bone samples *in vitro* to probe the dependence of ultrasonic backscatter on bone mineral density, frequency, mean trabecular thickness, fluid filler (marrow or water), and direction of ultrasound propagation relative to the predominant trabecular orientation. Three theoretical models for scattering from cancellous bone have demonstrated some consistency with experimental observations. So far, backscatter has demonstrated only modest clinical utility. Computer simulation models have helped to elucidate mechanisms underlying scattering from cancellous bones.

The Binary Mixture, Faran Cylinder, and Weak Scattering models are useful for prediction of scattering properties of cancellous bone. Because of 1) the limited accuracy and precision of experimental measurements of ultrasound backscatter and 2) the uncertainty of the values for material properties of cancellous bone, it is difficult, based on existing data, to conclude that one model performs superior to the others. Moreover, all three models are sufficiently simplistic in their assumptions that none can be expected to model the physics extremely well. The accuracy and precision of experimental measurements are limited by many factors, including small sample size, inhomogeneous samples, speckle noise, phase cancellation, coherent effects, and multiple scattering.

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Biography

Keith A. Wear graduated from the University of California at San Diego with a B.A. in Applied Physics in 1980. He received his M.S. and Ph.D. in Applied Physics with a Ph.D. minor in Electrical Engineering from Stanford University in 1982 and 1987.

He was a post-doctoral research fellow with the Physics department at Washington University, St. Louis from 1987–1989. He has been a research physicist at the FDA Center for Devices and Radiological Health since 1989. His research has included measurements of ultrasonic scattering properties from tissues, high-resolution spectral estimation, magnetic resonance spectroscopic image reconstruction methods, analysis of statistical properties of ultrasonic echoes from tissues, and improved measurement methodology in bone sonometry.

He is an adjunct professor of Radiology at Georgetown University. He is a Fellow of the American Institute for Medical and Biological Engineering (AIMBE) and the American Institute of Ultrasound in Medicine (AIUM). He is a senior member of IEEE. He is a member of the Acoustical Society of America, IEEE Ultrasonics Society, the National Osteoporosis Foundation and the AIUM Technical Standards Committee. He served as Vice-Chairman (2002–2004) and Chairman (2004–2006) of the AIUM Basic Science and

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1. Micro computed tomogram of calcaneus. Some trabeculae appear to terminate as they move into and out of the imaging plane. Image acquired by Andres Laib, Scanco Medical AG, Brüttisellen, Switzerland.

2.

Frequency-dependent backscatter coefficient measurements from human femoral cancellous bone specimen. Model predictions are also shown. Experimental measurements and the Weak Scattering model predictions were provided by Pascal Laugier and Frederic Padilla from the University of Paris.

Table I.

Material properties of bone and bone-like substances. The parameters listed are longitudinal sound velocity (c_l), shear velocity (c_s), density (ρ) and Poisson's ratio (ν). Note that the values for cancellous bone refer to only to the trabecular component, not to the composite medium consisting of the trabecular matrix filled with either marrow (*in vivo*) or water (*in vitro*).

Reference	Substance	c_l (m/s)	c_s (m/s)	ρ (g/cc)	ν
Hosokawa & Otani, [40]	Bovine cancellous bone	3800	2000	1.95	0.32
Anderson <i>et al.</i> , [102]	Hydroxyapatite	6790		3.22	0.28
Luo <i>et al.</i> , [45]	Cortical bone	2900	1303	1.85	
Gong <i>et al.</i> , [103]	Bovine cancellous bone			1.93	
Lang <i>et al.</i> , [104]	Bovine cortical bone			1.96	0.32
Williams, [105]	Bovine cancellous bone	3800 *			
Rho <i>et al.</i> , [106]	Bovine cancellous bone	2898±85			
Ashman <i>et al.</i> , [107]	Human cancellous bone	2639–2754		1.73–1.80	
-	Bovine cancellous bone	2501		1.74	
Grenoble <i>et al.</i> , [99] †	Powdered human femur	3917	2020		0.33
-	Fresh bovine femur	4890	2495		0.34
-	Hydroxyapatite (mineral)	5565	4765		0.27
-	Hydroxyapatite (synth.)	5628	4818		0.28

* Extrapolated (to zero porosity) from bulk measurements over a range of porosities (where porosity is the volume fraction of marrow). See (J. L. Williams, 1992), figure 2.

† Assuming $\rho = 1.96$ gm/cc.