Effect of intervening tissues on ultrasonic backscatter measurements of bone: An *in vitro* study

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Ultrasonic backscatter techniques are being developed to diagnose osteoporosis. Tissues that lie between the transducer and the ultrasonically interrogated region of bone may produce errors in backscatter measurements. The goal of this study is to investigate the effects of intervening tissues on ultrasonic backscatter measurements of bone. Measurements were performed on 24 cube shaped specimens of human cancellous bone using a 5 MHz transducer. Measurements were repeated after adding a 1 mm thick plate of cortical bone to simulate the bone cortex and a 3 cm thick phantom to simulate soft tissue at the hip. Signals were analyzed to determine three apparent backscatter parameters (apparent integrated backscatter, frequency slope of apparent backscatter, and frequency intercept of apparent backscatter) and three backscatter difference parameters [normalized mean backscatter difference (nMBD), normalized slope of the backscatter difference, and normalized intercept of the backscatter difference]. The apparent backscatter parameters were impacted significantly by the presence of intervening tissues. In contrast, the backscatter difference parameters were not affected by intervening tissues. However, only one backscatter difference parameter, nMBD, demonstrated a strong correlation with bone mineral density. Thus, among the six parameters tested, nMBD may be the best choice for *in vivo* backscatter measurements of bone when intervening tissues are present. © 2015 Acoustical Society of America.

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I. INTRODUCTION

The human and economic costs of fractures associated with osteoporosis are predicted to increase as the population ages.^{1–3} The diagnosis of osteoporosis is based mainly on the results of dual energy x-ray absorptiometry (DXA) testing, which evaluates bone mineral density (BMD) at a number of skeletal sites. Ultrasonic techniques also can be used to estimate bone density and predict fracture risk. Devices called bone sonometers operate by propagating ultrasonic pulses through bones or along bones to measure ultrasonic attenuation and/or the speed of sound (SOS). In their current form, however, bone sonometers have not been shown to provide improved diagnostic information compared to that provided by DXA. In addition, bone sonometers cannot be used at central skeletal sites, such as the hip and spine, where approximately two-thirds of osteoporotic fractures occur.⁴

Techniques based on measurements of ultrasonic backscatter have been proposed as a better approach for ultrasonic bone assessment. Backscatter techniques may facilitate easier access to central skeletal sites because they use a single ultrasonic transducer to transmit and receive ultrasonic signals. Indeed, a number of backscatter studies

have been performed at the hip and spine of human volunteers.^{5–8} Backscatter occurs as an ultrasonic wave interacts with the trabecular microstructure of cancellous bone. The conventional approach is to measure the backscatter coefficient or the frequency averaged backscatter coefficient from cancellous bone.^{9–32} However, to measure the backscatter coefficient one must know the ultrasonic attenuation, SOS, and thickness of all tissues along the propagation path of the signal. Such measurements are difficult to perform *in vivo* with a single transducer, especially at central skeletal sites.

Some investigators have proposed using apparent backscatter parameters such as apparent integrated backscatter (AIB) and the frequency slope of apparent backscatter (FSAB) because they do not require knowledge of the ultrasonic properties of the tissues through which the signals propagate. The term “apparent” means that the backscattered power is not corrected for the effects of attenuation and diffraction. The utility of AIB and FSAB as bone assessment parameters has been demonstrated in numerous studies, which have shown these parameters to correlate with the microstructural characteristics, mechanical properties, density, and tissue composition of cancellous bone.^{7,16,33–41}

Measurements at central skeletal sites, such as the hip and spine, are complicated by the presence of intervening tissues that lie between the ultrasonic transducer and the ultrasonically interrogated region of bone. The amount of

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intervening tissue can be substantial and can vary significantly between individuals. Intervening tissues include skin, fat, muscle, the bone cortex, and also cancellous bone tissue that lies between the transducer and the region of interest. Intervening tissues can distort the ultrasonic wave fronts and cause phase cancellation errors. In addition, reflection losses and attenuation losses can reduce the power in the backscatter signal and change its frequency dependence, thus affecting apparent backscatter parameters, such as AIB and FSAB, which do not account for these effects. Indeed, a recent study found that the bone cortex at the femoral head decreased AIB by 6 dB and FSAB by 3 dB/MHz on average.³⁴

Thus, intervening tissues represent a significant challenge to the clinical implementation of backscatter techniques of ultrasonic bone assessment. In principle, the backscatter coefficient can be corrected for the effects of intervening tissues, but in practice this is difficult to do because the thicknesses and the ultrasonic properties of the intervening tissues must be measured or known. This is especially challenging for *in vivo* measurements at central skeletal sites such as the hip and spine. Apparent backscatter parameters, such as AIB and FSAB, are more convenient for *in vivo* applications, but intervening tissues may produce errors in these parameters.

The solution to the problem of intervening tissues may come in the form of a backscatter difference technique that was introduced recently for bone assessment purposes.⁴² The technique compares the power difference (in dB) between two different portions of the same backscatter signal from bone. Similar techniques were developed to estimate the ultrasonic attenuation of human liver *in vivo*.^{43–46} Theoretical predictions indicate that the effects of intervening tissues will cancel when the power difference is computed. Two parameters based on this technique, the normalized mean backscatter difference (nMBD) and the normalized slope of the backscatter difference (nSBD) have demonstrated moderate to strong correlations with bone density.^{40,42} However, the sensitivity of these parameters to the effects of intervening tissues has not been tested.

The goal of the present study is to investigate the effects of intervening tissues on six different bone assessment parameters. Three parameters are based on the power difference between two gated portions of the backscatter signal: nMBD, nSBD, and normalized intercept of the backscatter difference (nIBD). The other three parameters are based on the apparent backscattered power from a single gated portion of the backscatter signal: AIB, FSAB, and frequency intercept of apparent backscatter (FIAB).

II. EXPERIMENTAL METHODS

A. Specimen preparation

A total of 24 cube shaped specimens of cancellous bone were prepared from the distal ends of five human femurs. Donor information is provided in Table I. A band saw was used to cut the specimens in the shape of cubes with side lengths of 12.5 mm. Specimens were oriented such that the axes of the cube were aligned with the anatomic axes of the

TABLE I. Donor information.

Donor ID number	Number of specimens	Age	Gender
1	4	51	Male
2	7	33	Male
3	4	48	Male
4	3	67	Female
5	6	56	Female

femur: superior–inferior, medial–lateral, and anterior–posterior. A water jet was used to remove as much marrow as possible from the intertrabecular spaces.

Two types of intervening tissue were prepared for this study. A 15 mm × 15 mm by 1 mm thick plate of cortical bone was prepared from a bovine tibia to simulate the bone cortex. The 1 mm thickness approximates the normal thickness of the bone cortex at the hip (proximal femur).⁴⁷ Soft tissues were simulated with a tissue mimicking phantom (TMP) fabricated from 300 ml of water, 27 g of graphite powder, 25 ml of 1-propanol, 9 g of agar, and 0.375 g of methylparaben. After mixing and heating to 85° C, the material was degassed and poured into cylindrical molds 2 cm in diameter and 3 cm long. The 3 cm length approximates the average thickness of soft tissue at the hip.^{48,49}

B. DXA measurements

DXA measurements were performed on the specimens of cancellous bone to measure their BMD. The specimens were scanned using a Hologic (Bedford, MA) model QDR 87157 running a small animal software package. BMD was determined from a 9.5 mm × 9.5 mm region of interest (ROI) centered on the specimen. All six sides of each specimen were scanned, and the resulting BMD values were averaged to obtain a single BMD measurement for each specimen.

C. Ultrasonic backscatter measurements

Cancellous bone specimens were placed on the bottom of a water filled tank after being degassed under vacuum. Ultrasonic backscatter measurements were performed using a broadband 5 MHz transducer (Panametrics V309, Waltham, MA) with an 80 mm focal length and 1.9 mm beam diameter. The transducer was mounted to the end of a vertical arm connected to a three axis mechanical scanner (Sonix, Springfield, VA) that was used to scan the transducer over the specimen with the focal point positioned at the front surface of the cancellous bone specimen. The transducer was connected to an ultrasonic pulser/receiver (Panametrics model 5800), and the received signals were digitized by an 8 bit analog to digital converter (Sonix STR*8100) operating at 500 MSa/s. Backscatter signals were analyzed from an 8 mm × 8 mm, 40 point by 40 point ROI centered on the specimen. Measurements were performed along four directions (medial, lateral, anterior, and posterior). In total, backscatter signals were acquired from 6400 sites on each specimen. Backscattered signals were digitized from each site of the scan and saved for analysis.

Measurements were repeated for two different configurations of intervening tissue. For one configuration, the cortical plate was situated between the transducer and cancellous bone specimen. For the other configuration, the TMP and cortical plate were both situated between the transducer and cancellous bone specimen as shown in Fig. 1. Figure 2 shows echoes and backscatter returned from the tissue configuration shown in Fig. 1.

D. Signal analysis

The backscatter signals were analyzed to determine six backscatter parameters: AIB, FSAB, FIAB, nMBD, nSBD, and nIBD. The first three parameters are related to the power in a single gated portion of the backscatter signal as shown in Fig. 3(a). Analysis was performed using a $4\text{ }\mu\text{s}$ wide gate delayed $2\text{ }\mu\text{s}$ from the start of the signal to avoid the large specular echo that is produced by the front surface of the specimen. A power spectrum $P_b(f)$ was obtained from the gated portion of the backscatter signal from the bone specimen. A reference spectrum $P_r(f)$ was obtained from a polished steel plate. The spectra were converted to dB and subtracted to obtain the apparent backscatter transfer function (ABTF)

$$\text{ABTF} = 10 \log_{10} P_b(f) - 10 \log_{10} P_r(f). \quad (1)$$

AIB was determined by frequency averaging the ABTF over the frequency range chosen for analysis. FSAB and FIAB were determined from the slope and intercept, respectively, of a line fitted to the ABTF over the same frequency range.

nMBD, nSBD, and nIBD are based on the power difference between two gated portions of the backscatter signal as shown in Fig. 3(b). Analysis was performed using $2\text{ }\mu\text{s}$ wide gates. The start of the first gate was delayed $2\text{ }\mu\text{s}$ from the start of the signal. Power spectra $P_1(f)$ and $P_2(f)$ were obtained from the first and second gated portions of the signal, respectively. The spectra were converted to dB and

FIG. 1. Configuration of intervening tissues. Measurements were performed for three configurations: no intervening tissue, cortical plate only, cortical plate and TMP.

FIG. 2. A signal showing echoes and backscatter returned from the tissue configuration shown in Fig. 1. Features indicated by asterisks were produced by water path reverberations between the tissues and transducer. Tissues were positioned so that no reverberations were located in the analyzed portion of the backscatter signal from cancellous bone shown.

subtracted to obtain the difference spectrum $D(f)$. The difference spectrum was divided by the time between the centers of the two gates, τ , to obtain a normalized difference spectrum $nD(f)$,

$$nD(f) = [10 \log_{10} P_1(f) - 10 \log_{10} P_2(f)] / \tau. \quad (2)$$

The normalization procedure removes the effect of gate choice as described previously.⁴² nMBD was determined by frequency averaging $nD(f)$ over the frequency range chosen for analysis. nSBD and nIBD were determined from the slope and intercept, respectively, of a line fitted to the normalized difference spectrum $nD(f)$ over the same frequency range. The analysis of the backscatter difference parameters is analogous to the analysis of the apparent backscatter parameters AIB, FSAB, and FIAB, which are determined from

FIG. 3. Typical backscatter signal from cancellous bone showing the location of gates used to determine (a) the apparent backscatter transfer function (ABTF) and backscatter parameters AIB, FSAB, and FIAB, and (b) the normalized backscatter difference spectrum $[nD(f)]$ and backscatter difference parameters nMBD, nSBD, and nIBD.

the mean, slope, and intercept of the ABTF, respectively. Table II summarizes how each backscatter parameter was determined.

The apparent backscatter parameters (AIB, FSAB, and FIAB) were analyzed over the same frequency range. The frequency range was determined according to the following procedure. Individual spectra $P_b(f)$ were acquired from every measurement site on every specimen for all three configurations of intervening tissue (none, cortical only, cortical plus 3 cm TMP), and were converted to decibels and averaged to obtain a single representative spectrum. The resulting -10 dB bandwidth was 1.3–5.0 MHz. This bandwidth was used as the frequency range of analysis for AIB, FSAB, and FIAB. The backscatter difference parameters nMBD, nSBD, and nIBD were analyzed over a frequency range that was determined using a similar procedure. Individual spectra $P_1(f)$ and $P_2(f)$ were acquired from every measurement site on every specimen for all three configurations of intervening tissue (none, cortical only, cortical and 3 cm TMP), converted to decibels and averaged to obtain two spectra representative of the spectrum from the first and second gated portions of the signal. The -10 dB bandwidth was determined for each spectrum. The frequency range overlapped by the two bandwidths, 1.2–4.7 MHz, was used as the frequency range for analysis.

E. Ultrasonic characterization of the TMP

SOS and normalized broadband ultrasonic attenuation (nBUA) were determined for the TMP using a shadowed reflector technique. A polished stainless steel plate was placed at the focal point of the transducer and aligned perpendicular to the beam. Echoes from the steel plate were acquired with and without the TMP resting on the steel plate. These two configurations are referred to as “shadowed” and “unshadowed,” respectively. SOS was determined according to

$$\text{SOS} = v_w \left(\frac{t_u - t_f}{t_s - t_f} \right), \quad (3)$$

where t_u is the time-of-flight of the unshadowed echo from the steel plate, t_s is the time-of-flight of the shadowed echo

TABLE II. Definition of backscatter parameters measured in this study. $P_b(f)$ is the power spectrum of the gated portion of the backscatter signal shown in Fig. 3(a). $P_r(f)$ is the power spectrum of an echo from a polished steel plate used as a reference reflector. $P_1(f)$ and $P_2(f)$ are power spectra of the first and second gated portions of the backscatter signal, respectively, as shown in Fig. 3(b).

Parameter	Definition
ABTF	$\text{ABTF} = 10 \log_{10} P_b(f) - 10 \log_{10} P_r(f)$
nD(f)	$\text{nD}(f) = [10 \log_{10} P_1(f) - 10 \log_{10} P_2(f)]/\tau$
AIB	AIB = frequency averaged ABTF
FSAB	FSAB = slope of ABTF
FIAB	FIAB = intercept of ABTF
nMBD	nMBD = frequency averaged nD(f)
nSBD	nSBD = slope of nD(f)
nIBD	nIBD = intercept of nD(f)

from the steel plate, t_f is the time-of-flight of the echo from the front surface of the TMP, and v_w is the SOS in water. The SOS in water was determined as a function of temperature using a fifth order polynomial expression.⁵⁰

To determine the nBUA, a 2 μ s gate was centered on the shadowed and unshadowed echo and a Hamming window applied. Power spectra $P_s(f)$ and $P_u(f)$ were obtained from the shadowed and unshadowed signals, respectively. nBUA was determined from the frequency slope of the attenuation coefficient

$$\alpha(f) = [10 \log_{10} P_u(f) - 10 \log_{10} P_s(f)]/2L, \quad (4)$$

where L is the length (i.e., thickness) of the TMP. The slope was determined over the linear portion of $\alpha(f)$, which was 1.3–4.7 MHz.

III. RESULTS

A. TMP

The following values were obtained for the TMP: SOS = 1505 m/s, nBUA = 0.85 dB/cm/MHz. Both values fall within the range of accepted values for soft tissues such as muscle and fat: SOS = 1450–1630 m/s, nBUA = 0.5–1.5 dB/cm/MHz.⁵¹

B. BMD

The DXA derived BMDs of the specimens of cancellous bone used in this study ranged between 0.13 and 0.71 g/cm².

C. Ultrasonic backscatter measurements

Figure 4(a) shows ABTFs described in Eq. (1) for all three configurations of intervening tissues (none, cortical bone, cortical bone plus 3 cm TMP). Each ABTF was obtained by averaging all ABTFs from all measurement sites

FIG. 4. The (a) ABTF and (b) normalized backscatter difference spectrum [nD(f)] for all three configurations of intervening tissue: no intervening tissue (none), cortical bone only, and cortical bone plus a 3 cm thick TMP.

on all specimens. Figure 4(b) shows normalized difference spectra $nD(f)$ described in Eq. (2) that were obtained in a similar fashion by averaging normalized difference spectra from all measurement sites on all specimens. Figure 4 shows that the intervening tissues have a pronounced effect on the ABTF, but much less of an effect on the difference spectra. These results indicate that the apparent backscatter parameters AIB, FSAB, and FIAB are more sensitive to the effects of intervening tissues than the backscatter difference parameters nMBD, nSBD, and nIBD.

Figure 5 shows results for the apparent backscatter parameters AIB, FSAB, and FIAB plotted as a function of BMD for all three configurations of intervening tissue (none, cortical bone, cortical bone plus 3 cm TMP). Figure 6 shows results for the backscatter difference parameters nMBD, nSBD, and nIBD plotted as a function of BMD for all three configurations of intervening tissue. Each data point in each of the graphs shown in Figs. 5 and 6 represents the mean value of

FIG. 5. Apparent backscatter parameters AIB, FSAB, and FIAB plotted as functions of BMD for all three configurations of intervening tissue: no intervening tissue (none), cortical bone only, and cortical bone plus a 3 cm thick TMP.

FIG. 6. Backscatter difference parameters nMBD, nSBD, and nIBD plotted as functions of BMD for all three configurations of intervening tissue: no intervening tissue (none), cortical bone only, and cortical bone plus a 3 cm thick TMP.

a particular parameter for a particular tissue configuration averaged over all measurements sites on a particular specimen. Statistical analysis with analysis of variance (ANOVA) was used to determine if the intervening tissues produced a significant ($p < 0.05$) effect on the backscatter parameters. All three apparent backscatter parameters (AIB, FSAB, and FIAB) were affected by the presence of the cortical plate and TMP. However, the presence of cortical bone by itself did not have a significant effect on FSAB. Intervening tissues did not have a significant effect on the backscatter difference parameters (nMBD, nSBD, and nIBD).

IV. DISCUSSION

A. Effect of intervening tissues on the apparent backscatter parameters AIB, FSAB, and FIAB

AIB, FSAB, and FIAB are determined from the ABTF. AIB represents the frequency averaged ABTF. FSAB and

FIAB represent the slope and intercept of a line fitted to the ABTF. All three parameters have been investigated previously as bone assessment parameters.^{7,16,33–36,38–40} The ABTF represents the frequency dependent power from a gated portion of the backscatter signal corrected for the frequency response of the measurement system. Any tissues that lie between the transducer and interrogated region of bone will reduce the backscattered power through attenuation and reflection loss effects. If these effects are frequency dependent, they will affect the frequency dependence of the ABTF. As seen in Fig. 4(a), intervening tissues cause the ABTF to decrease in overall power. The cortical plate has the effect of reducing the backscatter power by ~ 8 dB on average. This is comparable to the results of a previous study that found that the bone cortex produced a 6 dB decrease in AIB.³⁴

Figure 4(a) also shows that the plate of cortical bone significantly alters the frequency dependence of the ABTF, producing a pronounced dip around 3 MHz. This result may be due to a resonance phenomenon in the cortical plate that causes the transmission coefficient through the plate to be frequency dependent. Theoretical treatments of this phenomenon can be found in textbooks on acoustics.⁵² For a plane wave normally incident on a plate of cortical bone with thickness d , the intensity transmission coefficient T is given by

$$T = \frac{1}{1 + \frac{1}{4} \left(\frac{z_c}{z_w} - \frac{z_w}{z_c} \right)^2 \sin^2 k_c d} \quad (5)$$

The angular wave number in cortical bone is given by $k_c = 2\pi f / v_c$, where f is the frequency of the wave and v_c is the SOS in cortical bone. The acoustic impedance of water, z_w , is $\sim 1.48 \times 10^6$ kg/m²s and the thickness d of the cortical bone is 1 mm. The acoustic impedance of cortical bone depends on the density ρ_c and SOS in cortical bone: $z_c = \rho_c v_c$. Figure 7 shows a plot of the theoretical transmission coefficient as a function of frequency using Eq. (5) with

FIG. 7. The theoretical transmission coefficient through a 1 mm thick layer of cortical bone plotted as a function of frequency compared to the experimental result for the ABTF from cancellous bone with a 1 mm thick layer of cortical bone positioned between the transducer and cancellous bone specimen.

the approximate values for cortical bone: $\rho_c = 2000$ kg/m³ and $v_c = 4000$ m/s. The maximum values of the transmission coefficient coincide with the local maxima present in the ABTF, suggesting that the backscatter measurements are affected by a frequency dependent transmission coefficient through the cortical plate.

The TMP produces additional signal loss as seen in Fig. 4(a). The dip caused by the cortical plate is still apparent, but the frequency dependence of the ABTF is further influenced by the frequency dependent attenuation within the TMP. The echoes produced at the front and back surfaces of the TMP seen in Fig. 2 suggest that reflection losses at the water-TMP interfaces may be another mechanism of signal loss that affects the ABTF.

The effects of intervening tissues on the ABTF also can be seen in Fig. 5. AIB and FIAB decrease when intervening tissues are introduced, reflecting the downward shift of the ABTF seen in Fig. 4(a). Interestingly, FSAB, which represents the slope of the ABTF, appears not to be sensitive to the presence of cortical bone. This result is somewhat misleading, however, because the cortical plate clearly influences the frequency dependence of the ABTF as seen in Fig. 4(a).

The utility of backscatter parameters that are being developed to diagnose osteoporosis can be judged, in part, by how well they correlate with BMD. Linear regression analysis was performed to determine how well AIB, FSAB, and FIAB correlate with BMD. For 24 specimens, correlations are highly significant ($p < 0.001$) for $|R| > 0.62$. As seen in Fig. 5, FSAB and FIAB demonstrate highly significant correlations with BMD for all intervening tissue configurations.

B. Effect of intervening tissues on the backscatter difference parameters nMBD, nSBD, and nIBD

nMBD, nSBD, and nIBD are determined from the normalized difference spectrum $nD(f)$. nMBD represents the frequency averaged $nD(f)$. nSBD and nIBD represent the slope and intercept of a line fitted to the $nD(f)$. nMBD and nSBD have been previously investigated as bone assessment parameters.^{40,42} nIBD is a new parameter introduced in this study.

The normalized backscatter difference spectrum $nD(f)$ represents the power difference between two gated portions of the same backscatter signal. Theoretical predictions indicate that the effects of intervening tissues will cancel when the power difference is computed in Eq. (2). Figure 4 shows that the normalized difference spectrum $nD(f)$ is affected less by the intervening tissues than the ABTF. Statistical analysis with ANOVA finds no significant difference ($p > 0.05$) between the normalized backscatter difference spectra in Fig. 4(b). Likewise, intervening tissues are found not to have a significant effect on the backscatter difference parameters nMBD, nSBD, and nIBD. Of these parameters, however, only nMBD demonstrates a highly significant correlation with BMD (see Fig. 6).

C. Effect of measurement direction

Specimens were prepared from the distal end of the femur where the trabeculae align approximately along the

superior–inferior axis of the bone. The four measurement directions used in the present study (anterior, posterior, medial, lateral) were perpendicular to this axis. Thus, all measurements were performed approximately perpendicular to the trabeculae. As a result, measurement direction is not expected to affect the results presented in this study. To test this assumption, statistical analysis with ANOVA was applied to the subset of data acquired with no intervening tissue. No significant difference ($p > 0.05$) was found between measurement directions for any of the six parameters measured (AIB, FSAB, FIAB, nMBD, nSBD, and nIBD).

D. Limitations

The main limitation of this study involves the *in vitro* nature of the measurements. The design of the study allowed measurements to be highly spatially averaged, which may not be possible for *in vivo* measurements. Less spatial averaging may yield lower correlations between the reported ultrasonic parameters and BMD. Tissues were prepared with flat and parallel faces, and wave propagation was normal to these faces. The cortical bone was bovine, not human, and TMP was used instead of actual soft tissues. In addition, the TMP, cortical bone, and cancellous bone specimen were separated by a water gap. This was done to accommodate fixtures that allowed the TMP and cortical bone to be easily positioned between the transducer and the cancellous bone specimens and removed as needed. *In vivo*, of course, there is no separation between cancellous bone, cortical bone, and the surrounding soft tissues.

The geometry of the specimens also may represent a limitation. In particular, the cortical bone specimen possessed well-defined, flat, and parallel surfaces that may have produced a resonance phenomenon resulting in a frequency dependent transmission coefficient T . While cortical bone may produce a similar phenomenon *in vivo*, the effect may not be as pronounced, especially at locations where the cortical bone does not have a well-defined back surface to produce a strong reflection. A previous study that examined the effects of the actual (not simulated) cortex on backscatter measurements from the femoral head found that the cortex did not affect the correlation of AIB with density.³⁴ In contrast, the present study finds that cortical bone does affect the correlation of AIB with density. These results suggest that the cortical plate used in the present study may have had an exaggerated effect on the frequency dependence of the ABTF compared to the effect produced by an actual bone cortex.

V. SUMMARY AND CONCLUSIONS

Intervening tissues represent a significant challenge for ultrasonic bone assessment techniques that are being developed for use at central skeletal sites such as the hip and spine. The present study finds that intervening tissues have a significant effect on the ABTF and parameters derived from the ABTF: AIB, FSAB, and FIAB. These parameters have been identified in previous studies as potentially useful backscatter parameters for bone assessment.^{7,16,33–36,38–40}

A solution to the intervening tissue problem may come in the form of parameters based on the normalized backscatter difference spectrum $nD(f)$. The normalized backscatter difference spectrum represents the power difference between two gated portions of the same backscatter signal. Since intervening tissues affect the power in the first and second gated portions of the backscatter signal in the same way, the effects of intervening tissues should cancel when the power spectra are subtracted to obtain the difference spectrum. Indeed, the present study finds that the normalized backscatter difference spectrum $nD(f)$ is not affected significantly by the presence of intervening tissues. Likewise, none of the three parameters based on the normalized backscatter difference spectrum, nMBD, nSBD, and nIBD, are affected by the presence of intervening tissues. However, only nMBD demonstrates a strong correlation with bone density.

In conclusion, this study finds that parameters based on the ABTF, such as AIB, FSAB, and FIAB, may be useful bone assessment parameters for situations where the effects of intervening tissues are small. Examples may include measurements at peripheral skeletal locations such as the heel. Parameters based on the normalized backscatter difference spectrum, such as nMBD, nSBD, and nIBD, may be better suited for central skeletal locations where the amount of intervening tissue is large. Of these three parameters, nMBD may be the most useful bone assessment parameter because it exhibits the strongest correlation with bone density.

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