Characterization of a polymer, open-cell rigid foam that simulates the ultrasonic properties of cancellous bone

Brent K. Hoffmeister,^{a)} Matthew T. Huber, and Ann M. Viano
Department of Physics, Rhodes College, Memphis, Tennessee 38112, USA

Jinsong Huang
College of Medicine, University of Tennessee Health Science Center, Memphis, Tennessee 38163, USA

(Received 28 June 2017; revised 12 January 2018; accepted 16 January 2018; published online 14 February 2018)

Materials that simulate the ultrasonic properties of tissues are used widely for clinical and research purposes. However, relatively few materials are known to simulate the ultrasonic properties of cancellous bone. The goal of the present study was to investigate the suitability of using a polymer, open-cell rigid foam (OCRF) produced by Sawbones[®]. Measurements were performed on OCRF specimens with four different densities. Ultrasonic speed of sound and normalized broadband ultrasonic attenuation were measured with a 0.5 MHz transducer. Three backscatter parameters were measured with a 5 MHz transducer: apparent integrated backscatter, frequency slope of apparent backscatter, and normalized mean of the backscatter difference. X-ray micro-computed tomography was used to measure the microstructural characteristics of the OCRF specimens. The trabecular thickness and relative bone volume of the OCRF specimens were similar to those of human cancellous bone, but the trabecular separation was greater. In most cases, the ultrasonic properties of the OCRF specimens were similar to values reported in the literature for cancellous bone, including dependence on density. In addition, the OCRF specimens exhibited an ultrasonic anisotropy similar to that reported for cancellous bone. © 2018 Acoustical Society of America.

<https://doi.org/10.1121/1.5023219>

[SWY]

Pages: 911–920

I. INTRODUCTION

Published studies of the ultrasonic properties of bone date back at least to the 1970s. In the 1980s, heel bone (calcaneal) ultrasound was developed to screen patients for osteoporosis. The technique proved to be successful, resulting in widespread clinical implementation of calcaneal ultrasound devices by 2000. In the last two decades, a variety of other ultrasonic techniques have been developed to assess bone status. Many techniques, including calcaneal ultrasound, are sensitive to changes in cancellous bone caused by osteoporosis. Osteoporosis degrades the trabecular microstructure of cancellous bone, which increases the risk of fracture. Skeletal locations that have a high volume fraction of cancellous bone include the calcaneus, vertebrae, and proximal femur (hip). Approximately two-thirds of osteoporotic fractures occur at the hip and spine.¹

Calcaneal devices typically measure the velocity and attenuation of ultrasonic pulses propagated through the heel. These properties of cancellous bone have been investigated extensively. Several other ultrasonic bone assessment techniques have been investigated as well, many of which involve backscatter measurements of cancellous bone.² As new ultrasonic techniques are developed, and existing techniques refined, it is important that investigators be able to reproduce and validate each other's measurements. However, the natural variations that exist in cancellous bone can make this process difficult. A solution to this problem is to identify a

readily available material with consistent properties that mimics the ultrasonic characteristics of cancellous bone.

Artificial materials that simulate the properties of biologic tissues are called tissue phantoms. The main advantage of tissue mimicking phantoms is that they provide consistent and well-defined test subjects that simplify and standardize the testing environment. While there are several commercial phantoms for soft tissues, equivalent products for cancellous bone are less available. As a result, investigators who need cancellous bone phantoms for their research either fabricate their own phantoms, or use pre-existing materials that possess ultrasonic properties similar to those of cancellous bone. Table I lists various cancellous bone phantoms that investigators have used for research purposes.

Ultrasonic studies of the phantoms listed in Table I have focused mainly on characterizing the velocity and attenuation of the phantom materials. The ultrasonic scattering characteristics of most of the phantom materials have not been investigated. Also, the only commercially available materials listed in Table I are the metallic foams. The other phantoms require some degree of fabrication. The goal of the present study is to ultrasonically characterize another commercially available material to investigate its suitability as a cancellous bone phantom. The material is a polymer open-cell rigid foam (OCRF) manufactured by Sawbones[®] (Vashon Island, WA) for use as a biomechanical test material for cancellous bone. The present study reports measurements of the speed of sound (SOS), normalized broadband ultrasonic attenuation (nBUA), and three backscatter parameters that have been developed to detect changes in

^{a)}Electronic mail: hoffmeister@rhodes.edu

TABLE I. Various cancellous bone phantoms used for ultrasonic studies.

Phantom description	Ultrasonic measurements	Study
Epoxy mixed with granules of gelatin (Leeds phantom)	Velocity, attenuation	Clarke <i>et al.</i> ³ Striletski <i>et al.</i> ⁴
Three-dimensional printed model based on extruded two-dimensional image of human cancellous bone using photo-reactive resin	Velocity, attenuation	Langton <i>et al.</i> ⁵
Nylon wires	Velocity, backscatter	Wear, ^{6,7} Wear and Harris ⁸
Nylon wires in soft tissue mimicking material	Attenuation	Wear ⁹
Polyacetal model with cylindrical pores aligned along three orthogonal axes	Velocity, attenuation	Lee and Choi ¹⁰
Cellular aluminum foam	Velocity, attenuation, B/A ^a	Ji <i>et al.</i> ¹¹ Le <i>et al.</i> ¹² Zhang <i>et al.</i> ¹³ Lee ¹⁴ Lee ¹⁵
Cellular copper foam	Velocity, attenuation	Lee ¹⁶
Cellular nickel foam	Velocity, attenuation, backscatter	Lee ¹⁶
Epoxy resin and alumina powder with poppy or hemp seeds	Velocity, attenuation	Wydra <i>et al.</i> ¹⁷
Three-dimensional printed model based on X-ray micro-tomographic data from equine trabecular bone using photo-reactive resin	Velocity	Meziere <i>et al.</i> ¹⁸

^aB/A is a nonlinear parameter measured by Lee (Ref. 14).

cancellous bone caused by osteoporosis. In addition, the microstructural characteristics of the OCRF material are measured using high-resolution x-ray micro-computed tomography.

II. METHODS

A. Specimen preparation

Table II lists OCRF products offered by Sawbones[®] at the time of writing. They are produced in the shape of rectangular slabs with dimensions of 130 mm × 180 mm × 40 mm (see Fig. 1) in five different densities, which the manufacturer specifies in units of pounds per cubic foot (PCF). For consistency, the same abbreviation is used in the present paper. Four different densities were tested: 5.5, 7.5, 15, and 30 PCF. The 20 PCF material was not available at the time of testing. A label on the packaging of the 15 and 30 PCF specimens indicated that the short (40 mm) axis of the slab was the direction of the “rise,” suggesting a possible

directional dependence in the material characteristics of the OCRF [see Fig. 1(a)]. Four specimens were prepared from each slab for ultrasonic testing. The dimensions of the specimens were 40 mm × 40 mm × 12 mm. Two specimens were prepared so that the short (12 mm) axis was parallel to the rise direction, while the other two specimens were prepared so that the short axis was perpendicular to the rise direction. A total of 16 specimens (four specimens per slab, four slabs) were ultrasonically tested.

B. Ultrasonic scanning procedure

Ultrasonic measurements were performed in a water bath at room temperature. The OCRF specimens were vacuum degassed prior to ultrasonic measurements to remove any air trapped in the open cells. Two types of ultrasonic transducers were used. A 0.5 MHz diameter planar transducer (Panametrics V301, Waltham, MA) with a 25.4 mm element diameter, 53.8 mm near field length, and 6 mm beam diameter was used to perform SOS and attenuation

TABLE II. OCRF biomechanical test materials manufactured by Sawbones[®]. Properties listed in the table are specified by the manufacturer. All materials were tested for this study except for the 20 PCF material. Values obtained from the literature for human cancellous bone are provided for comparison. The properties of human cancellous bone vary due to factors such as age, health and anatomic location.

Description	Product number	Density (g/cm ³)	Compressive strength (MPa)	Compressive modulus (MPa)
5.5 PCF	1522-505	0.09	0.11	6.2
7.5 PCF	1522-507	0.12	0.28	18.6
7.5 PCF	1522-507-1	0.12	0.28	18.6
15 PCF	1522-524	0.24	0.67	53.0
20 PCF	1522-529-1	0.32	Not specified	Not specified
30 PCF	1522-525	0.48	3.20	270.0
Human cancellous bone	-	0.05–1.1 ^a	0.1–30 ^b	10–3000 ^b

^aHernandez (Ref. 19).

^bKeavney *et al.* (Ref. 20).

FIG. 1. (Color online) (a) $40 \times 40 \times 12$ mm specimens were prepared from $180 \times 130 \times 40$ mm monolithic slabs of Sawbones[®] polymer OCRF for ultrasonic testing. The short axis of the slab was identified by the manufacturer as the “rise” direction. Four specimens were prepared from each slab as shown. (b) Photo of a 15 PCF monolithic slab along with two specimens that were used for ultrasonic testing. (c) Photo of 5.5, 7.5, 15, and 30 PCF specimens (ordered left to right) used for ultrasonic testing.

measurements. Transducers with a center frequency of 0.5 MHz are commonly used for such measurements of cancellous bone.²¹ A 5 MHz focused transducer (Panametrics V309) with a 12.7 mm element diameter, 50.8 mm focal length, and 1.2 mm beam diameter was used to perform backscatter measurements. Transducers with a center frequency of 5 MHz have been used in several laboratory studies of the backscattering properties of cancellous bone.^{22–39} The beam diameters of both transducers were determined from technical notes provided by the manufacturer.⁴⁰ Measurement configurations are illustrated in Fig. 2. The transducers were mechanically scanned to interrogate a region of interest (ROI) centered on the specimen. The step size used for the scan was chosen to be equal to one half of the beam diameter of the transducer. The ROI size was chosen to ensure that the edge of the beam did not extend beyond the edge of the specimen. Specifically, the ROI for the 0.5 MHz transducer was 24 mm by 24 mm with a 3 mm step size (64 measurement points total). The ROI for the 5 MHz transducer was 36 mm by 36 mm with a 0.6 mm step size (3600 points total). The transducers were connected to a pulser-receiver (Panametrics 5800) and the signals were digitized using a 12 bit digitizer (Picoscope 5244B, Pico Technology, Cambridgeshire, UK) operating at 100 MSa/s for the 0.5 MHz transducer and 500 MSa/s for the 5 MHz

FIG. 2. Ultrasonic measurement configurations. A 0.5 MHz transducer was used to perform SOS and attenuation measurements by reflecting pulses from a polished steel plate (a) with and (b) without the OCRF specimen positioned between the transducer and steel plate. (c) A 5 MHz transducer was used to perform backscatter measurements with the focal point of the transducer located at the front surface of the OCRF specimen. (d) Two of the backscatter parameters (AIB and FSAB) required a reference signal that was obtained by reflecting pulses from a polished stainless steel plate.

transducer. After a specimen was scanned, it was turned over to position the back surface as the front surface and rescanned. To determine if the ultrasonic properties of the specimens were affected by extended exposure to water, the specimens were left in the water tank for one week. Measurements were repeated on the second and seventh days.

C. SOS measurements

SOS was measured using a shadowed reflector technique with the 0.5 MHz transducer. A “shadowed” signal was acquired by capturing a pulse reflected from the polished stainless steel plate with the specimen positioned in front of the plate as shown in Fig. 2(a). The specimen was then removed to capture an “unshadowed” signal [Fig. 2(b)]. SOS was determined from⁴¹

$$SOS = c_{water} / (1 - c_{water} \Delta t / 2L), \quad (1)$$

where Δt represents the arrival time difference between the shadowed and unshadowed pulses, L is the thickness of the specimen, and c_{water} is the SOS in water adjusted for temperature. Figure 3 shows a shadowed and unshadowed steel plate echo. Measurements used to determine Δt were based on times when the shadowed and unshadowed pulses first deviated from the baseline.

FIG. 3. Comparison of an ultrasonic pulse reflected from a polished steel plate (a) with and (b) without an OCRF specimen present to “shadow” the plate. The arrival time difference Δt was used to compute the SOS. Signals were acquired with a 0.5 MHz transducer.

D. Attenuation measurements

Attenuation measurements were performed by analyzing the log spectral power difference between the shadowed and unshadowed pulses acquired with the 0.5 MHz transducer. A Hamming window with a duration of $10 \mu\text{s}$ was centered on the shadowed and unshadowed pulses from which the power spectra in decibels $P_s^{dB}(f)$ and $P_u^{dB}(f)$ were computed, respectively. nBUA was determined from²¹

$$\text{nBUA} = \text{frequency slope of } [P_u^{dB}(f) - P_s^{dB}(f)] / 2L, \quad (2)$$

where L represents the thickness of the specimen. Linear regression was used to determine the slope over the frequency range 0.2–0.8 MHz, which was the linear portion of $P_u^{dB}(f) - P_s^{dB}(f)$ and also the –6 dB frequency range of the transducer specified by the manufacturer.

E. Backscatter measurements

Backscatter measurements were performed with the 5 MHz transducer. The focal point of the transducer was placed at the front surface of the specimen as shown in Fig. 2(c). Backscatter power spectra $P_1^{dB}(f)$ and $P_2^{dB}(f)$ were acquired from two gated portions of the backscatter signal. The gates were positioned on the signal to analyze scattering from the interior of the specimen while avoiding the echo from the front surface of the specimen. Gate sizes and locations are shown in Fig. 4(a). A reference power spectrum $P_{ref}^{dB}(f)$ was acquired by replacing the specimen with a stainless steel plate, and repositioning the transducer to locate the focal point at the front surface of the plate [Fig. 2(d)]. Apparent integrated backscatter (AIB) was determined from³¹

$$\text{AIB} = \frac{1}{f_{hi} - f_{lo}} \int_{f_{lo}}^{f_{hi}} [P_1^{dB}(f) - P_{ref}^{dB}(f)] df, \quad (3)$$

where f_{lo} and f_{hi} represent the lower and upper values of the frequency range analyzed. These values were based on the

FIG. 4. (a) A backscatter signal acquired from an OCRF specimen. Shaded regions labeled “1” and “2” indicate gated portions of the signal that were analyzed. Gate 1 was delayed by $2.8 \mu\text{s}$ from the start of the signal. Gates 1 and 2 had the same duration ($2.0 \mu\text{s}$). Gate centers were separated by $3.0 \mu\text{s}$. (b) An echo reflected from the stainless steel plate. Signals were acquired with a 5 MHz transducer.

–6 dB frequency range of the transducer: $f_{lo} = 1 \text{ MHz}$ and $f_{hi} = 6 \text{ MHz}$. The frequency slope of apparent backscatter (FSAB) was determined from³¹

$$\text{FSAB} = \text{frequency slope of } [P_1^{dB}(f) - P_{ref}^{dB}(f)], \quad (4)$$

where linear regression was used to measure the slope of $P_1^{dB}(f) - P_{ref}^{dB}(f)$ over the frequency range 1–6 MHz. AIB and FSAB have been identified in several studies as potentially useful backscatter parameters for ultrasonic bone assessment.^{24–26,29–32,37,38,42–44}

A third backscatter parameter, called the normalized mean of the backscatter difference (nMBD), has been investigated in recent studies as another potentially useful bone assessment parameter.^{26,34–36} Unlike AIB and FSAB, which are based on the power in a single gated portion of the backscatter signal, nMBD is based on the power difference between two gated portions of the same signal. nMBD was determined from³⁶

$$\text{nMBD} = \frac{1}{f_{hi} - f_{lo}} \int_{f_{lo}}^{f_{hi}} [P_1^{dB}(f) - P_2^{dB}(f)] df / \tau, \quad (5)$$

where $f_{lo} = 1 \text{ MHz}$ and $f_{hi} = 6 \text{ MHz}$, and $\tau = 3 \mu\text{s}$ represents the center to center separation between the two gates.

F. X-ray micro-CT measurements

High-resolution x-ray micro-computed tomography (μCT40 ; Scanco Medical, Basserdorf, Switzerland) was used to scan and measure the microstructural characteristics of the OCRF specimens. Four cube shaped specimens with 10 mm side lengths were prepared from each OCRF slab (5.5, 7.5, 15, and 30 PCF) for micro-CT measurements. The resulting 16 specimens were scanned at a $10 \mu\text{m}$ resolution (isotropic voxel size) using an energy level of 55 kVp, an

integration time of 200 ms, and an intensity of $145 \mu\text{A}$. Cancellous bone morphometric parameters were evaluated with a threshold of 100 (7.5, 15, and 30 PCF specimens) or 30 (5.5 PCF specimen). Images were generated from an $8 \text{ mm} \times 8 \text{ mm} \times 8 \text{ mm}$ ROI centered on the cube shaped specimen. Built-in image analysis software was used to measure three microstructural characteristics of the specimen: relative bone volume (BV/TV), trabecular thickness (Tb.Th), and trabecular separation (Tb.Sp).

III. RESULTS

Statistical analysis with analysis of variance (ANOVA) found no significant ($p > 0.05$) difference between ultrasonic measurements performed on the day the specimens were initially placed in the water tank and measurements performed two and seven days later. Thus, subsequent analyses of the five ultrasonic parameters (SOS, nBUA, AIB, FSAB, and nMBD) were based on measurements averaged over all three days. Figures 5 and 6 present results of the ultrasonic measurements. Columns in the graphs represent means, and error bars represent standard deviations of the mean. Results are shown for measurements performed perpendicular and parallel to the rise direction. Each column is based on a total of 12 scans (two specimens, two sides, three days). The means and standard deviations also are reported in Table III.

FIG. 5. Measured values of (a) SOS and (b) nBUA for four different densities of OCRF compared to typical values for human cancellous bone. Values are reported for measurements perpendicular and parallel to the rise direction of the OCRF slab [see Fig. 1(a)]. Columns represent means, and error bars represent standard deviations of the mean.

FIG. 6. Measured values of (a) AIB, (b) FSAB, and (c) nMBD for four different densities of OCRF compared to typical values for human cancellous bone. Values are reported for measurements perpendicular and parallel to the rise direction of the OCRF slab [see Fig. 1(a)]. Columns represent means, and error bars represent standard deviations of the mean.

Figure 5 shows results for SOS and nBUA along with values obtained from the literature that are typical for human cancellous bone.⁴⁵ Results for AIB, FSAB, and nMBD are presented in a similar fashion in Fig. 6 along with values for human cancellous bone (15 mm cubes) obtained from the literature.^{31,36}

The microstructural characteristics of the OCRF specimens can be visualized in Fig. 7, which shows three-dimensional micro-CT images representing the four densities investigated (5.5, 7.5, 15, and 30 PCF) as well as two specimens of human cancellous bone from the proximal femur for comparison. Animated fly-throughs (Mm. 1–Mm. 4) and three-dimensional rotations (Mm. 5–Mm. 8) of the OCRF

TABLE III. Measured values of ultrasonic parameters investigated in this study for four different densities of Sawbones® OCRF. Values are reported as mean $\pm$ standard deviation. Measurements were performed perpendicular and parallel to the rise direction of the OCRF slab [see Fig. 1(a)].

Specimen	Measurement Direction	SOS (m/s)	nBUA (dB/MHz/cm)	AIB (dB)	FSAB (dB/MHz)	nMBD (dB/ μ s)
5.5 PCF	Perpendicular	1564 $\pm$ 7	5.60 $\pm$ 0.48	−42.3 $\pm$ 6.5	−0.65 $\pm$ 1.96	0.81 $\pm$ 2.95
	Parallel	1572 $\pm$ 13	6.61 $\pm$ 0.38	−44.0 $\pm$ 6.5	−0.99 $\pm$ 1.97	0.70 $\pm$ 3.18
7.5 PCF	Perpendicular	1553 $\pm$ 10	6.08 $\pm$ 0.63	−38.1 $\pm$ 4.5	−0.37 $\pm$ 1.75	1.59 $\pm$ 2.15
	Parallel	1583 $\pm$ 16	7.85 $\pm$ 0.66	−41.4 $\pm$ 4.5	−0.54 $\pm$ 1.77	1.42 $\pm$ 2.07
15 PCF	Perpendicular	1587 $\pm$ 6	13.13 $\pm$ 1.72	−36.2 $\pm$ 4.3	−0.33 $\pm$ 1.67	2.54 $\pm$ 1.97
	Parallel	1644 $\pm$ 12	23.19 $\pm$ 1.12	−36.8 $\pm$ 4.5	−0.40 $\pm$ 1.72	2.55 $\pm$ 2.13
30 PCF	Perpendicular	1770 $\pm$ 30	23.41 $\pm$ 4.05	−39.8 $\pm$ 6.2	−1.22 $\pm$ 1.94	2.48 $\pm$ 2.55
	Parallel	1742 $\pm$ 44	27.44 $\pm$ 4.93	−39.8 $\pm$ 5.8	−1.07 $\pm$ 1.93	2.23 $\pm$ 2.49

specimens are available on-line. Figure 8 illustrates details of the microstructure of a 30 PCF specimen. Values for the microstructural characteristics of the OCRF specimens are reported in Table IV along with values obtained from the literature for human cancellous bone.⁴⁶

Mm. 1. X-ray micro-CT animated fly-through of a 5.5 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (6877 KB).

Mm. 2. X-ray micro-CT animated fly-through of a 7.5 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (8288 KB).

Mm. 3. X-ray micro-CT animated fly-through of a 15 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (12804 KB).

Mm. 4. X-ray micro-CT animated fly-through of a 30 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (21044 KB).

Mm. 5. X-ray micro-CT animated three-dimensional rotation of a 5.5 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (8844 KB).

FIG. 7. X-ray micro-CT images of the four different densities of OCRF (a)–(d) compared to specimens of human cancellous bone illustrating rod-like (e) and plate-like (f) trabecular features. Animated fly-throughs and three-dimensional rotations of the OCRF specimens are available on-line.

FIG. 8. (a) Three-dimensional microstructure of a 30 PCF specimen (highest density), and (b) a two-dimensional image slice taken from the center of the scan volume. The white square indicates the location of the magnified portion of the two dimensional image shown in (c).

TABLE IV. Bone-like microstructural characteristics of four different densities of Sawbones® open cell rigid foam determined using x-ray micro-computed tomography (micro-CT). Values are reported as mean $\pm$ standard deviation. Values obtained from the literature for human cancellous bone from various anatomic sites are provided for comparison.

Specimen	BV/TV	Tb.Th (mm)	Tb.Sp (mm)
5.5 PCF	0.068 ± 0.002	0.130 ± 0.006	1.99 ± 0.126
7.5 PCF	0.056 ± 0.004	0.171 ± 0.009	1.66 ± 0.035
15 PCF	0.082 ± 0.015	0.179 ± 0.020	1.62 ± 0.048
30 PCF	0.248 ± 0.037	0.244 ± 0.003	1.75 ± 0.142
Iliac crest ^a	0.156 ± 0.054	0.151 ± 0.027	0.747 ± 0.150
2nd lumbar spine ^a	0.083 ± 0.024	0.122 ± 0.019	0.792 ± 0.135
4th lumbar spine ^a	0.087 ± 0.033	0.139 ± 0.028	0.854 ± 0.143
Femoral head ^a	0.261 ± 0.078	0.194 ± 0.033	0.638 ± 0.114
Calcaneus ^a	0.120 ± 0.035	0.129 ± 0.018	0.679 ± 0.107

^aHildebrand *et al.* (Ref. 46).

Mm. 6. X-ray micro-CT animated three-dimensional rotation of a 7.5 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (10691 KB).

Mm. 7. X-ray micro-CT animated three-dimensional rotation of a 15 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (9183 KB).

Mm. 8. X-ray micro-CT animated three-dimensional rotation of a 30 PCF Sawbones open cell rigid foam specimen. This is a file of type “avi” (8553 KB).

IV. DISCUSSION

A. Ultrasonic properties

Figure 5 shows that the SOS and nBUA for the three lowest density OCRF specimens (5.5, 7.5, and 15 PCF) compare reasonably well to values reported by Laugier *et al.*, who measured phase velocity and nBUA in 15 specimens of human cancellous bone from the calcaneus with a 0.5 MHz transducer.⁴⁵ Wear *et al.*⁴⁷ reported similar values in a later study. Values can be found in the literature for cancellous bone that range from 1545 to 1990 m/s for SOS⁴⁸ to 3.5–31.0 dB/MHz/cm for nBUA.⁴⁹ Measured values reported in the present study for the OCRF specimens fall well within these ranges. Also, it should be mentioned that ultrasonic pulses propagated through cancellous bone may separate into so-called “fast waves” and “slow waves” that have propagation speeds of approximately 2000–3000 m/s (fast) and 1500 m/s (slow).⁵⁰ No evidence of this phenomenon was observed in the present study, possibly because the propagation speed difference between the two wave modes was not large enough to result in a visible separation. A similar observation has been made in recent studies of human cancellous bone.^{51,52}

Figure 6 compares the backscattering characteristics of the OCRF specimens to those of human cancellous bone. The values reported in Fig. 6 for cancellous bone were obtained from studies that used the same transducer and analysis gates with the same duration and position on the signal.^{31,36} The measured values of AIB and FSAB are known to depend on

the duration and position of the analysis gate due to attenuation effects that increase as the center of the gate is shifted to later times.^{33,38} Of the three backscatter parameters measured in the present study, AIB has been investigated most thoroughly as an ultrasonic bone assessment parameter. The measured values of AIB from the OCRF specimens are very similar to values reported for human cancellous bone. FSAB is another backscatter parameter that has been identified as potentially useful for ultrasonic bone assessment.^{26,29–31,33,35} Measured values of FSAB from the OCRF specimens are similar, but slightly greater (less negative) than values reported for cancellous bone. nMBD is a relatively new backscatter parameter that may be less sensitive to the effects of gate duration and position because it is corrected (normalized) for these effects.^{36,53} The present study finds that nMBD from the OCRF specimens is somewhat lower than values reported for cancellous bone.

B. Microstructural characteristics

Figure 7 shows three dimensional micro-CT images of four different densities of OCRF compared to two specimens of human cancellous bone from the proximal femur. The two bone specimens have the same apparent density but visibly different microstructure. The specimen shown in Fig. 7(e) has trabeculae that are more rod-like in appearance than the trabeculae of the specimen shown in Fig. 7(f), which are more plate-like. Rod-like and plate-like microstructural features that are characteristic of human cancellous bone also are observed in the OCRF specimens. The similarity between the OCRF specimens and real cancellous bone was examined quantitatively using software to compute the following morphometric parameters: relative bone volume (BV/TV), trabecular thickness (Tb.Th), and trabecular separation (Tb.Sp). Table IV reports results for the microstructural characteristics of the OCRF specimens along with values obtained from the literature for human cancellous bone from various anatomic sites.⁴⁶ BV/TV and Tb.Th are similar to values reported for human cancellous bone. However, Tb.Sp of the OCRF specimens is approximately twice that of human cancellous bone.

Linear regression analysis was used to quantitatively examine relationships between the microstructural characteristics and density of the OCRF specimens. Tb.Th correlated strongly with density ($R = 0.96$) and BV/TV ($R = 0.89$). In contrast, Tb.Sp did not correlate strongly with either density ($R = 0.29$) or BV/TV ($R = 0.04$). Thus, density and BV/TV appear to depend more on the trabecular thickness than on the mid-axis separation between the trabeculae. The density of the OCRF specimens may depend on material composition as well. For example, the 15 PCF material has approximately the same values for Tb.Th and Tb.Sp as the 7.5 PCF material, but is twice as dense. Labeling from the manufacturer identified the 15 and 30 PCF specimens as “composite,” indicating that the trabecular structures of the specimens are composed of more than one material. Micro-CT images of the 15 and 30 PCF specimens (see animated fly-throughs Mm. 3 and Mm. 4) confirmed the presence of particles embedded in the polymer that are more opaque to

x-rays and therefore possibly more dense, than the surrounding material. The particles are evident in Fig. 8(c) as well. Figure 8(c) also indicates evidence of closed-cell porosity within the trabecular structures of the 30 PCF material. Closed-cell porosity was less apparent in the other densities (see animated fly-throughs Mm. 1–Mm. 4 and three dimensional rotations Mm. 5–Mm. 8). The material characteristics of the pores are unknown, but it seems reasonable to speculate that the pores are gas filled. If so, gas filled pores could impact the ultrasonic properties of the 30 PCF material due to the large difference in acoustic impedance between the pores and the surrounding medium.

C. Effect of density on ultrasonic properties

SOS and nBUA are known to increase with the density of human cancellous bone.⁴¹ This trend also is evident in Fig. 5 for measurements performed on the OCRF specimens. AIB has been reported to increase or decrease with density, depending on the location of the analysis gate on the backscatter signal.^{33,38} As seen in Fig. 6(a), AIB increases with density up to 15 PCF after which a decrease is observed for the 30 PCF specimen. The decrease in AIB for the 30 PCF specimen may be linked to the possible closed-cell porosity of the trabecular structures as described earlier. Studies of human cancellous bone have reported that FSAB decreases with bone density.^{29–31,33} However, the trend between FSAB and the density of the OCRF specimens is less clear [see Fig. 6(b)]. nMBD has been reported to increase with bone density.^{34,36,53} Figure 6(c) shows that nMBD increases with the density of the OCRF specimens up to 15 PCF, after which the trend stops, possibly due to the closed-cell porosity of the 30 PCF material.

D. Ultrasonic anisotropy

The ultrasonic properties of cancellous bone are known to be anisotropic. The anisotropy is understood to be the result of alignment of the trabeculae. Interestingly, the ultrasonic properties of the OCRF specimens also appear to be anisotropic. If we exclude the 30 PCF material from consideration as being too dissimilar from real cancellous bone due to possible porosity in the trabecular structures, then SOS and nBUA are both significantly greater parallel to the rise direction than perpendicular to the rise direction. In human cancellous bone, SOS and nBUA have been reported to be greatest along the direction of trabecular alignment.⁵⁴ Thus, the direction parallel to the rise direction is ultrasonically similar to the direction of trabecular alignment in real bone. Likewise, two of the three backscatter parameters (AIB and FSAB) demonstrate a significant anisotropy (30 PCF specimen excluded) in which both parameters are greater in the perpendicular direction. Measurements on real cancellous bone have reported similar anisotropy for these parameters, depending on the choice of gate delay.³³ A weak anisotropy has been reported for nMBD measured in real bone,^{34,53} but no significant anisotropy is observed in this parameter for the OCRF specimens.

E. Effect of exposure to water

Most laboratory studies of cancellous bone are performed in a water bath so that water can acoustically couple the transducer to the specimen. Usually, the marrow is removed from the specimens so that water fills the inter-trabecular spaces. Ultrasonic measurements of the OCRF specimens were performed in the same way. In fact, the open-cell nature of the material is essential for water bath measurements because water must be able to infiltrate the inter-trabecular spaces.

It was not clear at the beginning of the study if prolonged exposure to water would change the ultrasonic properties of the specimens. To test this, all specimens remained in the water bath for one week after the initial measurements. Measurements were repeated on the second and seventh days. No significant difference was found in any of the ultrasonic measurements of any of the OCRF specimens. Thus, the ultrasonic properties of the specimens appear to be stable in water for at least one week.

F. Ultrasonic studies involving Sawbones® products

Several studies have used Sawbones® products to mimic the ultrasonic properties of cortical bone. For example, cortical bone mimicking products have been used to study guided ultrasonic waves propagated along long bones.^{55–57} Cortical bone mimicking phantoms also have been used to study heating distribution by therapeutic ultrasound.⁵⁸ However, it appears that only one other study has used Sawbones® OCRF as an ultrasound phantom for cancellous bone. Rosa *et al.*⁵⁹ used the 15 PCF material to test backscatter techniques for estimating the periodicity (trabecular separation) of cancellous bone. Ultrasonic velocity and attenuation of the material were not measured, and the backscatter signals were not analyzed to determine the bone assessment parameters AIB, FSAB, and nMBD.

V. SUMMARY AND CONCLUSIONS

The present study investigates the ultrasonic and microstructural characteristics of a polymer OCRF produced by Sawbones® for use as a biomechanical test material for cancellous bone. The microstructural characteristics of the OCRF materials are found to mimic the rod-like and plate-like microstructural characteristics of real cancellous bone. Relative bone volume and trabecular thickness are similar to those of human cancellous bone; however, the trabecular separation is approximately twice as great as that of real cancellous bone. Of the four materials tested, the microstructure of the 30 PCF material appears to be least similar to the microstructure of human cancellous bone due to the composite nature of the trabecular structures and the possible presence of closed-cell porosity within the trabecular structures.

The ultrasonic properties of the OCRF materials are similar to the ultrasonic properties of human cancellous bone in many ways. SOS and nBUA fall within ranges of values reported for cancellous bone, and AIB is very similar to values reported for cancellous bone. Most of the ultrasonic parameters demonstrate a dependence on density that is

similar to that reported for real cancellous bone. In addition, the ultrasonic properties of the OCRF specimens are found to be anisotropic, with the rise direction of the OCRF material behaving as a direction of trabecular alignment in cancellous bone.

ACKNOWLEDGMENTS

Research reported in this publication was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under Award No. R15AR066900. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

- ¹B. L. Riggs and L. J. Melton III, "The worldwide problem of osteoporosis: Insights afforded by epidemiology," *Bone* **17**, 505S–511S (1995).
- ²K. A. Wear, "Ultrasonic scattering from cancellous bone: A review," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **55**, 1432–1441 (2008).
- ³A. J. Clarke, J. A. Evans, J. G. Truscott, R. Milner, and M. A. Smith, "A phantom for quantitative ultrasound of trabecular bone," *Phys. Med. Biol.* **39**, 1677–1687 (1994).
- ⁴R. Strelitzki, J. A. Evans, and A. J. Clarke, "The influence of porosity and pore size on the ultrasonic properties of bone investigated using a phantom material," *Osteoporos. Int.* **7**, 370–375 (1997).
- ⁵C. M. Langton, M. A. Whitehead, D. K. Langton, and G. Langley, "Development of a cancellous bone structural model by stereolithography for ultrasound characterisation of the calcaneus," *Med. Eng. Phys.* **19**, 599–604 (1997).
- ⁶K. A. Wear, "Measurement of dependence of backscatter coefficient from cylinders on frequency and diameter using focused transducers—with applications in trabecular bone," *J. Acoust. Soc. Am.* **115**, 66–72 (2004).
- ⁷K. A. Wear, "The dependencies of phase velocity and dispersion on volume fraction in cancellous-bone-mimicking phantoms," *J. Acoust. Soc. Am.* **125**, 1197–1201 (2009).
- ⁸K. A. Wear and G. R. Harris, "Frequency dependence of backscatter from thin, oblique, finite-length cylinders measured with a focused transducer—with applications in cancellous bone," *J. Acoust. Soc. Am.* **124**, 3309–3314 (2008).
- ⁹K. A. Wear, "Mechanisms for attenuation in cancellous-bone-mimicking phantoms," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **55**, 2418–2425 (2008).
- ¹⁰K. I. Lee and M. J. Choi, "Phase velocity and normalized broadband ultrasonic attenuation in Polyacetal cuboid bone-mimicking phantoms," *J. Acoust. Soc. Am.* **121**, EL263–EL269 (2007).
- ¹¹Q. Ji, L. H. Le, L. J. Filipow, and S. A. Jackson, "Ultrasonic wave propagation in water-saturated cellular aluminum foams," *Ultrasonics* **36**, 759–765 (1998).
- ¹²L. H. Le, C. Zhang, D. Ta, and E. Lou, "Measurement of tortuosity in aluminum foams using airborne ultrasound," *Ultrasonics* **50**, 1–5 (2010).
- ¹³C. Zhang, L. H. Le, R. Zheng, D. Ta, and E. Lou, "Measurements of ultrasonic phase velocities and attenuation of slow waves in cellular aluminum foams as cancellous bone-mimicking phantoms," *J. Acoust. Soc. Am.* **129**, 3317–3326 (2011).
- ¹⁴K. I. Lee, "Relationships of linear and nonlinear ultrasound parameters with porosity and trabecular spacing in trabecular-bone-mimicking phantoms," *J. Acoust. Soc. Am.* **140**, EL528–EL533 (2016).
- ¹⁵K. I. Lee, "Dependences of ultrasonic properties on frequency and trabecular spacing in trabecular-bone-mimicking phantoms," *J. Acoust. Soc. Am.* **137**, EL194–EL199 (2015).
- ¹⁶K. I. Lee, "Dependences of quantitative ultrasound parameters on frequency and porosity in water-saturated nickel foams," *J. Acoust. Soc. Am.* **135**, EL61–EL67 (2014).
- ¹⁷A. Wydra and R. G. Maev, "A novel composite material specifically developed for ultrasound bone phantoms: Cortical, trabecular and skull," *Phys. Med. Biol.* **58**, N303–N319 (2013).
- ¹⁸F. Meziere, P. Juskova, J. Woittequand, M. Muller, E. Bossy, R. Boistel, L. Malaquin, and A. Derode, "Experimental observation of ultrasound fast and slow waves through three-dimensional printed trabecular bone phantoms," *J. Acoust. Soc. Am.* **139**, EL13–EL18 (2016).
- ¹⁹C. J. Hernandez, "Cancellous bone," in *Handbook of Biomaterial Properties*, edited by W. Murphy, J. Black, and G. Hastings (Springer, New York, 2016), pp. 15–21.
- ²⁰T. M. Keavney, E. F. Morgan, and O. C. Yeh, "Bone mechanics," in *Biomedical Engineering and Design Handbook*, edited by M. Kutz (McGraw-Hill, New York, 2009), pp. 221–244.
- ²¹C. M. Langton and C. F. Njeh, "The measurement of broadband ultrasonic attenuation in cancellous bone—A review of the science and technology," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **55**, 1546–1554 (2008).
- ²²M. A. Hakulinen, J. S. Day, J. Toyra, M. Timonen, H. Kroger, H. Weinans, I. Kiviranta, and J. S. Jurvelin, "Prediction of density and mechanical properties of human trabecular bone in vitro by using ultrasound transmission and backscattering measurements at 0.2–6.7 MHz frequency range," *Phys. Med. Biol.* **50**, 1629–1642 (2005).
- ²³M. A. Hakulinen, J. S. Day, J. Toyra, H. Weinans, and J. S. Jurvelin, "Ultrasonic characterization of human trabecular bone microstructure," *Phys. Med. Biol.* **51**, 1633–1648 (2006).
- ²⁴J. P. Karjalainen, O. Riekkinen, J. Toyra, M. Hakulinen, H. Kroger, T. Rikonen, K. Salovaara, and J. S. Jurvelin, "Multi-site bone ultrasound measurements in elderly women with and without previous hip fractures," *Osteoporos. Int.* **23**, 1287–1295 (2012).
- ²⁵J. P. Karjalainen, J. Toyra, O. Riekkinen, M. Hakulinen, and J. S. Jurvelin, "Ultrasound backscatter imaging provides frequency-dependent information on structure, composition and mechanical properties of human trabecular bone," *Ultrasound Med. Biol.* **35**, 1376–1384 (2009).
- ²⁶M. K. Malo, J. Toyra, J. P. Karjalainen, H. Isaksson, O. Riekkinen, and J. S. Jurvelin, "Ultrasound backscatter measurements of intact human proximal femurs—Relationships of ultrasound parameters with tissue structure and mineral density," *Bone* **64**, 240–245 (2014).
- ²⁷O. Riekkinen, M. A. Hakulinen, M. Timonen, J. Toyra, and J. S. Jurvelin, "Influence of overlying soft tissues on trabecular bone acoustic measurement at various ultrasound frequencies," *Ultrasound Med. Biol.* **32**, 1073–1083 (2006).
- ²⁸O. Riekkinen, M. A. Hakulinen, J. Toyra, and J. S. Jurvelin, "Dual-frequency ultrasound—New pulse-echo technique for bone densitometry," *Ultrasound Med. Biol.* **34**, 1703–1708 (2008).
- ²⁹B. K. Hoffmeister, "Frequency dependence of apparent ultrasonic backscatter from human cancellous bone," *Phys. Med. Biol.* **56**, 667–683 (2011).
- ³⁰B. K. Hoffmeister, A. P. Holt, and S. C. Kaste, "Effect of the cortex on ultrasonic backscatter measurements of cancellous bone," *Phys. Med. Biol.* **56**, 6243–6255 (2011).
- ³¹B. K. Hoffmeister, D. P. Johnson, J. A. Janeski, D. A. Keedy, B. W. Steinert, A. M. Viano, and S. C. Kaste, "Ultrasonic characterization of human cancellous bone in vitro using three different apparent backscatter parameters in the frequency range 0.6–15.0 MHz," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **55**, 1442–1452 (2008).
- ³²B. K. Hoffmeister, C. I. Jones III, G. J. Caldwell, and S. C. Kaste, "Ultrasonic characterization of cancellous bone using apparent integrated backscatter," *Phys. Med. Biol.* **51**, 2715–2727 (2006).
- ³³B. K. Hoffmeister, J. A. McPherson, M. R. Smathers, P. L. Spinolo, and M. E. Sellers, "Ultrasonic backscatter from cancellous bone: The apparent backscatter transfer function," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **62**, 2115–2125 (2015).
- ³⁴B. K. Hoffmeister, M. R. Smathers, C. J. Miller, J. A. McPherson, C. R. Thurston, P. L. Spinolo, and S. R. Lee, "Backscatter-difference measurements of cancellous bone using an ultrasonic imaging system," *Ultrason. Imaging* **38**, 285–297 (2016).
- ³⁵B. K. Hoffmeister, P. L. Spinolo, M. E. Sellers, P. L. Marshall, A. M. Viano, and S. R. Lee, "Effect of intervening tissues on ultrasonic backscatter measurements of bone: An in vitro study," *J. Acoust. Soc. Am.* **138**, 2449–2457 (2015).
- ³⁶B. K. Hoffmeister, A. R. Wilson, M. J. Gilbert, and M. E. Sellers, "A backscatter difference technique for ultrasonic bone assessment," *J. Acoust. Soc. Am.* **132**, 4069–4076 (2012).
- ³⁷Y. Q. Jiang, C. C. Liu, R. Y. Li, W. P. Wang, H. Ding, Q. Qi, D. Ta, J. Dong, and W. Q. Wang, "Analysis of apparent integrated backscatter coefficient and backscattered spectral centroid shift in calcaneus *in vivo* for the ultrasonic evaluation of osteoporosis," *Ultrasound Med. Biol.* **40**, 1307–1317 (2014).
- ³⁸C. Liu, T. Tang, F. Xu, D. Ta, M. Matsukawa, B. Hu, and W. Wang, "Signal of interest selection standard for ultrasonic backscatter in cancellous bone evaluation," *Ultrasound Med. Biol.* **41**, 2714–2721 (2015).

- ³⁹T. Tang, C. Liu, F. Xu, and D. Ta, "Correlation between the combination of apparent integrated backscatter-spectral centroid shift and bone mineral density," *J. Med. Ultrason.* **43**, 167–173 (2016).
- ⁴⁰Ultrasonic Transducers Technical Notes, <https://www.olympus-ims.com/en/resources/white-papers/ultrasonic-transducer-technical-notes/> (Last viewed January 10, 2018).
- ⁴¹C. F. Njeh, C. M. Boivin, and C. M. Langton, "The role of ultrasound in the assessment of osteoporosis: A review," *Osteoporos. Int.* **7**, 7–22 (1997).
- ⁴²B. K. Hoffmeister, S. A. Whitten, S. C. Kaste, and J. Y. Rho, "Effect of collagen and mineral content on the high-frequency ultrasonic properties of human cancellous bone," *Osteoporos. Int.* **13**, 26–32 (2002).
- ⁴³B. K. Hoffmeister, S. A. Whitten, and J. Y. Rho, "Low-megahertz ultrasonic properties of bovine cancellous bone," *Bone* **26**, 635–642 (2000).
- ⁴⁴O. Riekkinen, M. A. Hakulinen, J. Toyras, and J. S. Jurvelin, "Spatial variation of acoustic properties is related with mechanical properties of trabecular bone," *Phys. Med. Biol.* **52**, 6961–6968 (2007).
- ⁴⁵P. Laugier, P. Droin, A. M. Laval-Jeantet, and G. Berger, "In vitro assessment of the relationship between acoustic properties and bone mass density of the calcaneus by comparison of ultrasound parametric imaging and quantitative computed tomography," *Bone* **20**, 157–165 (1997).
- ⁴⁶T. Hildebrand, A. Laib, R. Muller, J. Dequeker, and P. Rueggsegger, "Direct three-dimensional morphometric analysis of human cancellous bone: Microstructural data from spine, femur, iliac crest, and calcaneus," *J. Bone Miner. Res.* **14**, 1167–1174 (1999).
- ⁴⁷K. A. Wear, A. P. Stuber, and J. C. Reynolds, "Relationships of ultrasonic backscatter with ultrasonic attenuation, sound speed and bone mineral density in human calcaneus," *Ultrasound Med. Biol.* **26**, 1311–1316 (2000).
- ⁴⁸M. J. Grimm and J. L. Williams, "Assessment of bone quantity and 'quality' by ultrasound attenuation and velocity in the heel," *Clin. Biomech. (Bristol, Avon)* **12**, 281–285 (1997).
- ⁴⁹C. M. Langton, C. F. Njeh, R. Hodgkinson, and J. D. Currey, "Prediction of mechanical properties of the human calcaneus by broadband ultrasonic attenuation," *Bone* **18**, 495–503 (1996).
- ⁵⁰K. Mizuno, M. Matsukawa, T. Otani, P. Laugier, and F. Padilla, "Propagation of two longitudinal waves in human cancellous bone: An *in vitro* study," *J. Acoust. Soc. Am.* **125**, 3460–3466 (2009).
- ⁵¹C. C. Anderson, A. Q. Bauer, M. R. Holland, M. Pakula, P. Laugier, G. L. Bretthorst, and J. G. Miller, "Inverse problems in cancellous bone: Estimation of the ultrasonic properties of fast and slow waves using Bayesian probability theory," *J. Acoust. Soc. Am.* **128**, 2940–2948 (2010).
- ⁵²J. J. Hoffman, A. M. Nelson, M. R. Holland, and J. G. Miller, "Cancellous bone fast and slow waves obtained with Bayesian probability theory correlate with porosity from computed tomography," *J. Acoust. Soc. Am.* **132**, 1830–1837 (2012).
- ⁵³B. K. Hoffmeister, A. M. Viano, L. C. Fairbanks, S. C. Ebron, and J. A. McPherson, "Effect of gate choice on backscatter difference measurements of cancellous bone," *J. Acoust. Soc. Am.* **142**, 540–550 (2017).
- ⁵⁴P. H. Nicholson, M. J. Haddaway, and M. W. Davie, "The dependence of ultrasonic properties on orientation in human vertebral bone," *Phys. Med. Biol.* **39**, 1013–1024 (1994).
- ⁵⁵N. Bochud, Q. Vallet, J. G. Minonzio, and P. Laugier, "Predicting bone strength with ultrasonic guided waves," *Sci. Rep.* **7**, 43628 (2017).
- ⁵⁶J. Chen, J. Foiret, J. G. Minonzio, M. Talmant, Z. Su, L. Cheng, and P. Laugier, "Measurement of guided mode wavenumbers in soft tissue-bone mimicking phantoms using ultrasonic axial transmission," *Phys. Med. Biol.* **57**, 3025–3037 (2012).
- ⁵⁷J. Chen and Z. Su, "On ultrasound waves guided by bones with coupled soft tissues: A mechanism study and *in vitro* calibration," *Ultrasonics* **54**, 1186–1196 (2014).
- ⁵⁸G. Sellani, D. Fernandes, A. Nahari, M. F. de Oliveira, C. Valois, W. C. Pereira, and C. B. Machado, "Assessing heating distribution by therapeutic ultrasound on bone phantoms and *in vitro* human samples using infrared thermography," *J. Ther. Ultrasound* **4**, 13 (2016).
- ⁵⁹P. T. C. R. Rosa, M. D. P. A. J. F. Pereira, C. B. Machado, and W. C. A. Pereira, "Evaluating periodicity of trabecular bone phantoms using ultrasound signals," Proceeding of Pan American Health Care Exchanges Conference, Rio de Janeiro, Brazil (March 28–April 1, 2011), pp. 309–313.