Ultrasound in Med. & Biol., Vol. 23, No. 7, pp. 1123–1126, 1997

0301-5629/97 $17.00 + .00

ELSEVIER

PII S0301-5629(97)00023-9

Original Contribution

MEASUREMENT OF SHEAR-WAVE VELOCITY BY ULTRASOUND CRITICAL-ANGLE REFLECTOMETRY (UCR)

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(*Received* 19 *November* 1996; *in final form* 24 *February* 1997)

Abstract—There exists a growing body of research that relates the measurement of pressure-wave velocity in bone to different physiological conditions and treatment modalities. The shear-wave velocity has been less studied, although it is necessary for a more complete understanding of the mechanical properties of bone. Ultrasound critical-angle reflectometry (UCR) is a noninvasive and nondestructive technique previously used to measure pressure-wave velocities both *in vitro* and *in vivo*. This note describes its application to the measurement of shear-wave velocity in bone, whether directly accessible or covered by soft tissue. © 1997 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Shear-wave velocity, Bone mechanics, Material elasticity, Pressure-wave velocity, Ultrasound critical-angle reflectometry (UCR).**

INTRODUCTION

Bone mechanical competence may be studied through its elastic properties. These are generally multidimensional: Even for an isotropic material, 2 properties, the modulus of elasticity (E and Poisson's ratio (ν) must be known to characterize elastic behavior. These are, in turn, related to 2 sound propagation velocities—the pressure-wave (V) and the shear-wave (W) velocity (ρ = density) (Lees 1975; Pierce 1994):

$$\frac{E}{\rho} = W^2 \frac{3V^2 - 4W^2}{V^2 - W^2} \text{ and } \nu = \frac{V^2 - 2W^2}{2(V^2 - W^2)} \quad (1)$$

Although various ultrasound methods have been proposed for assessing the biomechanical competence of bone (as recently reviewed by Kaufman and Einhorn 1993), no existing system has as yet successfully addressed the noninvasive, nondestructive measurement of bone elastic properties. Pulse-echo or transmission techniques can be used to measure both velocities, but they require the use of two different single-mode transducers (pressure and shear) placed in direct contact with bone (Ashman et al. 1984). An ultrasound critical-angle reflectometry (UCR) technique has been developed in our laboratory (Antich et al. 1993b) to obviate this and other difficulties in the clinical setting (Ashman et al. 1994).

Earlier studies have demonstrated the application of UCR to accurate measurement of pressure-wave velocity in bone not only *in vitro* (Antich 1993; Antich et al. 1991) but also *in vivo* (Antich et al. 1993a). The present study extends the technique to the measurement of the shear-wave velocity. The UCR method is validated by measuring shear velocity in a number of materials, including cortical bone, and by demonstrating the feasibility of performing the measurement in the presence of soft tissue.

MATERIALS AND METHODS

The bone samples used in this study were cortical bone specimens from the diaphysis of a bovine femur. Samples were cut with the z-axis (direction 3) parallel to the length of the femur, the x-axis (1) in the transverse direction and the y-axis (2) along the radial direction pointing towards the endosteum.

The UCR technique is described in detail elsewhere (Antich et al. 1991; Mehta 1995). Briefly, changes in the amplitude and phase of an ultrasound beam reflected from a bone/soft tissue interface are analyzed over a range of angles of incidence (Fig. 1)

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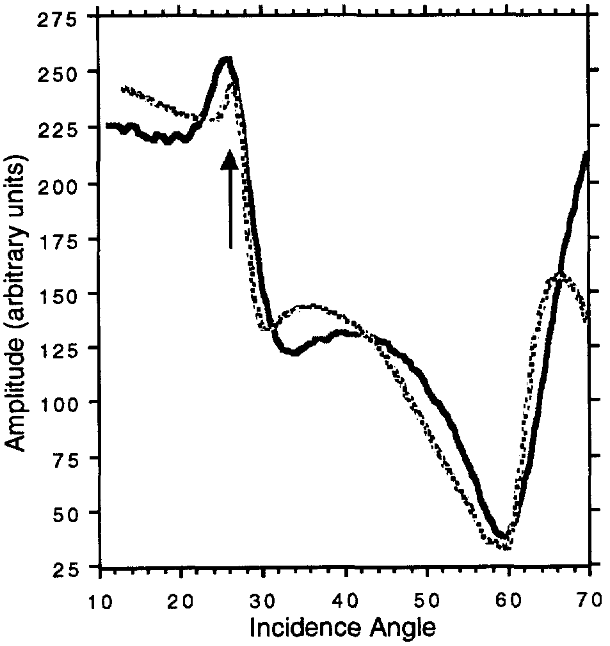

Fig. 1. Experimental data (solid line) and theoretical simulation (dotted line) for the amplitude of the pressure wave reflected from cortical bone. The pronounced peak in the amplitude spectrum allows determination of the pressure critical angle (arrow; pressure wave internally reflected). From this angle and the ultrasound velocity in water, known with high precision and accuracy, the pressure-wave velocity is obtained by Snell's law. By contrast, no pronounced peak is observed in correspondence to the shear-wave critical angle.

in the plane defined by the direction of the incident beam and the normal to the interface. From this analysis, the pressure- and shear-wave velocities in the solid are obtained as described in greater detail in Results.

Two pressure-wave transducers (5 MHz, planar with 0.373-inch and 0.5-inch diameter; Panametrics, Inc., Waltham, MA), a transmitter and a receiver, were mounted on arms that rotated about a center where the sample was situated. A mechanical positioning system was used to ensure that the normal to the sample surface was coplanar with the incident beam. Computer-controlled stepper motors (model M061-LS02; Superior Electric, Bristol, CT), moved the transducer arms along a circle in 0.3° steps. An ultrasound wave train of 4 cycles, generated by a signal generator (model AFG-5101; Tektronix Inc., Beaverton, OR) at 5 MHz, was reflected off the face of the sample and allowed to reach the receiving transducer, positioned symmetrically to the transmitter with respect to the normal. As the transducers are moved synchronously apart, the entire waveform, sampled and stored using a digital storage oscilloscope (Tektronix 2430A), was processed at each angle. The phase spectrum was obtained by measuring the phase shift of the waveform for each angle increment.

To intercompare the 2 ultrasound techniques, the UCR measurement was made in the plane normal to the lengthwise axis of the long bone and the transmission shear velocity was measured in the same plane using 2 shear- (transverse) wave transducers (Panametrics, 5 MHz) at 2 ends of the sample.

To explore the potential for the measurement of UCR shear velocity *in vivo*, the bones were covered with a layer of excised soft tissue. The soft-tissue layer, consisting of epidermal and dermal tissue fixed in formalin, was 3 mm thick and was held in contact with the bone sample by mechanical means. Acoustical continuity at the interface was ensured by physical contact and by the presence of air-bubble-free water at the interface. UCR shear-wave velocity measurements were obtained at the same location and orientation, first on the exposed bone sample and then on the sample covered with soft tissue. The 2 sets of readings were repeated at different orientations on each sample: 3 different bone samples were used for this experiment.

RESULTS AND DISCUSSION

Figures 1 and 2 show the amplitude and phase spectra of the wave reflected from a cortical bone sam-

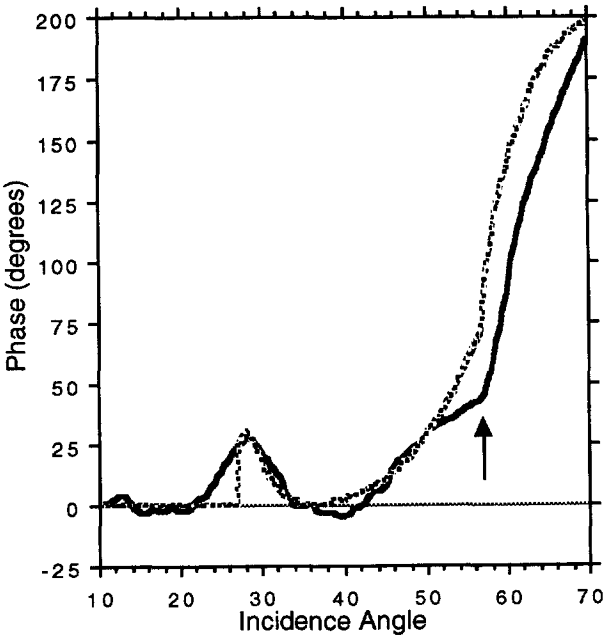

Fig. 2. Experimental (solid line) and theoretical simulation (dotted line) of variations in the phase of the pressure wave reflected from cortical bone. The sharp change in the slope of the phase spectrum (arrow; shear wave internally reflected) defines the shear critical angle. The shear-wave velocity is obtained from this angle and the ultrasound velocity in water using Snell's law, as before.

ple, measured using the experimental setup described above and compared with the spectra predicted by ultrasound reflection theory. The angular dependence of the amplitude and phase of the received signal match the theoretical expectations, even in the absence of corrections for beam width (Figs. 1, 2) (Antich 1988; Antich et al. 1991, 1993b; Mehta 1995).

The critical angle for total internal reflection of the pressure wave is obtained by measuring the angle of incidence at which the real part of the reflected amplitude is greatest (shown by an arrow in Fig. 1). This peak is followed by an abrupt drop in amplitude. In contrast, the critical angle for the shear wave in bone is not easily discerned in the received amplitude spectrum. However, the slope of the phase spectrum shows a distinct change in behavior at this point (arrow in Fig. 2), because it varies slowly before this angle, but rises rapidly after it to pass through a 90° phase shift corresponding to the minimum in the amplitude.

The 2 critical angles can be easily determined from these features in the amplitude and phase spectra of the reflected wave. The corresponding velocities are obtained by applying Snell's law:

$$V \text{ or } W = \frac{c}{\text{Sin}\ (\theta_c)} \tag{2}$$

where θ_c is the corresponding critical angle and c is the velocity of sound in water, an accurately and precisely known quantity. Thus, in the UCR method, only the critical angles, which can be measured with great accuracy, are needed to obtain the pressure- and shear-wave velocities in a solid.

The UCR measurements of shear-wave velocity were then compared with published values in several materials (Selfridge 1985) and to values directly measured in different bone samples using established transmission techniques with shear-wave transducers at the same frequency. The 2 sets of values are in excellent agreement ($R^2 = 0.999$, slope = 1, intercept 0, $p < 0.001$), validating the UCR measurement of shear velocities and demonstrating its accuracy (Fig. 3).

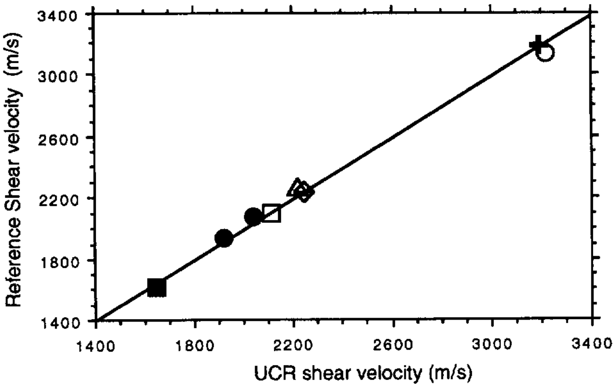

Fig. 3. Comparison of shear velocities measured by UCR (abscissa) to reference velocities (Selfridge 1985) and velocities measured by a reference transmission method (ordinate) for a variety of materials (○ = aluminum; □ = brass; △ = copper; + = steel; ● = cortical bone; ■ = silver; ◇ = bronze).

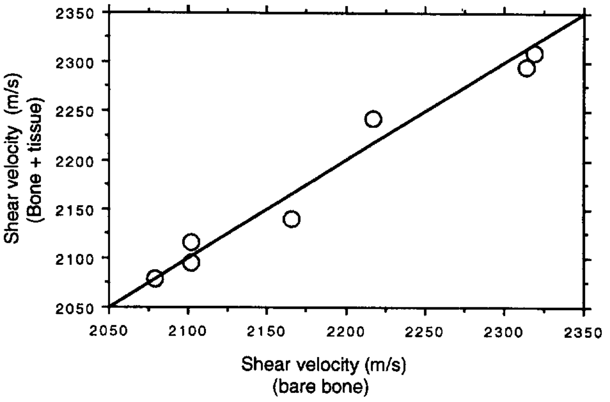

Fig. 4. Comparison of shear-wave velocities measured at different orientations, with or without overlying soft tissues. In 3 samples, the measurements were unchanged by soft tissue (slope = 1, $p < 0.001$; $R^2 = 1$), indicating the potential for applying this technique to measure the shear-wave velocity of bone *in vivo*.

An experiment was then conducted to explore whether or not reliable UCR measurements of shear velocity could be obtained in the presence of a soft-tissue layer covering the bone surface. As previously shown for pressure waves, the shear velocities obtained from bare bone were shown to be unchanged by the presence of soft tissues (Fig. 4).

In summary, the results shown here demonstrate for the first time that the accurate measurement of shear velocity can be obtained from the phase of the reflected amplitude. The measurement of shear velocity in bone covered with tissue indicates the potential for obtaining this measurement in the clinical setting *in vivo*. In addition, the UCR technique can also be applied to the analysis of elastic properties of composite materials other than bone.

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