Medical sciences

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Minkov Dimitar
MD PhD
Medical University Pleven,
Institute of Science and Research

ULTRASOUND CHARACTERIZATION OF THE BONE: A REVIEW

Summary. *Ultrasound parameters speed of sound and broadband ultrasound attenuation provide information about the mechanical properties of the bone. They serve to determine ultrasound bone density. Their correct interpretation is important for clinical practice.*

Key words: *speed of sound, broadband ultrasound attenuation*

Ultrasound is a mechanical wave. When the ultrasound wave propagates in the bone (through its two cortex and trabecular meshwork), its velocity and amplitude are influenced by the environment. Ultrasound velocity (SOS – speed of sound) and broadband ultrasound attenuation (BUA) are terms characterizing bone tissue [1].

Ultrasound Wave Velocity

The ultrasonic wave velocity that passes through a matter depends on the mechanical properties of the medium that are determined by the intermolecular bonds.

The relation of the ultrasound wave velocity with the mechanical properties of the medium is expressed by the following equation:

$$V=\sqrt{E/\rho} \quad (1.1)$$

where ρ is the density of the medium and E is the Young's modulus, a measure of resistance to deformation [2].

The equation (1.1) describes strictly anisotropic, heterogeneous and disperse matter to which the bone also belongs. That indicates why the value of the soft tissue is in the range of 1500 ms^{-1}, contrary to the cortical bone where the value is 3500 ms^{-1}. For comparison, for metals such as aluminium, the value is in the range of 8000 ms^{-1}.

The ultrasound wave velocity also depends on the type of propagation. The longitudinal waves are the most common type of ultrasound waves used in tissue investigations.

Broadband Ultrasound Wave Attenuation

Within the frequency range of 100 kHz to 1 MHz, which is the most suitable for bone testing, the attenuation is approximately linearly proportional to the frequency as follows:

$$\mu(f) = \alpha f \quad (1.2)$$

where α is the slope of frequency attenuation (dB MHz^{-1} cm^{-1}). In the clinical practice that is known as broadband ultrasonic attenuation (BUA) Fig. 1-b.

The broadband ultrasonic wave attenuation is measured by recording the amplitudes of the ultrasound pulse frequencies in a reference (calibration) medium. In this case, this is degassed water and through a sample of the test material, as shown in Fig. 1-a.

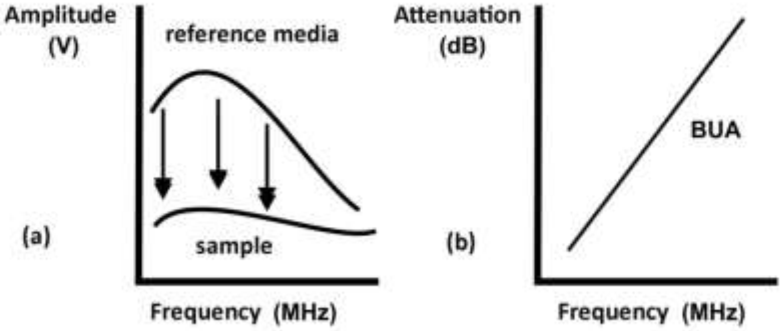


Fig. 1. Presentation of the BUA measurement (a), which describes the measurements of the sound frequency through the reference media (water) and the test sample. Graphic representation of the result (b).

The attenuation (dB) of each frequency (*f*) is calculated by subtracting the amplitude of the test material from the amplitude of the water. The result can also be expressed graphically (Fig. 1-b) in the range of 200 KHz and 600 KHz. The slope of this curve is defined as a *BUA index* with a unit of measurement dB MHz^{-1}. When the resulting analytical curve is divided by the width of the measured material, a volume parameter with a unit of measurement dB MHz $^{-1}$ cm^{-1} is obtained.

Clinical Measurement of the Ultrasound Wave Velocity

Ultrasonic methods used in bone densitometry are mainly transmissive techniques. The ultrasound pulse enters the bone at one point and is captured after it passes the entire distance through the tissues (Fig. 2).

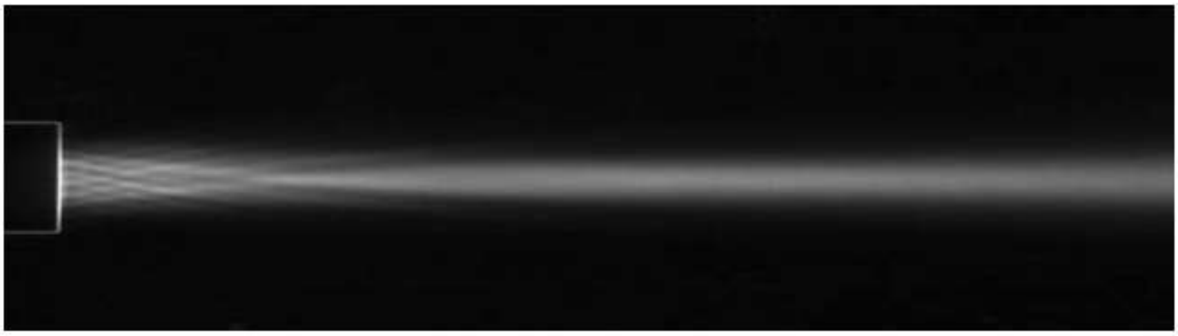


Fig. 2. A picture of an ultrasound wave emitted by a piezoelectric crystal at a frequency of 1.25MHz (after Guglielmi al., 2009) [3].

This technique differs from the conventional ultrasound imaging based on the reflection of the ultrasound pulse from a surface between the tissues. It returns to the point from which it was generated (pulse echo technique). The frequency used for bone densitometry (100 kHz to 1.5 MHz) is lower than that used in soft tissue sonography (2.5 MHz to 1.5 MHz). That pulse passes through the bone with measurable speed (SOS) and attenuation (BUA). The good acoustic contact between the transducers and the skin is of great importance. That can be achieved by using an ultrasound gel or immersing in water the two transducers and the examined body area [4].

Ultrasound Wave Formats

The ultrasound waves (Fig. 3) could be described in terms of their length over time as: an *uninterrupted wave*, which by definition is continuous for a relatively infinite period of time (Fig. 3-a); a wave *frequency packet type* that is part of the continuous wave and represents a frequent, repetitive series of a certain number of wavelengths (Fig. 3-b); an *ultrasound impulse* which is a section from a straight line in the frequency area and after passing through certain matter it acquires the shape depicted in Fig. 5c [5].

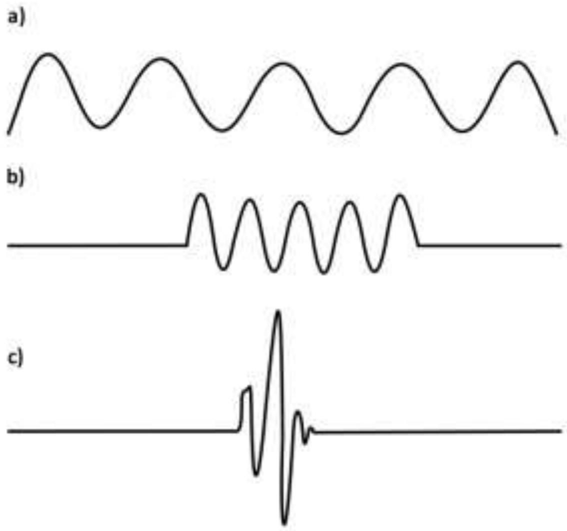


Fig. 3. Ultrasound wave along its time axis: (a) uninterrupted, (b) frequency packet type and (c) ultrasonic impulse passed through the tested sample

Methods for Measuring the Ultrasound Wave

The clinical ultrasound speed measurement could be performed by *pulse-echo* or a *transmissive method*. The pulse-echo method uses a single transducer for transmitting and receiving the signal (Fig. 4).

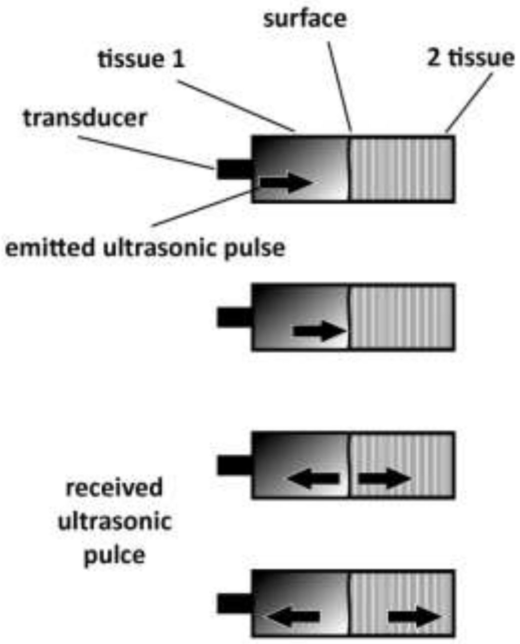


Fig. 4. A pulse echo technique where a single transducer emits an ultrasound pulse and then receives the ultrasound pulses reflected by the tissues

The generated ultrasound impulse passes through the tissues; it is reflected and received by the same transducer.

In the pulse-echo measurements, the propagation time is increased 2 times because the wave falls into the zone of interest and returns back to the transducer. The ultrasound scanners for clinical use assume that all tissues have a constant velocity however that may lead to measurement errors or the appearance of artifacts in the resulting image.

With this method, the standard equation for calculating the sound wave velocity is:

Pulse speed = ***Thickness of the measured tissue*** / ***Time for passing through the tissue*** (1.3)

that could be converted into

Tissue thickness = ***Assumed to be the accurate velocity for passing through the tissue*** x ***Measured time for passing*** (1.4)

In the transmission method, one transducer is a transmitter and the other one a receiver. Both transducers could be located coaxially (5-a) or pseudo-reflective (5-b).

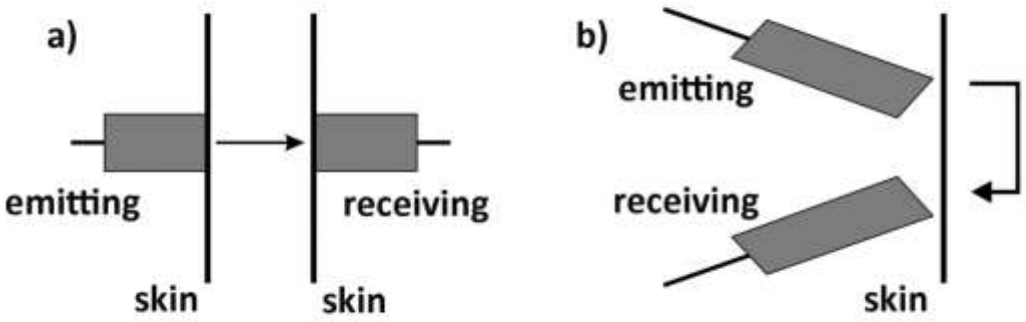


Fig. 5. Transmission technique in which individual transducers are intended for emitting and receiving the ultrasound pulse. The transducers may be located coaxially (a) or pseudo-reflective (b)

The transmission method is preferred for bone tissue testing because bone tissue implies a high degree of ultrasound wave attenuation [6].

Anatomic Regions for *in vivo* Osteometry by Quantitative Ultrasound

Bone assessment by quantitative ultrasound is done in different regions of the skeleton:

- calcaneus;
- phalanges of the fingers;
- tibia;
- patella;
- radius.

Calcaneus is the most preferred site for quantitative ultrasound testing due to several reasons. It is built in 90% of the trabecular bone that provides a large volume surface. The heel bone is a zone where large metabolic changes occur, unlike the cortical bone, and that allows for early bone tissue changes to be detected [7].

The heel bone anatomical characteristics are an additional advantage to be a preferred location for peripheral ultrasound testing.

Calcaneus is covered by soft tissues with a thickness from 5 to 10 mm. *Chappard* has found the heel bone width to be within the range 30.7 ± 2.7 mm and the soft tissue thickness 8.8 ± 1.7 mm medially and 8.5 ± 1.5 mm laterally. All measurements were performed in a nuclear magnetic resonance study [8].

The calcaneal width measured by *Wu* in a X-ray study was 29.6 ± 2.9 mm [9].

Another anatomical feature that makes the calcaneus suitable for ultrasound testing is its flat and parallel to one another medial-lateral surfaces.

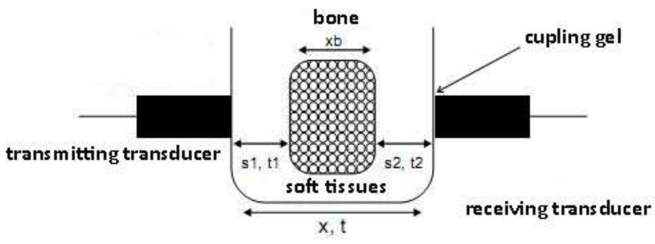
Wasnich and Black have defined the heel bone as the optimal region for bone mineral density routine screening for osteoporotic fractures in postmenopausal women [10].

The Scientific Group on the Prevention and Treatment of Osteoporosis at the WHO defines calcaneus as the only anatomical site suitable for ultrasound osteometry [11].

Ultrasound osteometry in the region of phalanges of the fingers, tibia, patella and radius, provides values that cannot be used for bone status assessment in postmenopausal women. Quantitative ultrasound devices that perform measurements in these regions should not be applied in osteoporosis screening.

Methods for Calculating Ultrasound Wave Velocity in Calcaneus Testing

Three different methods for calculating the ultrasound wave velocity are used in heel bone testing. They are based on: velocity related to the heel (the wave passes through the calcaneus and the soft tissue, Fig. 6-a), bone velocity (the wave passes only through the calcaneus), and velocity associated with the time for passing of the wave. In the latter method (Fig. 6-b), fixed transducers are used and the time for passing of the wave in an aqueous medium is recorded [12].



(a) Contact method

(b) Substitution method

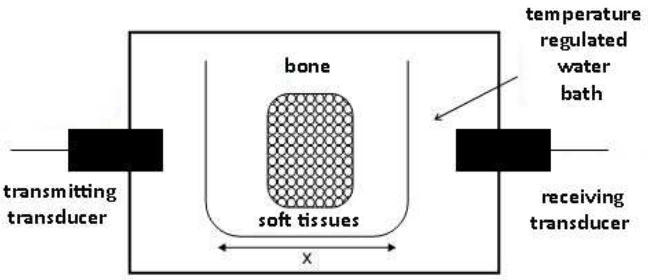


Fig. 6. Schematic presentation of methods for ultrasound measurement in the region of the calcaneus. Contact (a) and substitution (b) method (after Njeh et al., 1997) [13]

Let ***x*** be the heel thickness including the soft tissues (fig. 6), and ***xb*** – the calcaneus thickness without the soft tissues covering it, ***tx*** and ***tb*** are the corresponding times for passing through ***x*** and ***xb***.

Let the soft tissues thickness be ***s1*** and ***s2***, and the time for passing of the ultrasound through them is ***t1*** and ***t2***, respectively.

Then the velocity related to the heel (the wave passing through the calcaneus and the soft tissues, 2.5) and the bone velocity (the wave passes only through the calcaneus, 2.6) can be expressed by the following formulas:

$$\text{Скорост на звука (пета)} = \frac{x}{t_x} \quad (1.5)$$

$$\text{Скорост на звука (петна кост)} = \frac{X_b}{t_b} = \frac{x-(s_1+s2)}{t_x-(t_1+t2)} \quad (1.6)$$

The calculations obtained for the ultrasound wave velocity expressed in formulas (1.5) and (1.6) show small differences in the values but correlate well with each other: r = 0.83 - 0.98 [14].

When the ultrasound enters the medium, part of its energy is lost. The intensity of the flat wave (the wave composed of parallel small waves) propagating in ***y***-direction decreases with the distance as follows:

$$I_y = I_0 e^{-\mu(f)y} \qquad (1.7)$$

where **μ(*f*)** is the frequency coefficient **(*f*)** – contingent on the attenuation intensity (dB/cm), I_0 is the incidental intensity and ***Iy*** is the intensity along the distance ***y***.

The attenuation factors include beam propagation (diffraction), diffusion and absorption and mode change [15].

The ultrasound attenuation in the spongy bone is predominantly by diffusion, while in the cortical bone it is mainly due to absorption [16].

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