ULTRAS 4683
4 October 2013
ARTICLE IN PRESS
No. of Pages 8, Model 5G

Ultrasonics xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Numerical investigation of ultrasound reflection and backscatter measurements in cancellous bone on various receiving areas

Atsushi Hosokawa *

Department of Electrical and Computer Engineering, Akashi National College of Technology, 679-3 Nishioka, Uozumi, Akashi 674-8501, Japan

A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Cancellous bone
Reflection
Backscatter
Membrane hydrophone
Numerical simulation

A B S T R A C T

In this study, new ultrasound reflection and backscatter measurements in cancellous bone using a membrane-type hydrophone are proposed. A membrane hydrophone made of a piezoelectric polymer film mounted on an annular frame allows an incident ultrasound wave to pass through its aperture because it has no backing material. Therefore, in measurements using the membrane hydrophone, the receiving area could be located independently from the transmitting area. In addition, the size and shape of the receiving area, which corresponded to those of the electrode deposited on the piezoelectric film, could be arranged in various ways. To investigate the validity of the proposed measurements, before bench-top experiments, the reflected and backscattered waves from cancellous bone were numerically simulated using a finite-difference time-domain method. The reflection and backscatter parameters were measured on various receiving areas, and their correlation coefficients with the structural parameters in the cancellous bone were derived. The simulated results suggested that appropriate receiving areas for the reflection and backscatter measurements could exist and that the proposed measurements could be more effective for evaluating bone properties than conventional measurements.

1. Introduction

Various ultrasound measurements in bone have been studied to establish accurate and precise quantitative ultrasound (QUS) techniques for clinical assessment of bone quality [1–4]. Among these, ultrasound reflection and backscatter measurements in cancellous bone have been attempted [4–6] because of their easy applicability to skeletal sites where through-transmission measurements are difficult. The reflected and backscattered waves are generally received using only one transducer that acts as both transmitter and receiver in pulse-echo mode. Thus, the sizes, shapes, and locations of the transmitting and receiving areas must be the same; however, independent arrangement of the receiving area is desirable to effectively detect the wave characteristics associated with the bone properties.

In this study, new reflection and backscatter measurements in cancellous bone are proposed in which a membrane-type hydrophone is inserted between the ultrasound transmitter and the bone. The membrane hydrophone is composed of a piezoelectric polymer film and an annular frame without a backing material, which allows an incident ultrasound wave to pass through its aperture [7,8]. The advantage of the technique is that when the membrane hydrophone is used, the receiving area can be easily changed, which was the advantage in the proposed measurements. It is difficult to verify an ultrasound measurement in bone because an immense number of experiments are required owing to the variability in bone structure. Numerical simulations are helpful as a surrogate for experiments [9,10]. Thus, by using a finite-difference time-domain (FDTD) method [11–14], the reflected and backscattered waves from the cancellous bone were numerically simulated for various receiving areas. The correlations of the reflection and backscatter parameters with the structural parameters of the cancellous bone—specifically the porosity and mean intercept lengths (MILs) [15] of the trabecular elements and pore spaces—were investigated to demonstrate that the dependences of QUS parameters on bone properties can change with the receiving areas.

2. Ultrasound measurements using a membrane hydrophone

2.1. Membrane hydrophone

Piezoelectric polymer films such as poly(vinylidene fluoride) are a suitable piezoelectric material for an ultrasound receiver in water (namely hydrophone) because their acoustic impedances are relatively close to the impedance of water. Hydrophones made of piezoelectric films can be classified into two types: needle-type [16] and membrane-type [7,8]. The former is composed of the piezoelectric film and a cylindrical backing material, and the latter is composed of the film and an annular frame. A schematic of the

* Tel.: +81 78 946 6123; fax: +81 78 946 6138.
E-mail address: hosokawa@akashi.ac.jp

0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.09.017

construction of the membrane hydrophone is shown in Fig. 1. In the case of the general construction in Fig. 1(a), circular and linear electrodes are deposited on the piezoelectric film. The circular electrodes on either surface overlap, but the linear electrodes are separated. Therefore, an incident ultrasound wave can be received only in the circular area, which corresponds to the receiving area. In a membrane hydrophone, various receiving areas can be easily realized by changing the overlapping area of the electrodes, as in the annular area in Fig. 1(b). Moreover, as shown in Fig. 1, no material exists on the back of the receiving area.

2.2. Measurement of reflected and backscattered waves

Fig. 2 illustrates the method of measuring the reflected and backscattered ultrasound waves from cancellous bone using the membrane hydrophone. The hydrophone was arranged between the needle-type ultrasound transmitter and the cancellous bone in water. Because the acoustic impedance of the hydrophone's piezoelectric film was close to that of water, the transmitted ultrasound wave could pass through the film and arrive at the cancellous bone. The reflected and backscattered waves from the bone were received by the membrane hydrophone.

If the inner diameter of the annular frame mounting the piezoelectric film is sufficiently larger than the diameter of the ultrasound beam, the membrane hydrophone cannot significantly disturb the ultrasound field. The half-width 2θ of the ultrasound beam (wavelength: λ) transmitted from a circular flat surface (diameter: $2a_t$) is approximated as

$$2\theta \approx 2\arcsin\left(0.705\frac{\lambda}{a_t}\right), \quad (1)$$

and the beam diameter $2a_b$ at a distance d from the transmitter is calculated as

$$2a_b \approx 2d\tan\theta. \quad (2)$$

For example, for $\lambda = 1.48$ mm at a frequency of 1 MHz in water, $2a_t = 10$ mm, and $d = 40$ mm, the calculated $2a_b$ is approximately 17.1 mm; thus, an inner diameter of 20 mm is adequate for the annular frame. Practically, a smaller inner diameter is acceptable because a focused transmitter is generally used in QUS apparatuses for bone assessment.

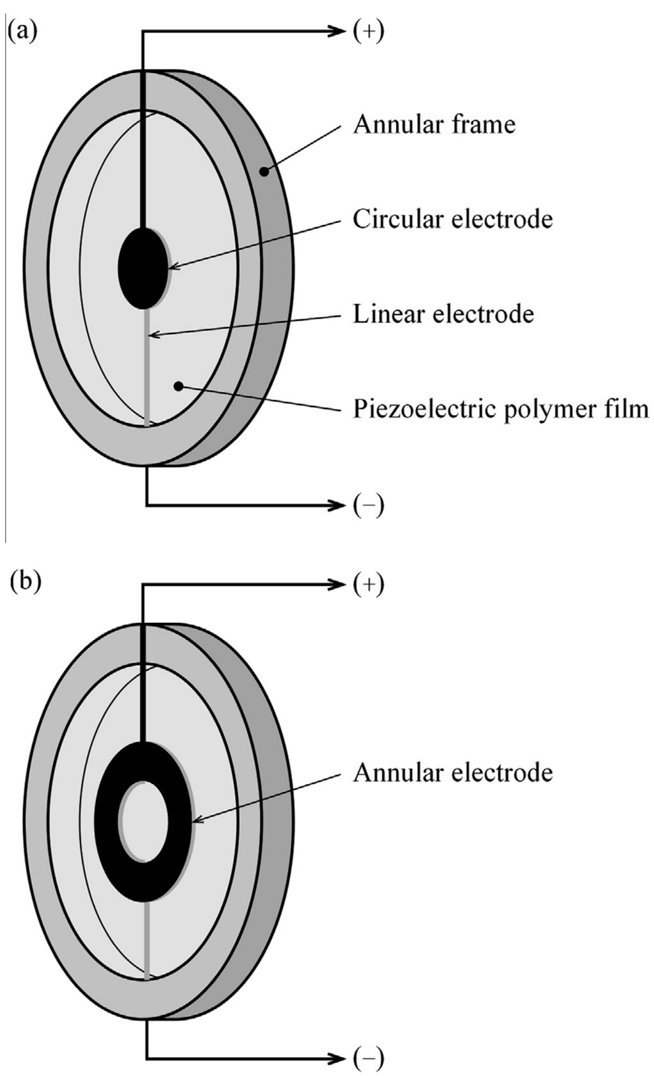

Fig. 1. Schematic construction of membrane hydrophones with (a) circular and (b) annular receiving areas.

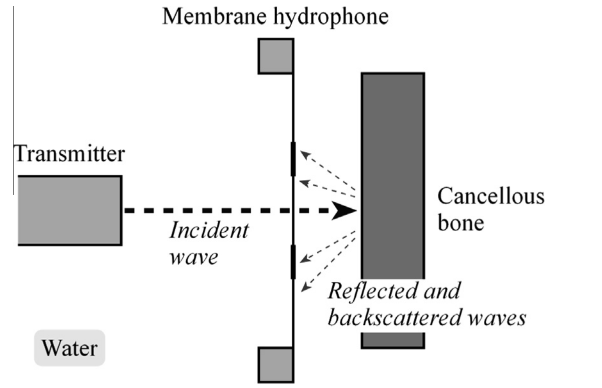

Fig. 2. Method of measuring reflected and backscattered ultrasound waves from cancellous bone using a membrane hydrophone.

3. Numerical simulations of reflection and backscatter measurements

3.1. Simulation model

Three-dimensional (3D) FDTD simulations of reflection and backscatter measurements using the membrane hydrophone were performed using self-made FDTD software [14]. The simple simulation model was constructed with consideration of *in vitro* experiments, which will be performed for comparison between the experimental and simulated results in the future. A cross-sectional view of the simulation model is shown in Fig. 3. This model had a spatial interval of 57 μm and consisted of cancellous bone and water regions, whose dimensions were $5.016 \times 6.84 \times 6.84$ mm^3 ($88 \times 120 \times 120$ points) and $7.98 \times 6.84 \times 6.84$ mm^3 ($140 \times 120 \times 120$ points), respectively. In Fig. 3, the x-direction corresponds to the direction of ultrasound transmission, and the y–z plane corresponds to the cancellous bone surface.

The transmitting area with a rigid backing material had a circular concave shape with a diameter of 5.7 mm (100 points), which was set at the center of the y–z plane at $x = 0$ mm at a distance of 7.98 mm (140 points) from the cancellous bone surface. The focal distance was 10.488 mm (184 points), which corresponded to the focal point 2.508 mm (44 points) inside of the cancellous bone. The transmitted waveform was a single sinusoid at 1.0 MHz multiplied by a Hanning window (note that the center frequency was shifted to approximately 1.25 MHz owing to the window). Its time interval was 4 ns. At x = 0, 1.995, 3.99, and 5.016 mm (0, 35, 70, and 88 points) from the transmitting area [7.98, 5.985, 3.99, and 2.964 mm (140, 105, 70, and 52 points) from the cancellous bone

Please cite this article in press as: A. Hosokawa, Numerical investigation of ultrasound reflection and backscatter measurements in cancellous bone on various receiving areas, Ultrasonics (2013), http://dx.doi.org/10.1016/j.ultras.2013.09.017