Experimental study of transmission of a pulsed focused beam through a skull phantom in nonlinear regime
S. A. Tsyr, A. V. Nikolaeva, V. D. Svet, V. A. Khokhlova, P. V. Yuldashev, and O. A. Sapozhnikov

Citation: AIP Conference Proceedings 1685, 040013 (2015); doi: 10.1063/1.4934408
View online: http://dx.doi.org/10.1063/1.4934408
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1685?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
An MR-compatible phantom for evaluating the propagation of high intensity focused ultrasound through the skull

Experimental and numerical investigation of ultrasonic transmission through the skull bone and associated temperature rise

Frequency-dependent ultrasound transmission through the human skull
J. Acoust. Soc. Am. 117, 2412 (2005); 10.1121/1.4786266

Focusing of therapeutic ultrasound through a human skull: A numerical study

Linearity of sound transmission through the human skull in vivo
Experimental Study of Transmission of a Pulsed Focused Beam through a Skull Phantom in Nonlinear Regime

S. A. Tsyan1,a), A. V. Nikolaeva1, V. D. Svet2, V. A. Khokhlova1, P. V. Yuldashev1 and O. A. Sapozhnikov1,3

1Physics Faculty, Moscow State University, Leninskie Gory, Moscow 119991, Russian Federation
2Andreyev Acoustics Institute, 4, Shvernik Street, Moscow 117036, Russian Federation
3Center for Industrial and Medical Ultrasound, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA

a)Corresponding author: sergey@acs366.phys.msu.ru

Abstract. In the paper the use of receiving and radiating system, which allows to determine the parameters of bone by nonlinear pulse-echo technique and to image of brain structures through the skull bones, was proposed. Accuracy of the skull bone characterization is due to higher measured harmonic and is significantly better than in linear case. In the experimental part focused piezoelectric transducer with diameter 100 mm, focal distance 100 mm, the frequency of 1.092 MHz was used. It was shown that skull bone profiling can be performed with the use of 3rd harmonic since 1st harmonic can be used for visualization of the underlying objects. The use of wideband systems for both skull profiling and brain visualization is restricted by skull attenuation and resulting low effective sensitivity.

INTRODUCTION

The problem of ultrasound imaging of brain structures is complicated by the presence of a strongly inhomogeneous absorbing skull. Number of papers demonstrates the controlled transmission of the ultrasonic beam through the skull bone, mainly in the problems of therapeutic ultrasound. Defining the parameters of the skull bones was performed by computed tomography [1] or by phase conjugation of the acoustic field in the presence of a strong scatterer inside the skull [2]. In case of biopsy interstitial technique with MR guidance is applicable [3]. A few groups work on acoustic methods of the skull bone characterization [4]. In current paper we propose the use of receiving and radiating system, which allows to determine the parameters of bone by nonlinear pulse-echo technique and to image of brain structures through the skull bones by 1st harmonic pulses. The use of higher harmonics allows to expect improved accuracy of the skull bone characterization, which is due to higher measured harmonic and is significantly better than in linear case.

SKULL BONE PHANTOMS

Numerous investigations of skull bone parameters show wide range of values of density, speed of sound and shear waves, absorption coefficient [5]. For the principal investigations of method mentioned the stable properties of the samples are preferred. In current work a phantom skull bones were created with using of modified epoxy resin and aluminum oxide powder. Hardener composition is suitable for making thick layers (up to 10 cm) without typical defects inherent classical type hardener. The density of the resin is 1.2 g/cm³, the density of aluminum oxide is 4 g/cm³, hardener density is 1 g/cm³. When preparing the samples, first a hardener and the resin are mixed in a constant proportion of 3:5 by weight, and then aluminum oxide was added to vary absorption coefficient.

To determine the acoustic parameters of bone phantom an experimental setup consisting of transmitter and receiver located in a tank with degassed water was used. The flat sample layer was placed between the transducers.
FIGURE 1. Acoustic properties of created bone phantoms with different aluminum oxide mass portion: speed of longitudinal waves (a), circles, and shear waves (a), squares. Absorption coefficient (b) at 1 MHz (circles), 2.2 MHz (triangles) and 3 MHz (squares).

As the emitting and receiving transducers flat wideband piezoceramic Panametrics NDT sources with diameter 3.8 cm, with the center frequency of 1.0, 2.25, 5 MHz, and the width of the operating frequency range of 62% by -6 dB were used. Transducers are coaxially arranged at a distance of 9 cm from each other. Probing acoustic signal was transmitted in the form of a short pulse with duration of 1-2 microseconds. For used set of the phantoms the following parameters were obtained: speed of sound 2.6 mm/μs, shear waves speed 1.3 mm/μs, absorption coefficient 4 dB/cm at 1 MHz (see Fig. 1).

SKULL BONE PROFILING

In current study synthesized two-dimensional ultrasound array was used. Despite of time-consuming problem it has an advantage in term of high flexibility of geometric and acoustic parameters. Once technique developed and tested with the synthesized array parameters for the real 2D array can be found. In this paper one single-element focused piezoelectric transducer with diameter 100 mm, focal distance 100 mm, the frequency of 1.092 MHz was used. The transducer was positioned in front of skull phantom at distance of 100 mm, so the focus of the beam was localized on the front surface of a phantom skull. The transducer emits short radioimpulse signals with effective duration of 5-20 periods of the fundamental frequency. The radiation power was adjusted so as to give nonlinear mode of propagation, while the focus region contains noticeable harmonics, up to 5th. Signal reflected from the phantom was detected by the same transducer. Because of the fact that the piezoelectric transducer is sensitive to the odd harmonics only, the electrical signal contains information about the pulses with carrier frequencies of about 1, 3, and 5 MHz. The movement of a focused transducer was performed by computer controlled positioning system with 4 degrees of freedom (Velmx UniSlide VP9000 and Precision Acoustics UMS 3) so that the focus is moved over the surface of the phantom skull. Thus the synthesis of two-dimensional ultrasound array was performed. Using data from the reflected signal, the thickness of the phantom for each location point of focal spot was measured. The procedure of the measurements consists of several steps. First, position of the front surface of the skull phantom was detected by the measurements of time delay of reflected pulse. Due to resonant behavior of the piezoceramic transducer it generates long pulse with effective length of 15-20 cycles even with 1-2 cycles excitation. It leads to interference of pulses reflected from front and back surfaces of the phantom and measured reflected signal represents result of interference and reverberation for all harmonics presented. Nevertheless, this mixed signal contains information about skull thickness or at least position of the back surface. Thus, the back surface detection procedure is the next step. Here we can use again time delay measurement of the initial part of the signal reflected from the back surface. In order to extract this initial part of the back-reflected signal we need some reference signal. Ideally it should be pulse reflected from very thick phantom. In this case mixed signal subtraction from the reference one forms the new signal, initial part of which is the beginning of back-scattered pulse. In a real conditions, of course, such ideal reference signal does not exist.
Solution is in the use of the signal from the point with the higher thickness as reference. In this case subtraction of all mixed signals for other points over the phantom from the reference results the signal as for ideal case but with quite short trusted interval. Size of this trusted time window $\Delta\tau$ defined by the skull thickness variation $\Delta l$ over the region of investigation as $\Delta\tau = 2\Delta l/c_l$. Here $c_l$ is sound speed in phantom. Determination of the point corresponding to the higher thickness can be performed with simple iteration procedure. Here assumption about constant reflection properties of the front surface of the phantom was made. In practice, reflection conditions vary from point to point but this variation is smooth due to low curvature of the outer surface of the skull and can be corrected by signal scaling. Typical set of subtracted signals for 3rd harmonic for linear scan is presented on Fig. 2a. Scanning over 2D surface allows to extract 3D structure of the back surface (see Fig. 2b). Note, the beginning of the trusted interval is located after zone with constant phase. The final step is filtering and fitting (radial basis functions were used) of extracted data (see Fig. 3a). In addition with front time delay data for mixed signals which contain information about front surface it is possible to reconstruct thickness profile of the bone phantom as shown on Fig. 3b.

Skull phantom thickness measurements were also performed with wideband focused transducer (Panametrix NDT, aperture 1", focal distance 3", band 1-5 MHz) and results were compared with the nonlinear technique. Results are in a good agreement. The main difference is in generated pulse length. In case of wideband transducer signals reflected from front and back surfaces of the skull phantom do not interact and both surfaces can be clearly seen. It seems to be more adequate method for skull profiling but it cannot be used for brain visualization simultaneously (as described in the next chapter) and therefore is not optimal for complex problem of both profiling and visualization.

FIGURE 2. (a) Typical set of subtracted signals (see text for description) for 3rd harmonic along one direction. (b) Points of back surface detected with the scan over 2D region 4x4 cm with the step of 0.5 mm.

FIGURE 3. (a) Filtered and fitted with a radial basis functions back surface of the skull phantom. (b) Left: photo of the skull phantom with 4x4 cm region of scan. Right: reconstructed location and thickness profile of the 4x4 cm part of the used skull bone phantom.
FIGURE 4. Left column: view of the measurement process in a free field (top) and behind the skull (bottom). Center: image of the 5 styrofoam scatterers on the 1st harmonic of the backscattered signal. Right: 3rd harmonic imaging of the same scatterers.

**IMAGING ABILITY**

In order to test the imaging ability of the nonlinear components reconstruction of a set of a strong scatterers of different size (1-5 mm) placed behind a phantom skull was performed. Visualization of the objects was based on the registration of the signal passed through the phantom skull, reflected from the investigating objects and propagated backward to the transducer through the phantom for each focus position. Enhanced resolution of high harmonics which is due to shorter wavelength can be achieved only without skull layer (Fig 4, top line). As it can be seen reflected signal from the strong scatterers are below the noise level even for up to 5k samples averaging on 14 bit ADC in presence of skull phantom. First harmonic has sufficient level of reflections and can be used for imaging. This will allow us to take into account the inhomogeneity of the skull bones and to compensate the refraction of the ultrasonic beam transmitting through bone during data processing which is a topic for the future work.

**ACKNOWLEDGMENTS**

We acknowledge funding from RSF №14-15-00665.

**REFERENCES**