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● *Technical Note*

OBSERVATION OF GUIDED ACOUSTIC WAVES IN A HUMAN SKULL

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Abstract—Human skull poses a significant barrier for the propagation of ultrasound waves. Development of methods enabling more efficient ultrasound transmission into and from the brain is therefore critical for the advancement of ultrasound-mediated transcranial imaging or actuation techniques. We report on the first observation of guided acoustic waves in the near field of an *ex vivo* human skull specimen in the frequency range between 0.2 and 1.5 MHz. In contrast to what was previously observed for guided wave propagation in thin rodent skulls, the guided wave observed in a higher-frequency regime corresponds to a quasi-Rayleigh wave, confined mostly to the cortical bone layer. The newly discovered near-field properties of the human skull are expected to facilitate the development of more efficient diagnostic and therapeutic techniques based on transcranial ultrasound. E-mail: hector.estrada@helmholtz-muenchen.de, hector.estrada@posteo.org © 2018 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

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INTRODUCTION

Bones carry out important mechanical and hematopoietic functions and their mechano-structural anomalies, such as osteoporosis, can in principle be detected using ultrasonic methods (Laugier and Haïat 2011). Yet, the human skull bone poses a challenge in the study of the brain by ultrasound-mediated techniques (Fry and Barger 1978). Understanding the interaction of ultrasound waves with the human skull (Clement and Hynynen 2002a, 2002b; Clement et al. 2004; Fry and Barger 1978; Marquet et al. 2009; Pichardo et al. 2011; Pinton et al. 2012) has been paramount in achieving focused ultrasound therapy deep inside human brain (Coluccia et al. 2014). In small animals, optoacoustic neuroimaging techniques (Dean-Ben et al. 2017; Yao and Wang 2014) have been successful in delivering transcranial images of cerebral vasculature by means of ultrasonic waves generated on absorption of nanosecond laser pulses in the brain (Estrada et al. 2016; Kneipp et al. 2016). While for high-intensity focused ultrasound (HIFU) therapy, the sources of narrowband ultrasound vibrations are located outside the head and far away from the skull, in optoacoustic neuroimaging applications, the broadband ultrasound waves are generated mainly inside the brain in close proximity to the skull, supporting the existence of skull-guided acoustic waves (GAWs) in mice (Estrada et al. 2017). GAWs also exist in long cylindrical bones (Moilanen 2008; Moilanen et al. 2014; Talmant et al. 2011), enabling the assessment of cortical bone thickness and stiffness (Bochud et al. 2017). However, the inner structure of the human skull, composed of two cortical bone layers separated by a substantial layer of trabecular spongious bone (the diploë), is considerably different from that of other types of bones. It also significantly deviates from the structure found in murine skulls (Brookes and Revell 1998; Estrada et al. 2016, 2017; Jilka 2013), where the cortical bone layer occupies a larger proportion of the cross section while, in some regions, the diploë is considerably thinner or nonexistent.

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In addition to transcranial ultrasonography (Baykov et al. 2003; Lindsey et al. 2014; Shapoori et al. 2015), new ultrasound-mediated techniques are currently being proposed (Seo et al. 2013, 2016) to monitor neural activity in cortical areas of the human brain transcranially. It is thus desirable to extend the current knowledge of the near-field ultrasound wave propagation of the human skull.

METHODS

Experimental setup

Fresh-frozen frontotemporal bone sample derived from decompressive hemicraniectomy was collected according to protocols established by the ethics committee of the Department of Neurosurgery at the University Hospital Cologne. The skull sample was kept at −80°C and was later degassed for 3 hours and immersed in 0.9% saline solution during the imaging experiments, which were performed in full compliance with the institutional guidelines of the Helmholtz Center Munich. To investigate the existence of GAWs in a human skull, we adapted an approach similar to that of Estrada et al. (2017), where the exact shape of the skull surface was first obtained from a pulse-echo scan (Fig. 1b) performed with a focused transducer (20-mm focal distance, 15-MHz central frequency; V313-SM, Olympus, Waltham, MA, USA) with a step size of 200 μm. To excite broadband optoacoustic responses, a 200-μm-thick layer of a black burnish attached on the interior side of the skull sample was illuminated with 1-mJ laser pulses of 10-ns duration and 532-nm wavelength (Lab-190-30, Spectra Physics, Santa Clara, CA, USA) focused down to a 1-mm spot. The generated responses were recorded by a needle hydrophone (0.5-mm diameter; Precision Acoustics, Dorchester, UK) that was scanned following the path $r_{||}$ in close proximity to the skull's surface across the right temporal bone (see Fig. 1). The scanning step size (0.4 mm) was selected to allow analysis in the spatial frequency domain up to 1.25 (mm^{-1}). The laser pulse was fired at a repetition frequency of 15 Hz, and the data acquisition was synchronized using a photodiode (DET10A, Thorlabs, Newton, NJ, USA) to avoid jitter in the laser trigger signal (Fig. 1). The laser energy fluctuations were further accounted for using pulse-to-pulse photodiode measurements. The data were digitized at 60 MS/s by the data acquisition card (M3i.4142, Spectrum Instrumentation GmbH, Grosshansdorf, Germany) and stored for further analysis on a personal computer.

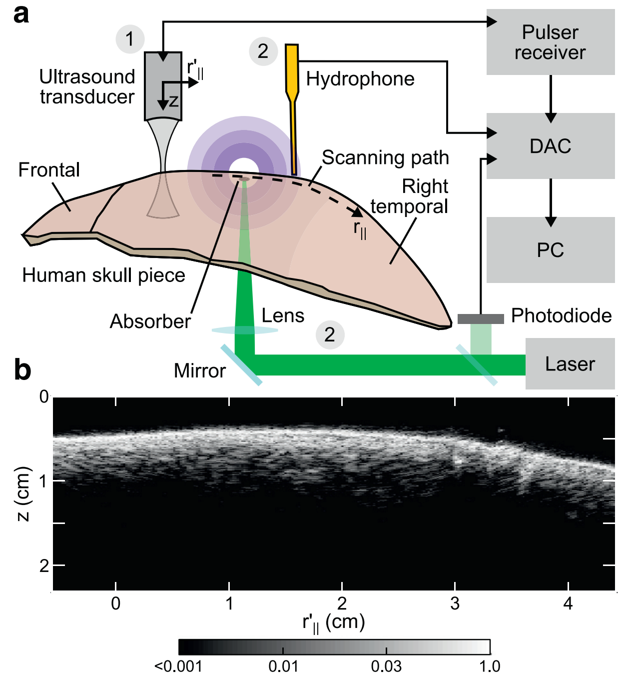

Fig. 1. Experimental setup and skull surface mapping. (a) Schematic of the experimental setup depicting the water-immersed piece of human skull sample. The skull's surface is first extracted from a pulse-echo ultrasound scan (1). The propagation of waves generated by laser excitation of an optical absorber placed on the inner side of the skull is measured by a needle hydrophone scanned in close proximity (near field) of the skull (2).The signals digitized by the acquisition card (DAC) are stored in a personal computer (PC), which also controls the scanning stages. (b) B-Mode ultrasound scan of the skull's cross section along the hydrophone scanning path.

Simulations

As a first approximation, we modeled a flat multilayered viscoelastic solid embedded in a fluid (Estrada et al. 2017) by means of the global matrix method (Lowe 1995). For a given frequency and wavevector $k_{||}$ (incidence angle), a plane (inhomogeneous) wave is propagated from the input fluid, through the solid layers, to the output fluid. In the solid layers, longitudinal and transverse waves are considered in the propagation, as well as reflections at each interface between different media (Estrada et al. 2017), forming a linear system of equations with 14 unknowns (complex transmitted and reflected amplitudes in each medium). First, the transmission problem was solved at a given region of the reciprocal space (frequency wavevector), and then the transmission maxima at the output fluid were extracted. Second, a modal solution of the system was found by further refining the position of the extracted transmission maxima in reciprocal space using a golden-section search for singularity of the global matrix. The calculation of the linear system of equations (Lowe 1995) was implemented in C++, and the analysis of the results was performed in Python. We assumed a total skull thickness of $h = 6$ mm (manually measured average) and elastic constants close to those reported in the literature for cortical and trabecular bones (Culjat et al. 2010) (see Table 1).