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Transcranial focusing of arbitrary ultrasonic fields using acoustic holograms

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Abstract

We present ultrasonic phase plates that are able to produce arbitrary field distributions, i.e., acoustic holograms, inside the skull. Using 3D printing techniques, we are able to produce lenses that correct the aberrations of the skull and, simultaneously, produce ultrasonic fields whose spatial distribution fits a target organ at the central nervous system. In particular, using experimental techniques on a human skull phantom and full-wave simulations, several configurations are tested. First, a multiple-point focusing lens is designed to simultaneously focus at both human hippocampi. Second, a beam following an arbitrary curved trajectory, i.e., a self-bending beam is presented. Finally, we report a holographic plate producing a broad focus that overlaps with the left hippocampus. The results show that 3D printed holographic lenses can be used to control the spatial features of ultrasonic beams inside the skull in an unprecedent manner using single-element ultrasonic sources.

Keywords: Acoustic holograms; Transcranial focusing; Biomedical ultrasound.

1 INTRODUCTION

Acoustic holographic lenses are complex surfaces that can modify the phase of the transmitted or reflected wavefront in such a manner that a complex image can be formed. Acoustic holographic lenses have demonstrated the ability to manipulate acoustic waves in free media, i.e., without inhomogeneities [1, 2, 3, 4]. In the context of biomedical applications, when the target tissue lays behind high-impedance tissues, e.g., soft-tissue surrounded by bones, the beam experiences strong aberrations due to refraction, reflection and absorption processes [5]. In the particular case of transcranial propagation skull bones are always present in the path towards the central nervous system (CNS). In this way, the precise control of acoustic focus into the CNS is mainly limited due to the strong phase aberrations produced by the refraction and attenuation of the skull [6].

Only few works have tackled the problem of beam focusing through aberrating layers using metamaterials [7] or phase plates [8]. In Ref. [7] a 2D configuration was proposed theoretically using a metasurface based on membranes. Recently, the use of phase plates to generate simple focused sources have been reported to avoid beam aberrations in transcranial propagation [8]. However, the technique was limited to focus the beam into a single focal spot at the near field of the source. Besides, in some non-thermal transcranial ultrasound applications such as blood-brain barrier opening [9] or neuromodulation [10] the ultrasound beam might be set to fully-cover a geometrically complex CNS structure rather than focusing over a small focal spot.

In this work [11], we propose the use of 3D-printed holographic phase plates to produce ultrasonic fields of arbitrary shape into the human brain. The holographic lenses designed in this work allow the reconstruction of complex diffraction-limited acoustic images including the compensation of the aberrations produced by a skull phantom. In particular, we theoretically, numerically and experimentally demonstrate the generation of several holographic patterns, of increasing complexity, all with direct practical application to biomedical ultrasound: an arbitrary set of points, an arbitrary curved line, and an arbitrary volume.

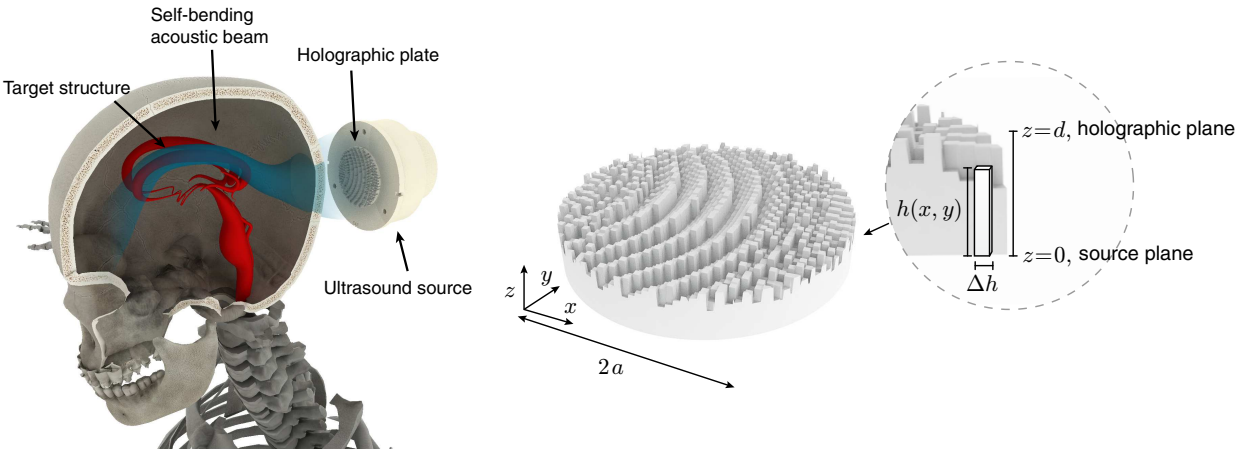


Figure 1. (a) Scheme of the holographic lens focusing over a target CNS structure. (b) Geometry of the holographic lens. The lens, of aperture $2a$ is subdivided in pixels of height $h(x,y)$. The source is located at $z=0$, while the holographic plane is located at $z=d$.

2 Results

2.1 Multiple-point holograms

First, two points located at the center of mass of both left and right human hippocampi are selected. The details about the hologram generation and the methods used can be found in Ref.[11]. The field produced by the bifocal lens propagating through a human occipital/parietal skull phantom including the compensation for the aberrations of the skull is shown in Figs. 2 (a-f). First, Figs. 2 (a,b) show the axial field cross-section, $p(x,y=0,z)$, using the pseudo-spectral simulation method and measured experimentally, respectively. We observe that the reconstructed field accurately matches the target foci, and the experimental results agree with the simulations. The corresponding transverse field distributions at $z=105$ mm are shown in Figs. 2 (c,d) where sharp focusing is observed.

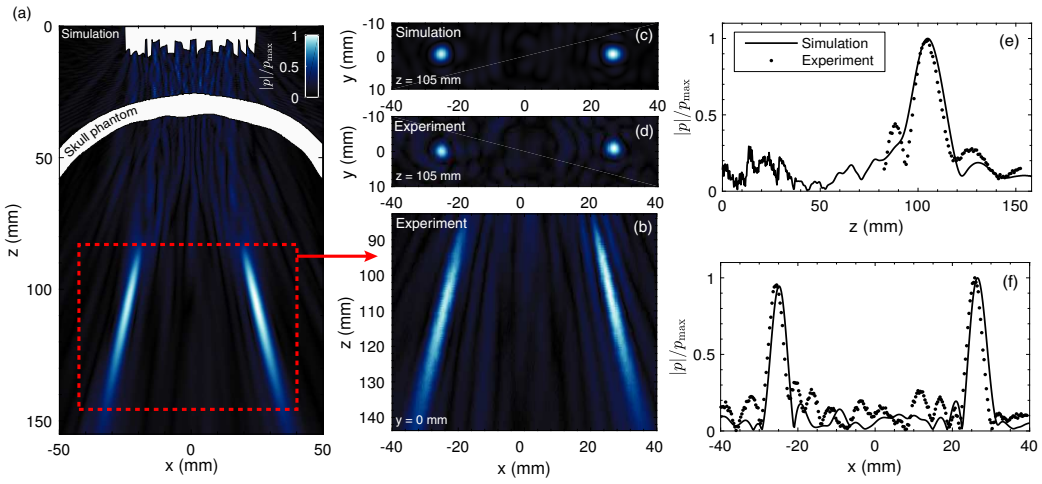


Figure 2. Axial field cross-section obtained for the bifocal lens using simulations (a) and experiments (b). (c-d) Corresponding transversal pressure field distributions. Colorbar in units normalized to the peak pressure. (e,f) Simulated and experimental normalized axial and transversal field cross-sections, respectively.

2.2 Self-bending beams

The previous results show that holographic phase plates can retain phase information of multiple foci. Using this idea, we can set more complex targets following the shape of functional structures found in the CNS. Here, we set the target holographic pattern to a beam following a curved trajectory. A sketch of the target trajectory is shown in Fig. 3 (a). The axial cross-sections of the forward propagated field in water is shown in Fig. 3 (a). We observe that using TR method the self-bending beams can be obtained, and the beam accurately follows the target trajectory. Using simulation and a lens made of elastic material a similar result is obtained, as shown in Fig. 3 (b). The experimental tests show a similar pressure field distribution in comparison with theory using the Rayleigh-Sommerfeld integral and simulations using pseudo-spectral methods. Finally, when the aberration layer of the skull phantom is included the corresponding holographic lens also reconstructs the target acoustic image with curved trajectory, as shown in Figs. 3 (c). A similar lateral shift of the peak pressure location in the experiments, of 0.25 mm in the x direction is observed at $z = 30$ mm and $y = 0$ mm. Both results demonstrate that using TR methods self-bending beams following a target curve can be obtained inside the skull phantom using acoustic holographic lenses.

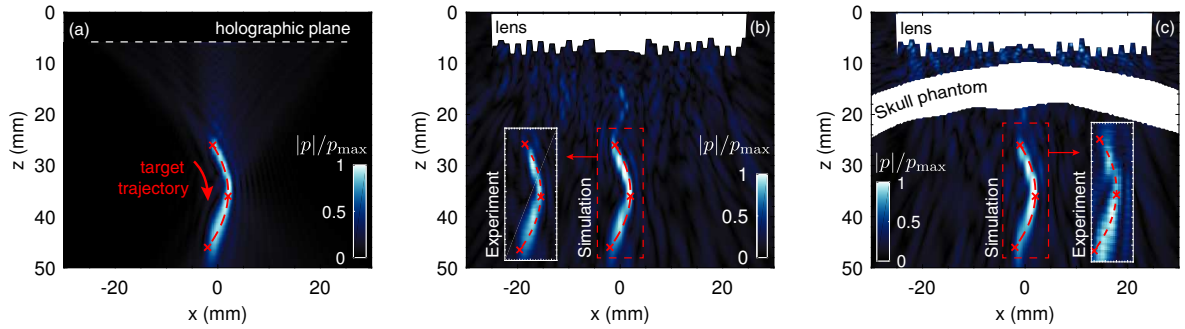


Figure 3. Theoretical (a) axial pressure field distribution for the self-bending beam in water. Simulated (b) axial pressure field distribution for the self-bending beam in water. Corresponding experimental results are shown in the insets in (b). (c) Simulated axial and transversal pressure field including the skull phantom. Corresponding experimental results are shown in the insets.

2.3 Volumetric holograms overlapping CNS structures

Going further, we designed a holographic lens which produces an acoustic image that fits the right human hippocampus volume. The holographic surface was placed near the occipital/parietal bones to adapt the acoustic image to the elongated geometry of the human hippocampus. However, we locate the lens at the center of the skull symmetry plane in order to demonstrate the steering capabilities of this holographic lens.

The field distribution produced by acoustic holographic lenses including the skull phantom is shown in Figs. 4. Both holographic images present the same qualitative performance and provide a similar overall covering of the interest zone. In addition, both axial (Fig. 4 (a,b)) and transversal (Figs. 4 (c,d)) field distributions are similar of those produced in water without the skull phantom, showing that, first, limited-diffraction holographic volumes can be reconstructed and, second, the aberrations produced by the skull phantom on these complex beams can be compensated at the source plane by the acoustic holographic lenses. Finally, the transversal and axial cross-sections, shown in Figs.4 (e,f), show that the experimental and simulated acoustic holographic lens produces a field enhancement that matches the target distribution.

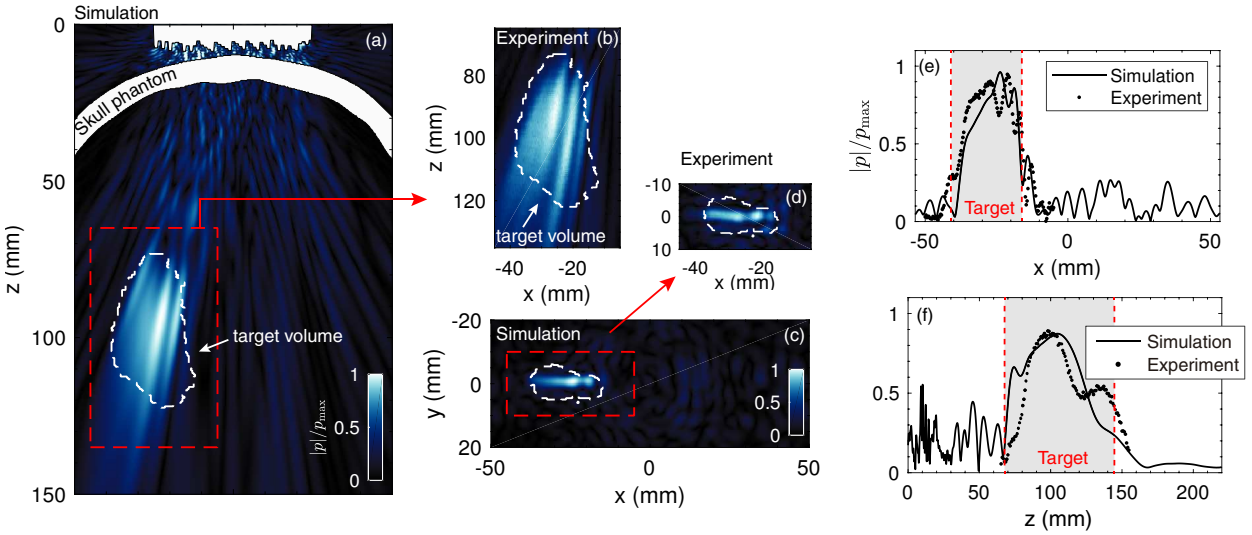


Figure 4. Volumetric hologram results. (a,b) Simulated and experimental axial pressure distribution. (c,d) Transversal field cross-sections. (e) Simulated, experimental transversal field distribution. (f) Simulated and experimental axial pressure distribution.

3 CONCLUSIONS

We have shown that using 3D printed acoustic holograms it is possible to conform diffraction-limited ultrasonic fields of arbitrary shape compensating the aberrations of a the human skull. In particular, experimental tests using a 3D printed skull phantom and numerical simulations using a realistic skull were performed to accurately generate multiple focal holograms, self-bending beams and volumetric holographic fields overlapping a target CNS structure. The proposed approach using holographic lenses represents a step forward when compared with the existing solutions using phase arrays, since it opens new venues to develop reliable and cost reduced ultrasonic applications.

The concept shown in this work opens new doors to optimize and widespread incoming therapy treatments such as ultrasound-assisted blood-brain barrier opening for drug delivery and neuromodulation, or ultrasonic imaging of the central nervous system using low-cost devices. Considering the emergence of metamaterials [12] and their huge flexibility, we also advance incoming biomedical applications of active holographic metasurfaces for the generation of complex fields in the central nervous system.

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