Sculpting thermal and acoustic fields by 3D-printed holograms

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Abstract: In this work, we present the recent advances of acoustic holograms and structured media to engineer the acoustic wavefront to focus ultrasound beams for biomedical applications. We show how acoustic holograms can shape therapeutical acoustic images for the non-invasive treatment of neurological disorders, to produce cavitation patterns for localized drug delivery, and thermal patterns of arbitrary shape for targeted hyperthermia. In this way, acoustic holograms emerge as a disruptive and low-cost approach for biomedical ultrasound applications.

Optical holograms can modulate light wavefronts to generate visible images [1]. In the same way, acoustic images can also be synthesized by holograms, shaping the areas where mechanical waves present a high amplitude, and areas where the media is at rest. In recent years, acoustic holograms have been exhaustively studied, mainly triggered by the emergence of 3D printing technologies. Artificially structured materials have enabled accurate wavefront engineering for many applications such as particle trapping and manipulation, scattering control and vortex generation, fast 3D-printing, volumetric displays, or 3D imaging [2-3]. Acoustic holograms have found recent application in emerging therapeutic applications of focused ultrasound [4-8].

We show how acoustic holograms can shape therapeutical acoustic images for the non-invasive treatment of neurological disorders, to produce cavitation patterns [7] and thermal [8] patterns. When targeting acoustic beams into the brain, accurate focusing is mainly limited by strong phase aberrations produced by the refraction and attenuation of the skull. Acoustic holographic lenses can overcome these limitations by synthetizing aberration-free ultrasonic fields of complex spatial distribution inside the skull. Our results show that, using low-cost 3D-printed lenses, ultrasonic beams can be focused not only on a single point, but overlapping at one or various target structures simultaneously, e.g., left and right hippocampi. Other complex fields such as vortex beams for trapping small objects can also be obtained [6]. The technique was tested to perform localized drug-delivery in the brain of a small laboratory animal. Local gadolinium extravasation was confirmed by magnetic resonance imaging, where two spherical focal spots were observed. In addition, acoustic holograms encode the multiple reflections inside the skull, increasing the angular spectrum of the acoustic image. In this way, acoustic holograms enabled localized drug-delivery in the brain with diffraction-limited beyond the performance of existing approaches. The technique was also tested to shape thermal patterns in soft tissue to rise the temperature locally. Magnetic resonance imaging (MRI)-compatible holograms were designed by time-reversal simulations and manufactured using 3D-printing for the experiments. We observed that holograms can shape heating patterns in arbitrary regions, sculpting the focal spot of the source to match a therapeutical target.

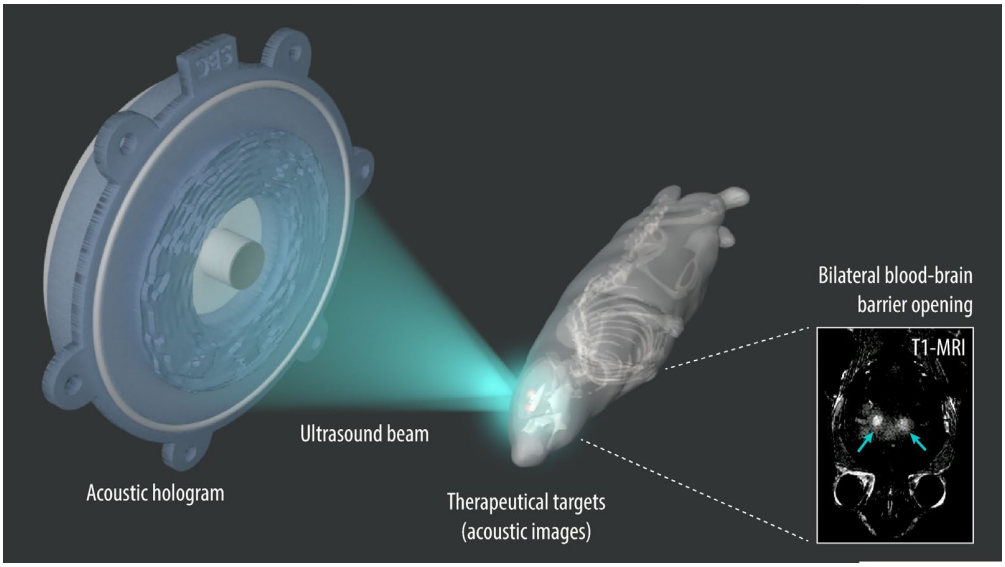


Fig. 1. Scheme of an acoustic hologram simultaneously targeting an ultrasonic beam at two brain hemispheres in a mouse, T1-MRI after the treatment shows contrast agent (gadolinium) extravasation at two spherical spots, demonstrating localized drug-delivery and blood-brain barrier opening.

These results open new paths for emerging therapeutic ultrasound applications in neurology, including blood-brain barrier opening for localized drug-delivery or neuromodulation using low-cost systems. On the other hand, increasing the temperature using low-cost and MRI-compatible holographic transducers might be of great interest for many biomedical applications, such as ultrasound hyperthermia, physiotherapy, or high intensity focused ultrasound, where the control of specific thermal patterns is needed.

References

1. D. Gabor, "A New Microscopic Principle" Nature, Vol. 161, pp. 777–778 (1948).
2. N. Jiménez, J.-P. Groby, and V. Romero-García, "Spiral sound-diffusing metasurfaces based on holographic vortices" Sci. Rep. Vol. 11, pp. 10217 (2021).
3. K. Melde, E. Choi, Z. Wu, S. Palagi, T. Qiu, and P. Fischer, "Acoustic Fabrication via the Assembly and Fusion of Particles", Adv. Mater. Vol. 30, pp. 1704507 (2018).
4. S. Jiménez-Gambín, N. Jiménez, J. M. Benlloch, and F. Camarena, "Holograms to Focus Arbitrary Ultrasonic Fields through the Skull" Phys. Rev. Appl. Vol. 12, pp. 014016 (2019).
5. D. Andrés, N. Jiménez, J. M. Benlloch, and F. Camarena. "Numerical Study of Acoustic Holograms for Deep-Brain Targeting through the Temporal Bone Window". Ultrasound Med. Biol. (2022).
6. S. Jiménez-Gambín, N. Jiménez, and F. Camarena, "Transcranial Focusing of Ultrasonic Vortices by Acoustic Holograms", Phys. Rev. Appl. Vol. 14, pp. 054070 (2020).
7. S. Jimenez-Gambin, N. Jiménez, A. Pouliopoulos, J. M. Benlloch, E. E. Konofagou, and F. Camarena, "Acoustic Holograms for Bilateral Blood-Brain Barrier Opening in a Mouse Model". IEEE Trans. Biomed. Eng. Vol. 69, No. 4, pp. 1359-1368 (2022).
8. D. Andrés, J. Vappou, N. Jiménez, F. Camarena. "Thermal holographic patterns for ultrasound hyperthermia" Applied Physics Letters, Vol. 120, No. 8, pp. 084102, (2022).