P-BRT-12

Topic: Brain Technical
Presentation Type: Poster

Conformation of ultrasonic vortex beams through the skull using acoustic holograms for particle trapping

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Background: Acoustic tweezers are a versatile and powerful emerging tool to biomedical applications, such as cell manipulation or drug delivery, as they allow contactless particle manipulation using low-power devices. Single beam acoustic tweezers based on vortex beam require a focused ultrasound beam containing a phase dislocation at its axis. While these beams have demonstrated great potential to trap particles in homogeneous media, phase aberrations produced by strongly heterogeneous and refracting media distorts the wavefront and inhibit the generation of trapping forces. In this work we report a method to conform aberration-free focused vortex beams through the skull for transcraneal particle trapping using acoustic holograms.

Materials and Methods: The method is based on a single-element focused ultrasound source and a spiral-holographic lens. First, using x-ray CT images of an ex-vivo human skull and time-reversal full-wave simulations we model the wave propagation from the desired trapping-location inside the skull towards the location of the focused transducer. The holographic information at 500 kHz is recorded at source location and a holographic lens based on Fabry-Perot resonators is designed using phase-conjugation methods. The acoustic hologram is manufactured using stereolithographic 3D-printing with a 50 μm resolution in a rigid polymer. Then, the target acoustic vortex is generated by exciting the lens with a custom single-element focused transducer of 100-mm aperture and 140-mm focal length. The hologram was excited with a 500-kHz pulsed burst using a duty-cycle of 5 %. The focusing performance of the ultrasonic vortex was evaluated by hydrophone measurements of the acoustic field performed in a water tank using a micro-positioning system, scanning with a resolution of 100 μm over a 2 cm per 5 cm area [measurements shown in Figure 1 for water and Figure 2 for transcranial propagation]. Finally, a series of elastic 3D-printed spheres of apertures from 1 to 0.25 mm in radius were stably trapped at the centre of the acoustic, and calibrated optical tracking techniques were applied to measure its location inside the water bath.

Results: A phase dislocation was identified at the focal area. The magnitude of the field shows a ring-shaped focused spot with a FWHM of 11.36 mm in the axial direction [see Figure 1(a) for water and Figure 2(a) for skull] and 4.9-mm in the transversal direction [see Figure 1(b,d) for water and Figure 2(b,d) for skull], while the topological charge of the measured vortex is the unity [see Figure 1(c,e) for water and Figure 2(c,e) for skull]. In contrast, when using a holographic vortex-lens designed for homogeneous media, the phase aberrations produced by the skull distort the wavefront and the vortex was not observed. A particle was placed at the focal spot [see Figure 1(f) for 1-mm radius sphere trapping] and optical tracking measurements show that in water its position remained stable while the ultrasound transducer was active. The location of the particle matched the location of the phase singularity of the beam in water.

Conclusions: The results show that, by compensating the phase aberrations produced by the skull, wavefront containing phase dislocation can be generated in the cranial cavity. Such a focused vortex beam can be used to trap a solid particle in an arbitrary position. These results open new paths for contactless manipulation of objects in complex biomedical environments such as relocating clots during an ischemic stroke or the propulsion of large drug-delivery vehicles. Beyond particle trapping applications, focusing vortex beams containing phase dislocations opens new venues to transfer angular momentum to brain tissues that might be used for non-thermal therapeutic purposes.

Acknowledgements: This research has been supported by the Spanish Ministry of Science, Innovation and Universities through grants "Juan de la Cierva – Incorporación" IJC2018-037897-I and PID2019-111436RB-C22, by the Agència Valenciana de la Innovació through grants INNVAL10/19/016 and INNCON/2020/009, and by Generalitat Valenciana through grant ACIF/2017/045. Action co-financed by the European Union through the Programa Operativo del Fondo Europeo de Desarrollo Regional (FEDER) of the Comunitat Valenciana IDIFEDER/2018/022.

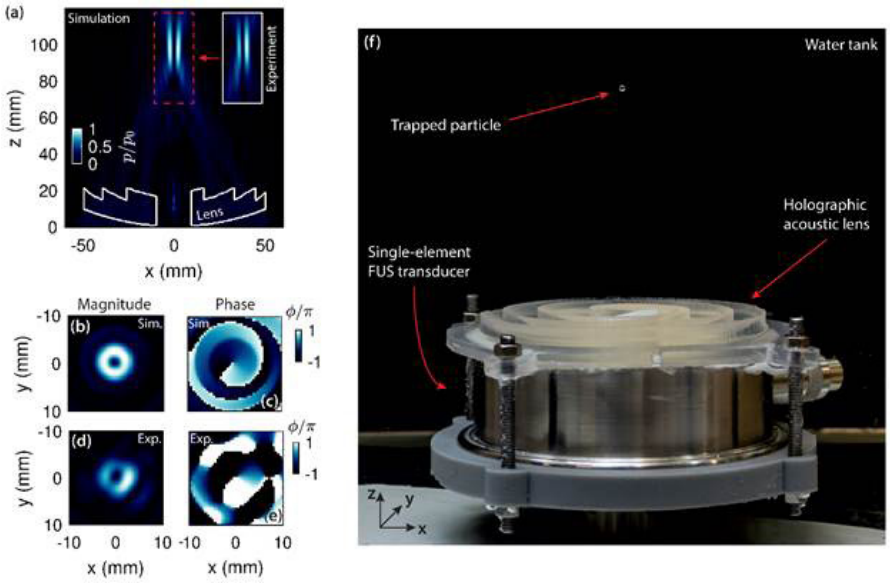


Figure 1. Pressure-field distribution and particle trapping using the acoustic hologram in water. (a) Simulated axial pressure-field distribution at y=0 mm; experimental result shown in the inset.

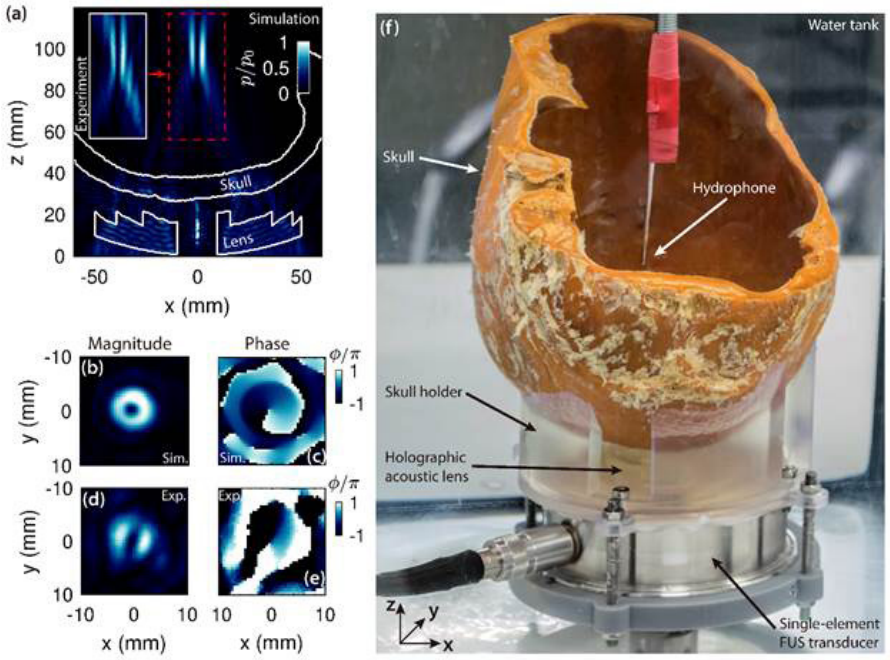


Figure 2. Pressure-field distribution using the acoustic hologram through the skull. (a) Simulated axial pressure-field distribution at y=0 mm; experimental result shown in the inset.