ACOUSTIC HOLOGRAMS FOR TRANSCRANIAL FOCUSING OF ARBITRARY ULTRASONIC FIELDS INTO THE BRAIN

Sergio Jiménez-Gambín, Noé Jiménez, José María Benlloch, Francisco Camarena

Instituto de Instrumentación para Imagen Molecular, CSIC- Universitat Politècnica de València, 46022 València, Spain

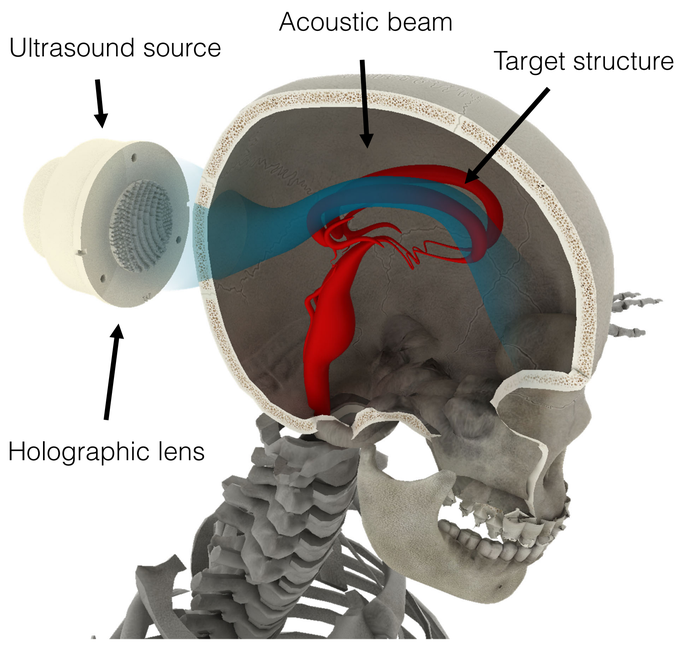
INTRODUCTION

Background

Focused ultrasound is currently used in many emerging therapeutic applications for the non-invasive treatment of neurological disorders and pathologies inside the central nervous system. The accurate focusing ultrasound beams at the central nervous system is mainly limited due to the strong phase aberrations produced by refraction and attenuation of the skull.

Our proposal

We present 3D-printed acoustic holographic lenses for the generation of ultrasonic fields of complex spatial distribution inside the skull.



METHODS

Theory

To describe acoustic propagation in water we make use of the Rayleigh-Sommerfeld integral:

$$p(\mathbf{r},\omega) = \frac{i\omega\rho_0}{2\pi}\int_S \frac{v_0(\mathbf{r}_0)\exp\left(-k_0\left|\mathbf{r}-\mathbf{r}_0\right|\right)}{\left|\mathbf{r}-\mathbf{r}_0\right|}dS,$$

This expression is used to model back-and-forward propagated fields.

Simulations

When the skull in present, a numerical method based on the pseudo-spectral (*k*-space) and time-domain approximation of the constitutive relations for acoustic waves in heterogenous media including frequency-power law absorption and dispersion is used:

$$\frac{\partial\rho}{\partial t} = -\rho_0\nabla\cdot\mathbf{u} - \mathbf{u}\cdot\nabla\rho_0,$$
$$\frac{\partial\mathbf{u}}{\partial t} = -\frac{1}{\rho_0}\nabla p,$$
$$p = c_0^2\left(\rho + \mathbf{d}\cdot\nabla\rho_0 - \mathrm{L}\rho\right),$$

Experiments

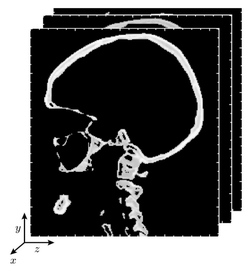
Calculations are validated with measurements in a water tank at 1.1 MHz using a transducer of 50 mm of aperture and a skull phantom.

HOLOGRAM DESIGN

Lens design consist in:

(1) Image acquisition

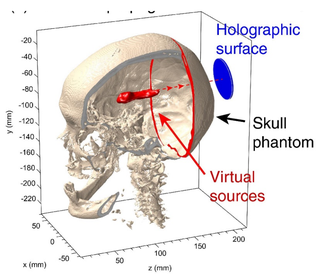
CT images provide bone apparent density used for simulation methods.



MRI tomographic data segmentation of the soft-tissues under interest is required for treatment planning.

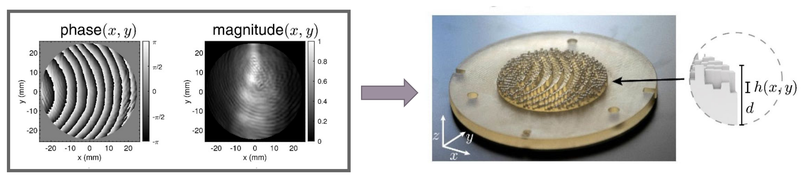
(2) Back-propagation

Time-reversal: the field is numerically backpropagated from the target CNS structure to the lens surface. A diffraction-limited version of the wavefront is captured.



(3) Lens construction

Only-phase plates: The holographic information is used to calculate the lens geometry [1]. We assume each pixel of the lens vibrates as a Fabry-Pérot resonator.



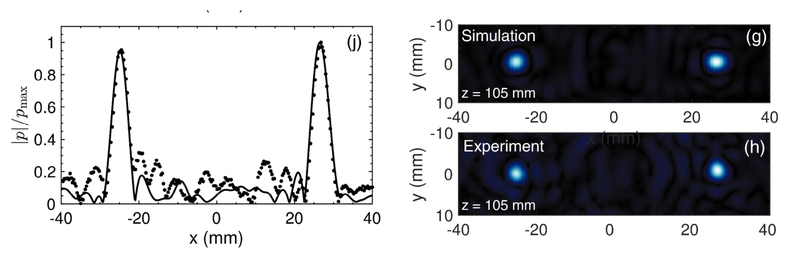
3D-printing: lenses are manufactured using a SLA printer and photo-sensitive polymers.

RESULTS

a) Multiple target focusing

Acoustic beams are simultaneously targeted at multiple locations matching structures of primary biomedical interest: the center of both hippocampi.

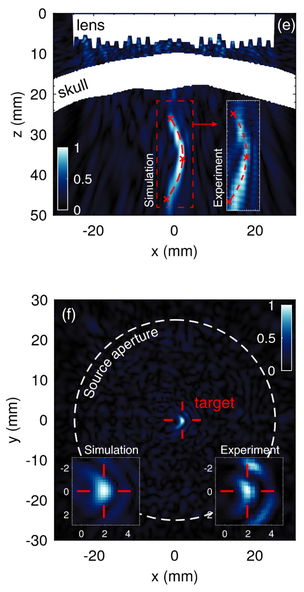
Using holograms energy is focus at target locations. Theory, simulations and experiments agree in water. Simulations and experiments agree including the skull with sub-millimetric accuracy.



b) Self-bending beams

Beams following arbitrary curved paths are designed. The holographic phase-plate corrects the strong aberrations produced by the skull.

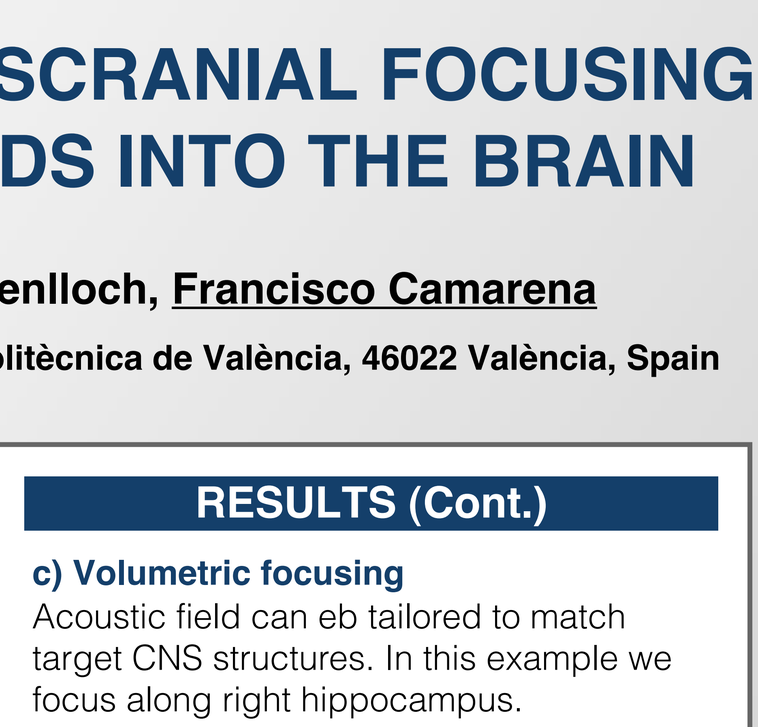
In this way these *self-bending* beams are generated inside the skull adapting its trajectory to target CNS structures: hippocampi, caudate, etc.



RESULTS (Cont.)

c) Volumetric focusing

Acoustic field can eb tailored to match target CNS structures. In this example we focus along right hippocampus.



The focus of the corresponding holographic lens overlaps with the target volume in excellent agreement between theory in free-media, experiments and simulations including a skull.

CONCLUSIONS

Summary

Using holographic lenses we experimentally, numerically and theoretically produce acoustic beams whose spatial distribution match target structures of the central nervous system.

Conclusion

Ultrasonic beams can be focused not only at a single point, but overlapping at one or various target structures simultaneously, e.g., left and right hippocampi, using low-cost 3D-printed acoustic holographic lenses.

Impact

These results open new paths to spread emerging therapeutic ultrasound applications including blood-brain barrier opening (BBBO) or neuromodulation using low-cost systems.

A **patent** of invention has been approved.

Next steps

ex-vivo ongoing experiments using skulls.
in-vivo experiments using holograms and small laboratory animals are scheduled for BBBO.

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