Thermal patterns generated by ultrasound holograms

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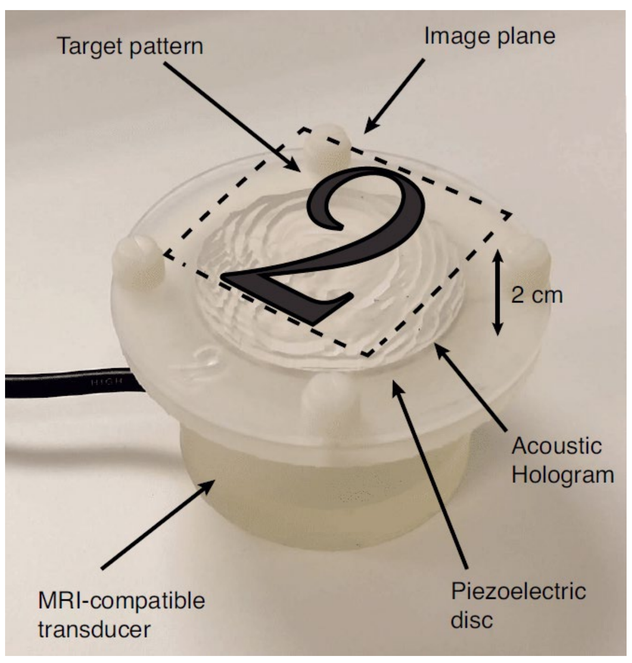
INTRODUCTION

Background

Acoustic waves transport energy that is converted into heat in absorbing media. This property, combined with a precise focalization, is used for therapeutical applications, such as **ultrasound hyperthermia**. Ultrasound fields are often controlled with phased-array systems, of high cost and complexity. With the emergence of 3D printing technologies, new methods for controlling the acoustic field based on lenses appeared, allowing even for **acoustic holography**.

Our proposal

In this work we present the capability of **acoustic holograms to generate controlled thermal patterns** in *ex vivo* biological tissues using 3D printed lenses coupled to low-cost MRI-compatible transducers. A number '2' and an ellipsoidal-shaped holograms were designed for flat and a focused transducer of 1 MHz central frequency.



METHODS

Simulations

Pseudo-spectral (*k*-space) and time-domain simulations of the constitutive relations for acoustic waves in heterogenous media including frequency-power law absorption and dispersion is used [1]:

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

Heating produced by these pressure waves is obtained by a time-domain numerical solution of Penne's bio-heat equation for liver tissue [2]:

$$\rho_t C_t \frac{\partial T}{\partial t} = \nabla(\kappa \nabla T) - W_b C_b (T - T_a) + Q,$$

Holographic lens design

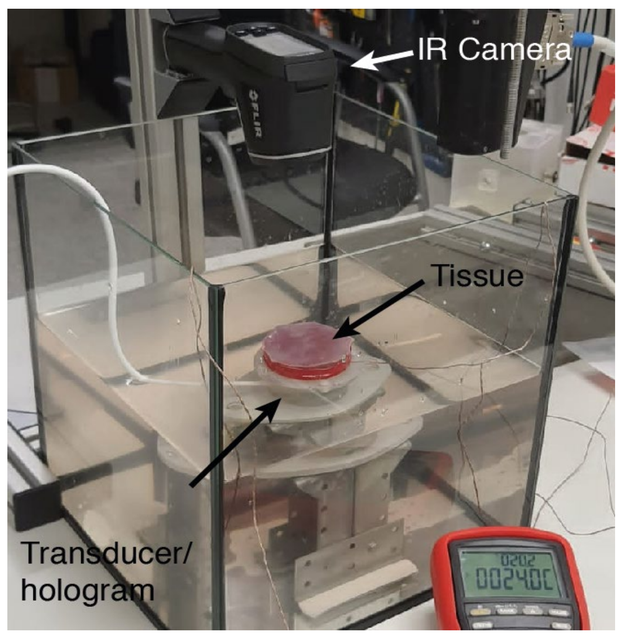
Acoustic holograms are obtained with a time-reversal method and virtual sources in liver tissue. Resulting holographic lens is designed assuming each pixel of the lens vibrates as a Fabry-Pérot resonator, encoding the phase of the wave [3]. The resulting lens is 3D printed with photo-sensitive polymers.



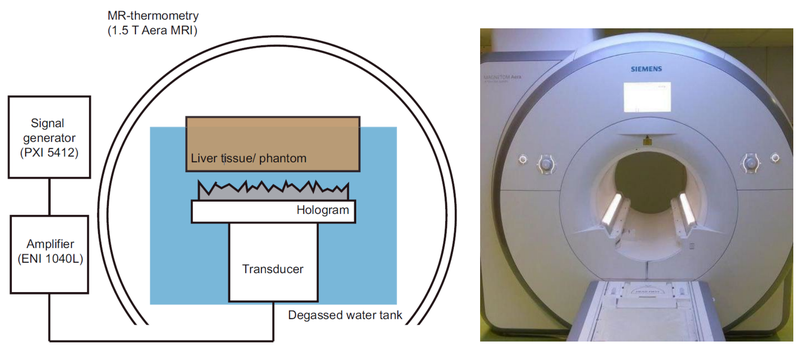
Experiments

Acoustic and thermal simulations were validated:

- **Acoustic** measurements were done with a piezoelectric hydrophone in a degassed water tank.



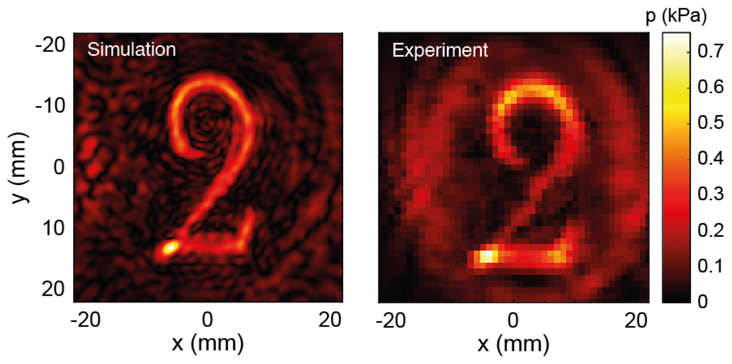
- **Thermal** validation was performed with both Infrared camera and MR-Thermometry in ex vivo liver tissue and tissue-mimicking phantom.



RESULTS

a) Acoustic fields

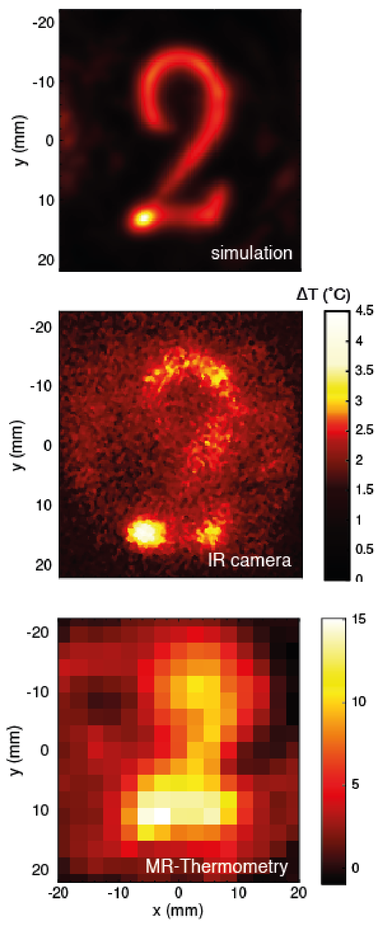
First, acoustic field generated by holographic lenses was characterized. Both simulated and measured pressure fields were in good agreement, with an average relative error of 31% at the target region



RESULTS (cont.)

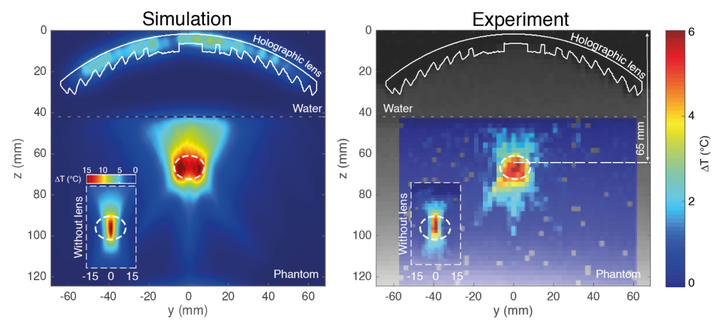
b) Thermal fields

For the '2'-shaped hologram, peak temperature increases 4.5 °C after 12 s heating at 20 W and 15 °C after 40s heating at 40 W.



For the ellipsoidal-shaped hologram temperature raised to 6 °C in both simulation and MRI thermal measurement after 30 seconds heating, while for the natural focus of the transducer the same sonication time led to a temperature increase of 15 °C

For the ellipsoidal hologram, regions inside which simulated temperature elevation was greater than 4 °C were 17 × 16 mm^2 and 7 × 25 mm^2 without and with the lens respectively, while these same experimental measurements resulted in region sizes of 11 × 16 mm^2 and 7 × 30 mm^2. Standard deviation inside these regions was equal to 40% of the maximum temperature without the holographic lens and 12% using it.



CONCLUSIONS

Conclusion

3D-printed acoustic holograms can create controlled thermal **holographic patterns inside absorbing media**. This shows the capabilities of this technology to be used as **a low-cost and MRI compatible alternative** to phased-array systems to perform thermal treatments such as hyperthermia as the heating region can be adapted to therapeutical targets of arbitrary shape and location.

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AVI Agència Valenciana de la Innovació

Ultrasound emitter (low-cost + MRI compatible) → **Acoustic hologram** (arbitrary acoustic image) → **Thermal pattern** (patient/application specific) → **Ultrasound hyperthermia** (large volume therapy)