3D-printed acoustic holograms to generate thermal holographic patterns

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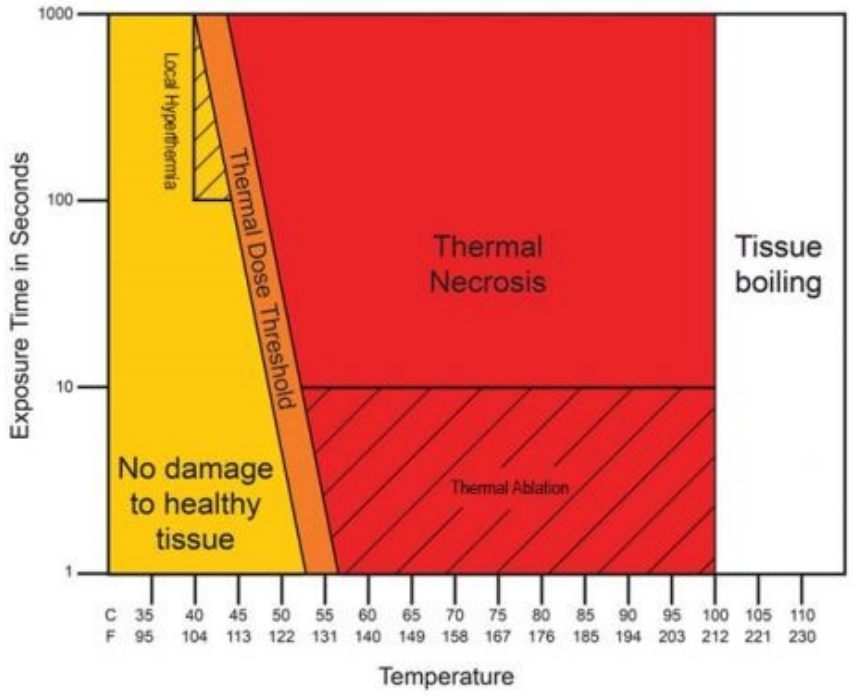
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Strasbourg University - Centre National de la Recherche Scientifique (CNRS),
Strasbourg, France

22nd International Symposium on Nonlinear Acoustics, Oxford, UK, July 2022

Introduction

Motivation

- Ultrasound-based volumetric **mild** hyperthermia: a promising and emerging field
- Rise temperature locally around 42, below ablative regime.
- Phased-array systems: high cost and complexity





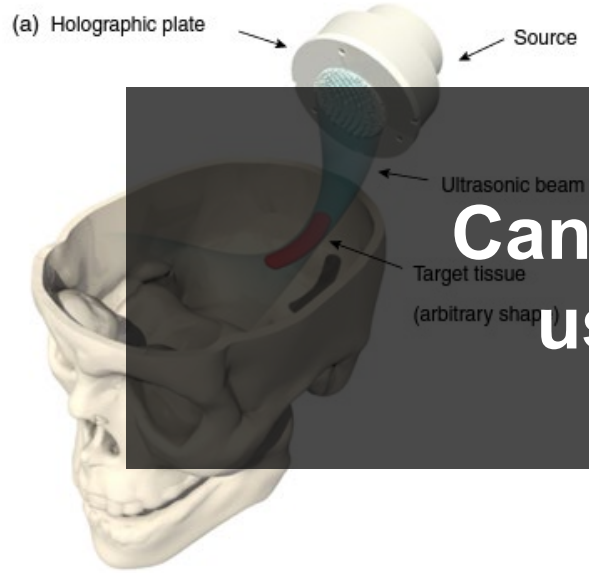
Ablatherm ® HIFU system (EDAP TMS S.A)

Introduction

Motivation

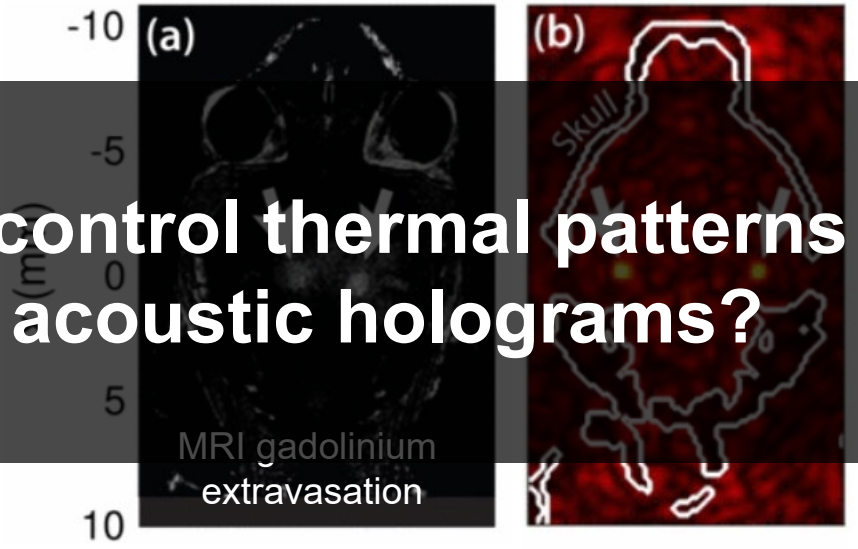
- **Holographic lenses**→ Acoustic images, cavitation holograms → Therapeutic applications

Acoustic hologram for transcranial therapy



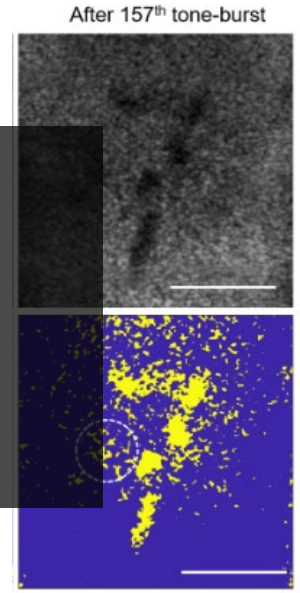
Jiménez-Gambín, S., Jiménez, N., Benlloch, J. M., & Camarena, F. (2019). Holograms to focus arbitrary ultrasonic fields through the skull. Physical Review Applied, 12(1), 014016.

In-vivo bilateral BBBO



Jiménez-Gambín, et al. Acoustic holograms for bilateral blood-brain barrier opening in a mouse model," in *IEEE Transactions on Biomedical Engineering*, doi: 10.1109/TBME.2021.3115553

Cavitation patterns



Kim, et al. Appl. Phys. Lett. 118, 051902 (2021)

Can we control thermal patterns using acoustic holograms?

Introduction

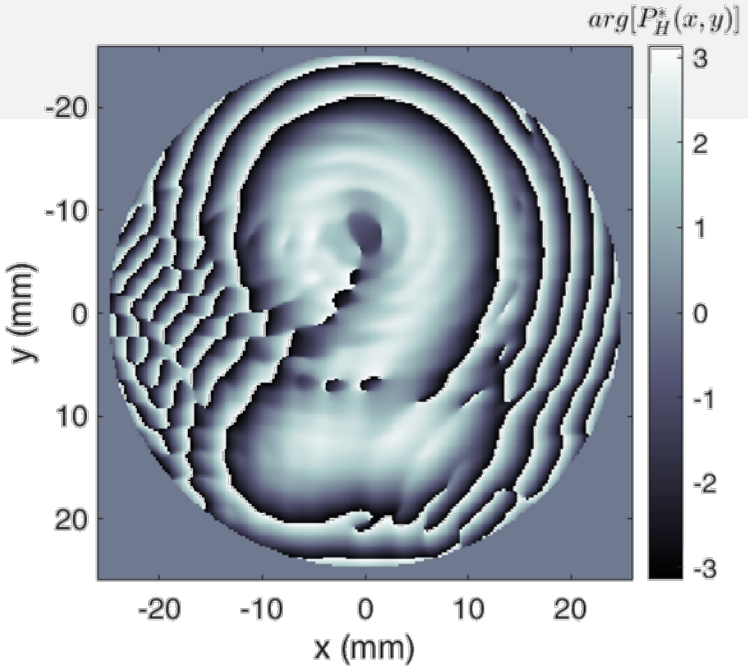
Goal

- The objective of this work is to design and validate **thermal holograms** and apply them for **large-volume hyperthermia**
- Numerically determine how **nonlinearities** affect to the produced thermal pattern
- Experimental validation using 3D-printed hologram

Summary of methods

- Ultrasound lenses will be 3D printed
- Experiments
  - Cow liver tissue using an **infra-red camera**
  - Gelatin+milk-based phantom using Proton Resonance Frequency Shift **MR-thermometry** (MRT)
- Simulations
  - **Nonlinear acoustics**: k-Wave (pseudospectral time-domain simulation)
  - **Thermal simulation**: k-Wave (pseudospectral time-domain simulation)

Nonlinear acoustic simulations



Simulation method

- k-space pseudoespectral simulations (linear and non-linear) with k-Wave
- Virtual sources + linear time-reversal methods to design the hologram

Parameters:

- Pressures ranging from p_0 = 0,3 to 4,5 MPa
- Frequency: f = 1.1 MHz, continuous.
- Nonlinear parameter: B/A = 7,7 (liver tissue)

Discretization:

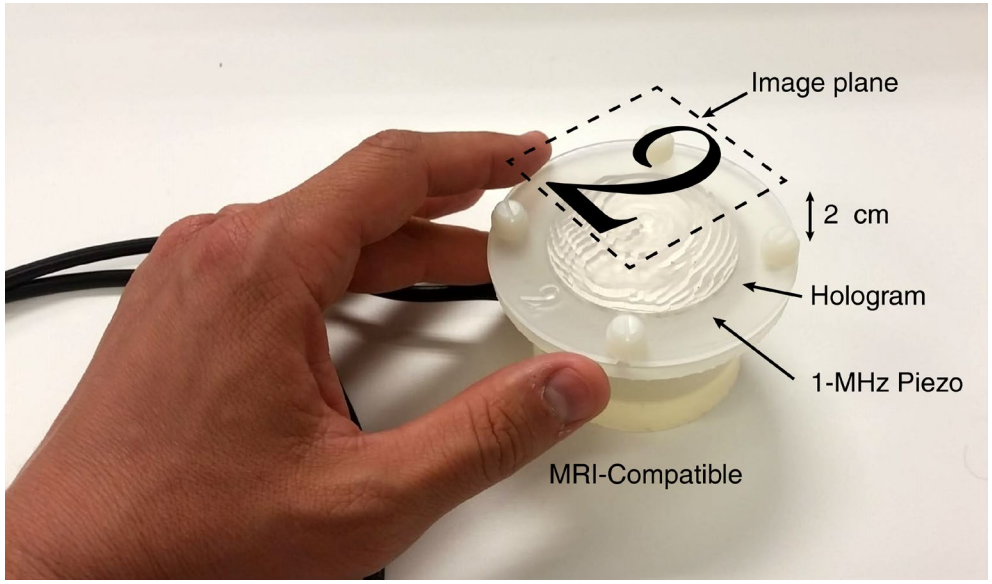
- 6 ppw for the 3rd harmonic.
- CFL of 0,2

Domain size:

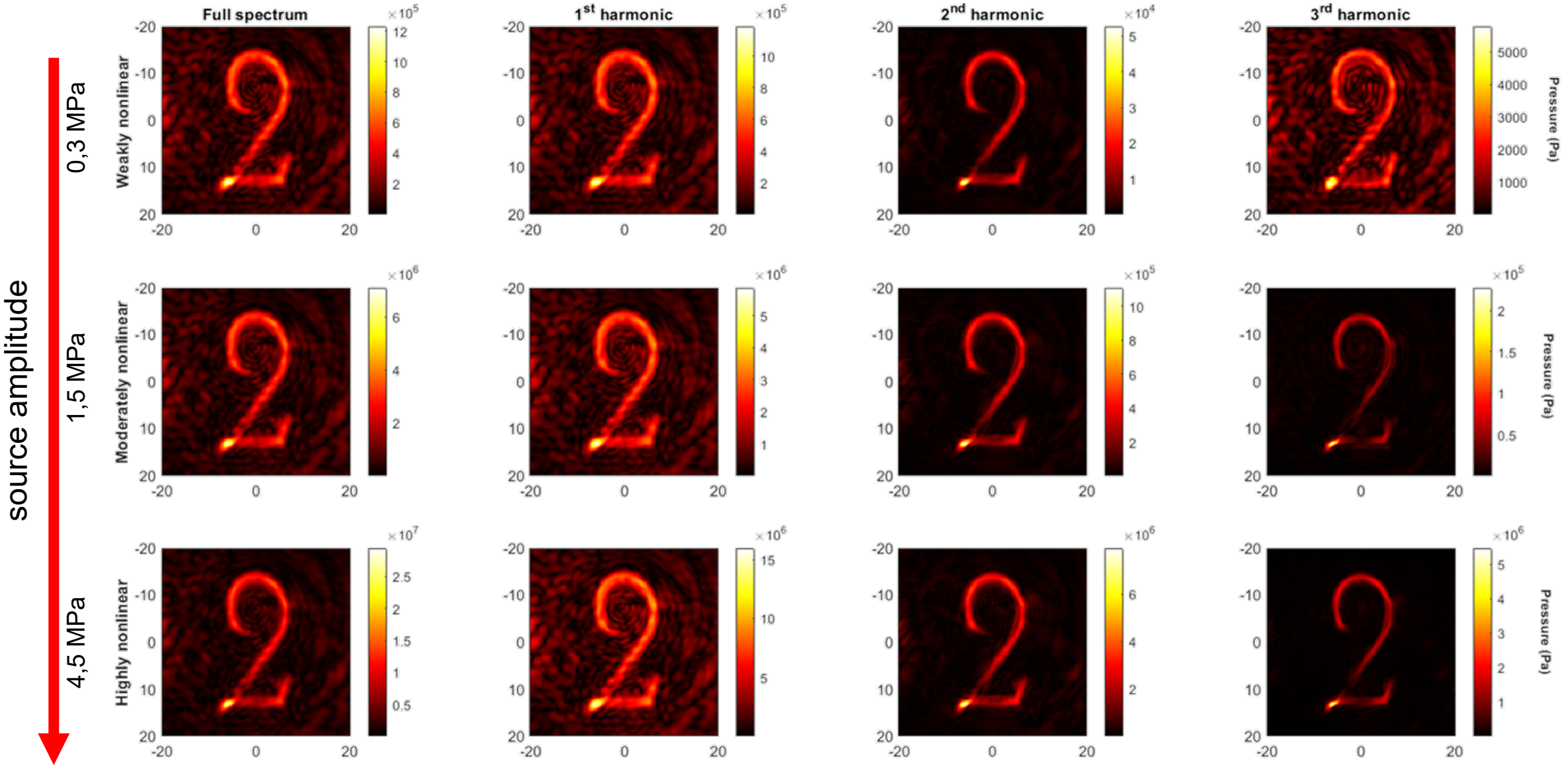
- Propagation path length: 50 mm (37 wavelengths)
- Domain width: 110 mm (82 wavelengths)

Post-process:

- Analyze acoustic field and thermal pattern for each harmonic



Nonlinear acoustic field



Holographic thermal simulations

- Thermal simulation → Pennes' bioheat equation
- Contribution of each harmonic to the Q term:

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

0 (no blood perfussion)

$$Q = \sum_i 2\alpha_i I_i$$

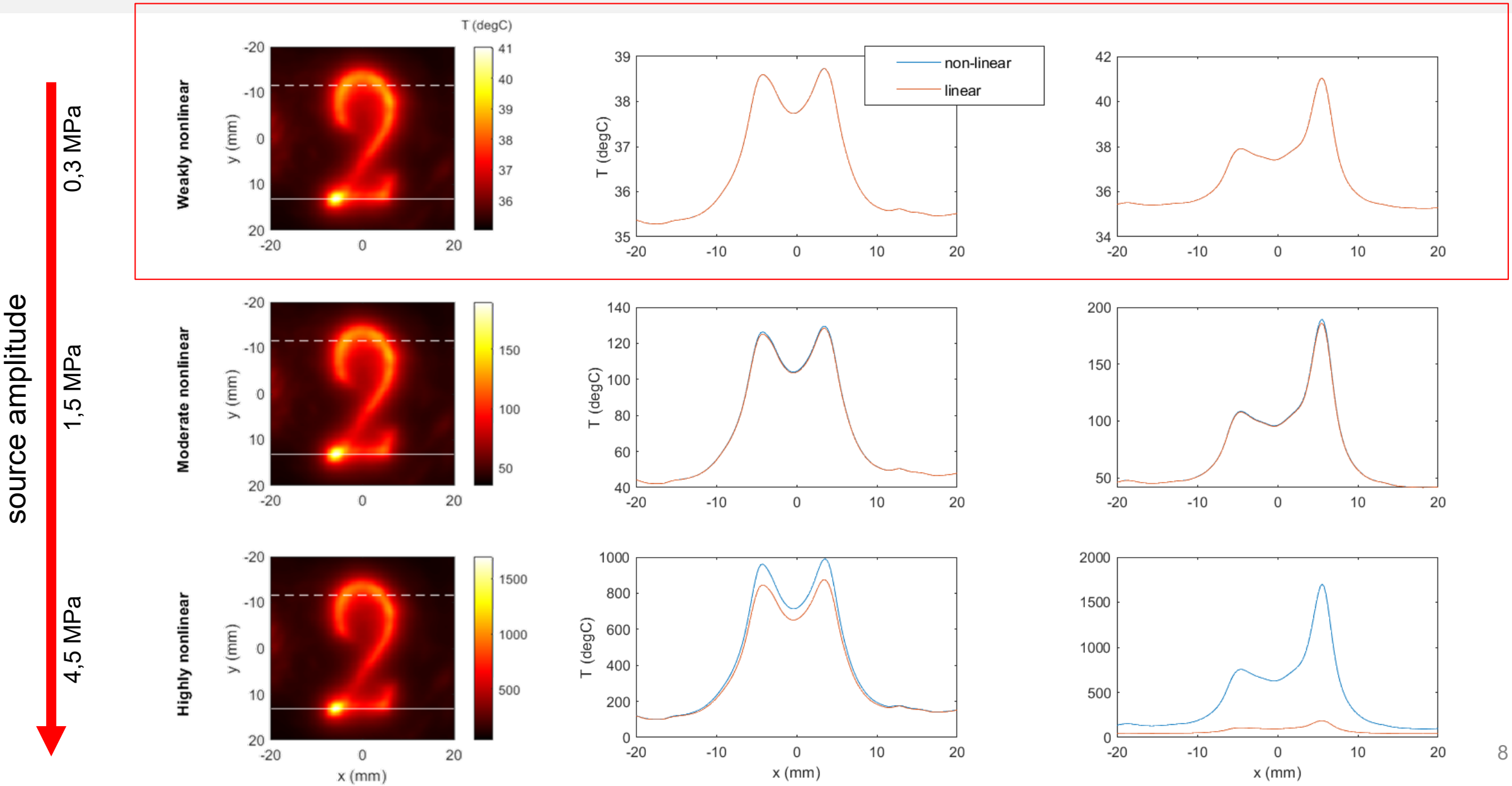
$$i = 1,2,3 \text{ (harmonic number)}$$

$$I_i = p_i^2 / 2\rho_t c_t$$

$$\alpha_i = \alpha_0 f_i^{\gamma}$$

Q: volume rate of heat deposition
ρ_t, c_t, C_t: Tissue density, sound speed and specific heat capacity (1079 kg/m^3, 1586 m/s and 3540 J/(kg·K))
κ: Tissue thermal conductivity (0.52 W/(m·K))
T: Tissue temperature
$W_b, C_b, \mathrm{T_a}$: Blood perfussion rate, specific heat capacity and temperature

Holographic thermal patterns



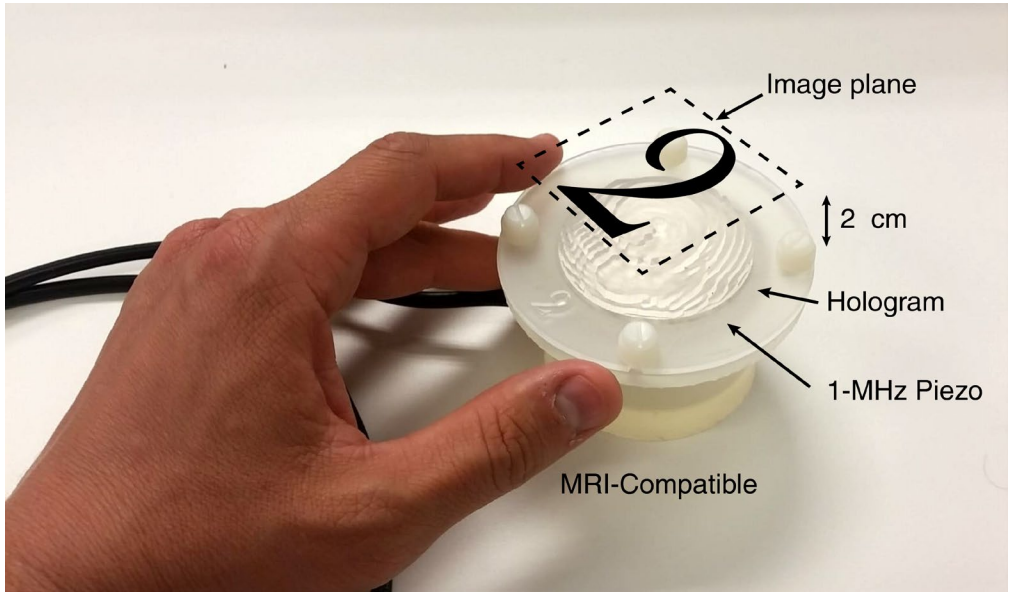
Acoustic hologram

Andrés, D., et al. *App Phys Lett* 120.8 084102 (2022)

Experimental demonstration (weakly nonlinear regime)

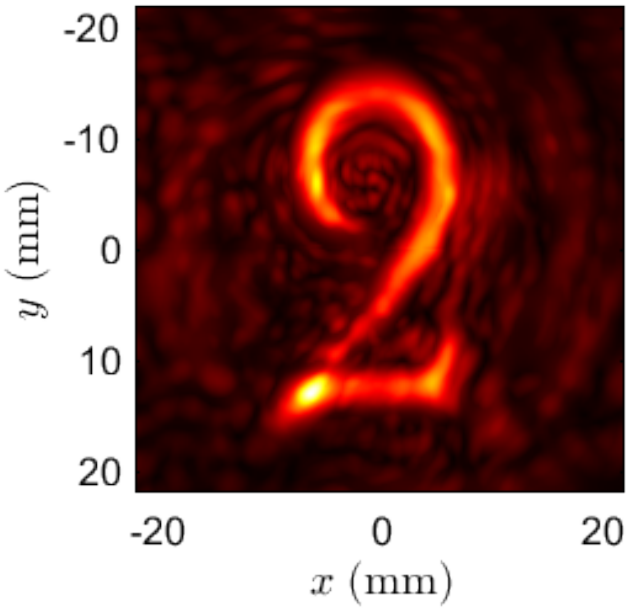
- 3D printed hologram
- Plane transducer: 2a = 50 mm, f = 1,1 MHz
- Max pressure ~ 2 MPa (weakly nonlinear)
- Degassed water tank
- Measurements: hydrophone

Experimental setup

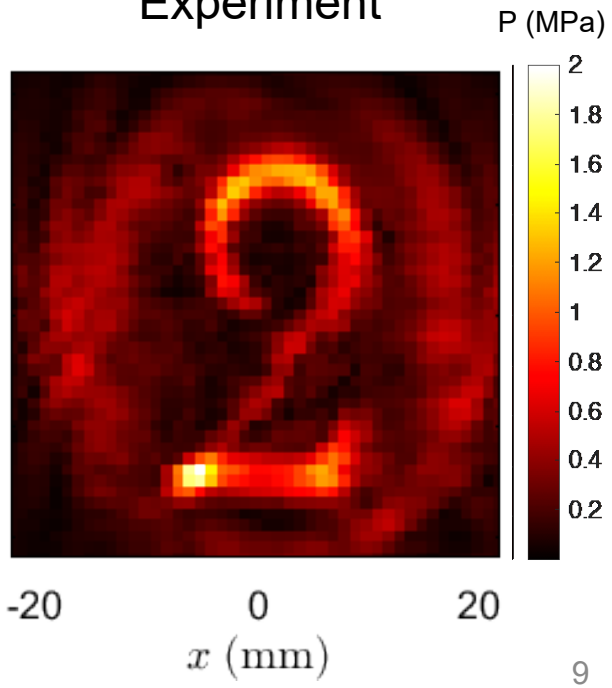


Acoustic field

Simulation



Experiment



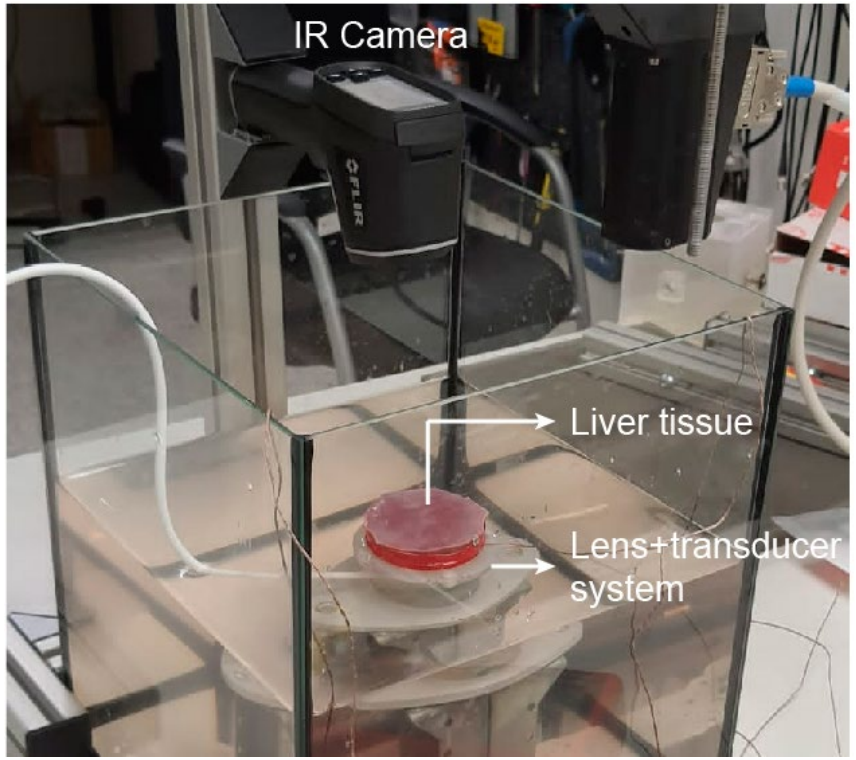
Holographic thermal patterns

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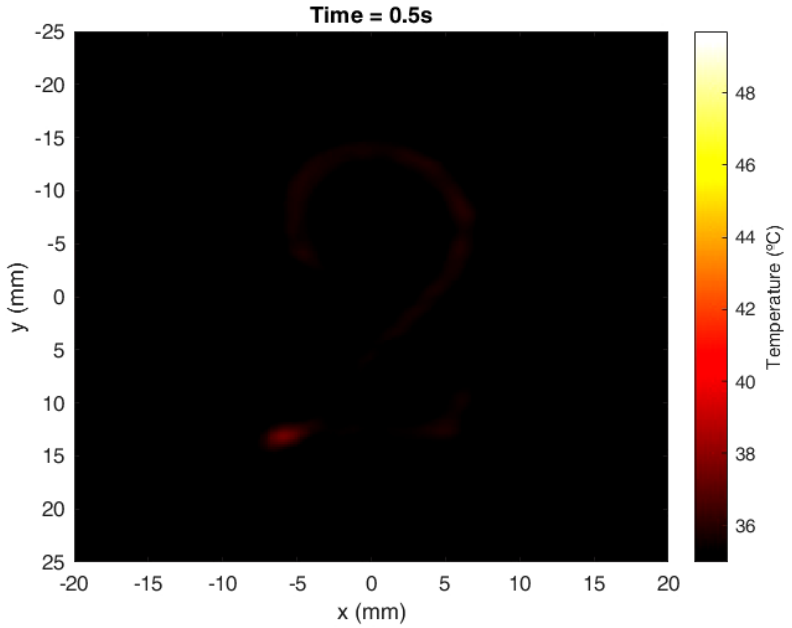
- 3D printed hologram
- Plane transducer: 2a = 5 mm, f = 1 MHz
- Cow liver tissue
- Measurements: thermal imaging infrared camera

IR camera (FLIR TG165)

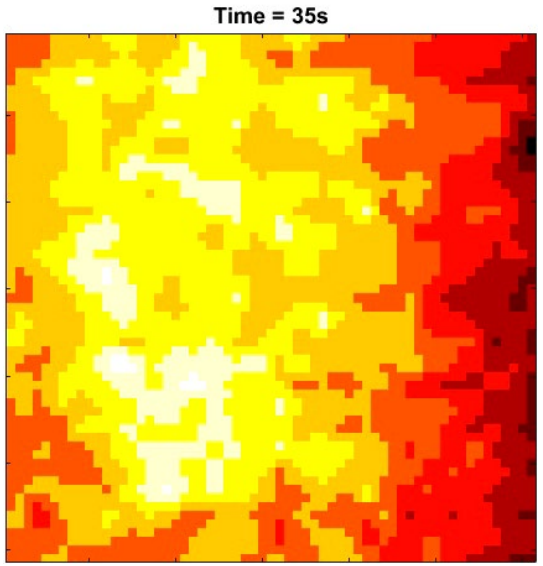


Thermal pattern

Simulation



Experiment



Holographic thermal patterns

Andrés, D., et al. *App Phys Lett* 120.8 084102 (2022)

Experimental demonstration (weakly nonlinear regime)

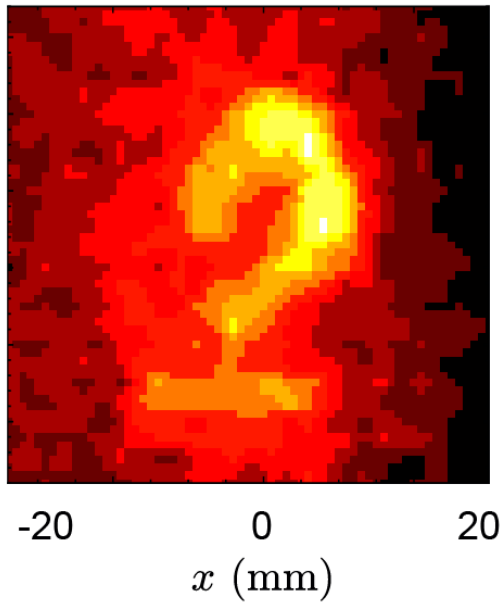
- 3D printed hologram
- Plane transducer: 2a = 5 mm, f = 1 MHz
- Gelatin + milk phantom
- Measurements: 1.5-Tesla MRI thermometry

1.5T Aera MRI (Siemens)
Strasbourg facility

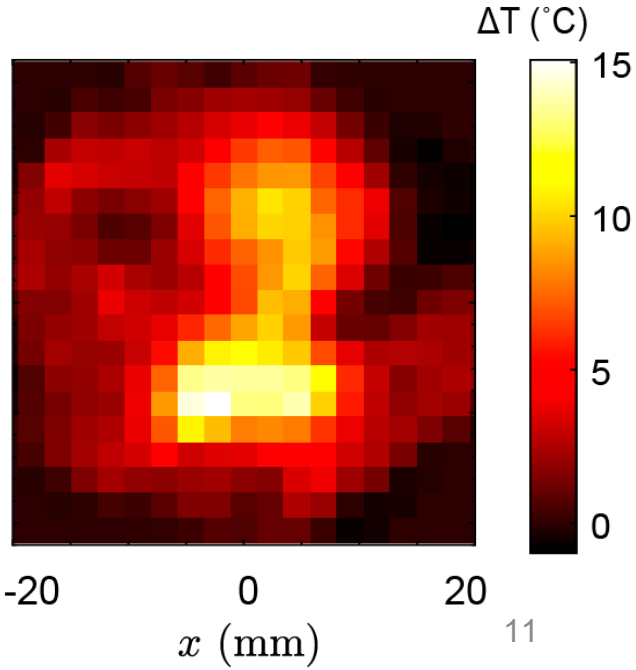


Thermal pattern

IR Camera



MR thermometry



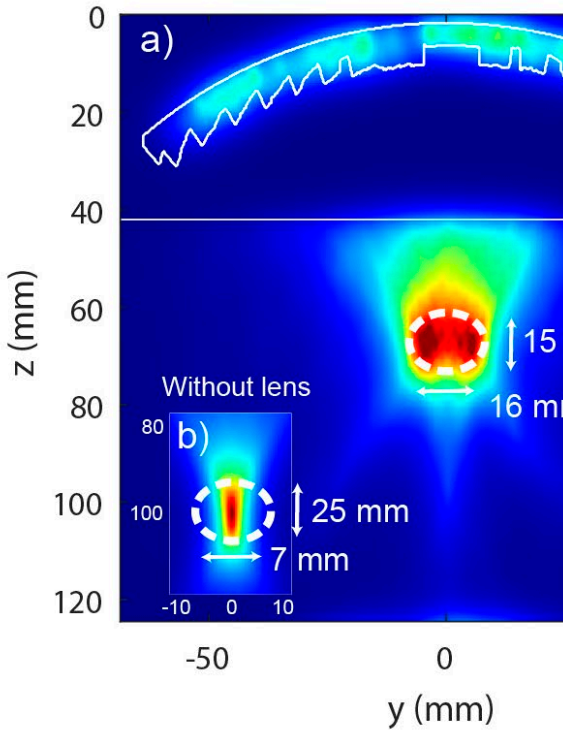
Holographic thermal patterns

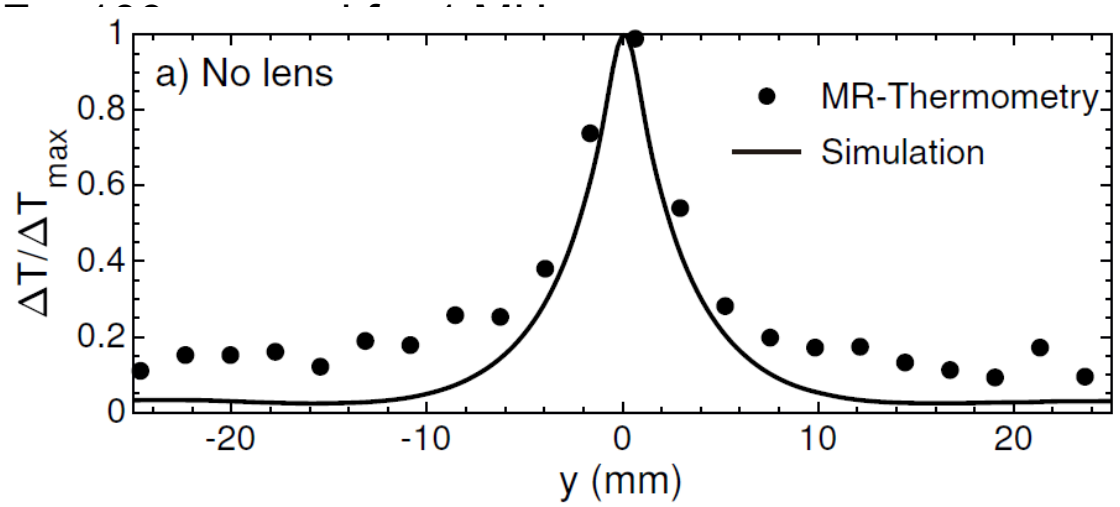
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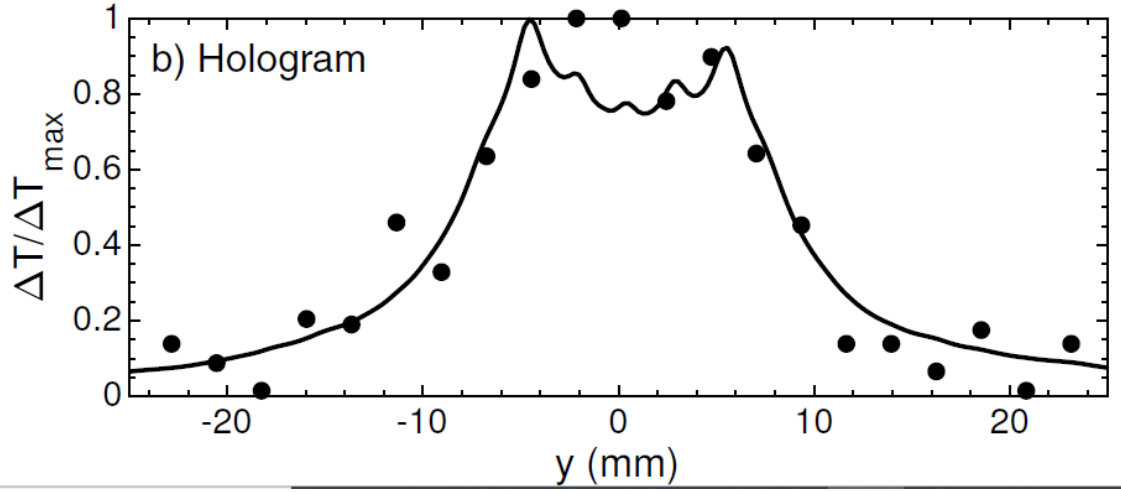
Large-volume hyperthermia

- Curved transducer with
- Wider and more uniform

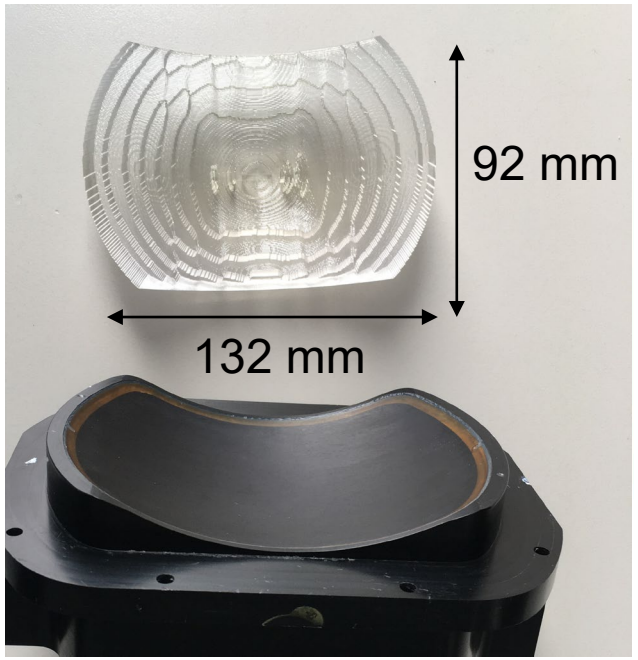
Thermal simulat







Experimental setup



Conclusions

Holographic thermal patterns

- Holograms allow controlling and enlarging thermal spot, ensuring more uniform temperature profile
- Higher harmonics increase acoustic hologram resolution (sharper acoustic images)
- Nonlinearity has little impact on thermal patterns for mild hyperthermia: first harmonic dominates heating source.
- However, this effect can be relevant for cavitation-based therapeutical applications.

Applications

- Thermal patterns can be matched to complex structures for localized and volumetric hyperthermia
- Low-cost and simple-to-use method for volumetric hyperthermia

Limitations

- Experiments done in phantom and ex-vivo tissues → No perfusion

Next steps

- in-vivo experimental validation using **small animals** for mild hyperthermia
- Quantify **lens heating** for long exposures and HIFU applications.

Acknowledgements

Instituto de Instrumentación para Imagen Molecular

- Diana Andrés (FPU - MICIU)
- Noé Jiménez (Postdoc – Juan de la Cierva)
- Francisco Camarena (Prof. UPV)

Icube Laboratory

- Jonathan Vappou (Researcher CNRS)

Funding

- MCIU: Juan de la Cierva – Incorporación, IJC2018-037897-I, Plan Nacional Retos: PID2019-111436RB-C22.
- MICIU: FPU19/00601
- Generalitat Valenciana: ACIF/2017/045.
- European Union: IDIFEDER/2018/022



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