Effect of numerical realistic diploe on focused ultrasound propagation: comparison between skull porosity and transducer used

Federico Rossano[1,2], Micaela Liberti[1,3], Francesca Apollonio[1,3], Giancarlo Ruocco[1], Salvatore Maria Aglioti[1,2]

[1] Center for Life Nano- and Neuro-Science, Istituto Italiano di Tecnologia, Rome, Italy
[2] Department of Psychology, Sapienza University of Rome, Italy
[3] Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome

federico.rossano@uniroma1.it

Scientific Context

Transcranial focused ultrasound (tFUS) stimulation is a novel non-invasive technique, nowadays used for therapeutic and neuromodulatory brain applications. Despite its potential, the presence of the skull and its heterogeneous structure, caused by the presence of the diploe, hampers the propagation of the ultrasound wave (US) both in terms of scattering, beam focus shifting, and a dramatic attenuation of the ultrasound wave intensity [1]. This effect becomes more significant as the frequency of the stimulation signal increases, which is used to achieve higher spatial resolution and precision of the sonication target.

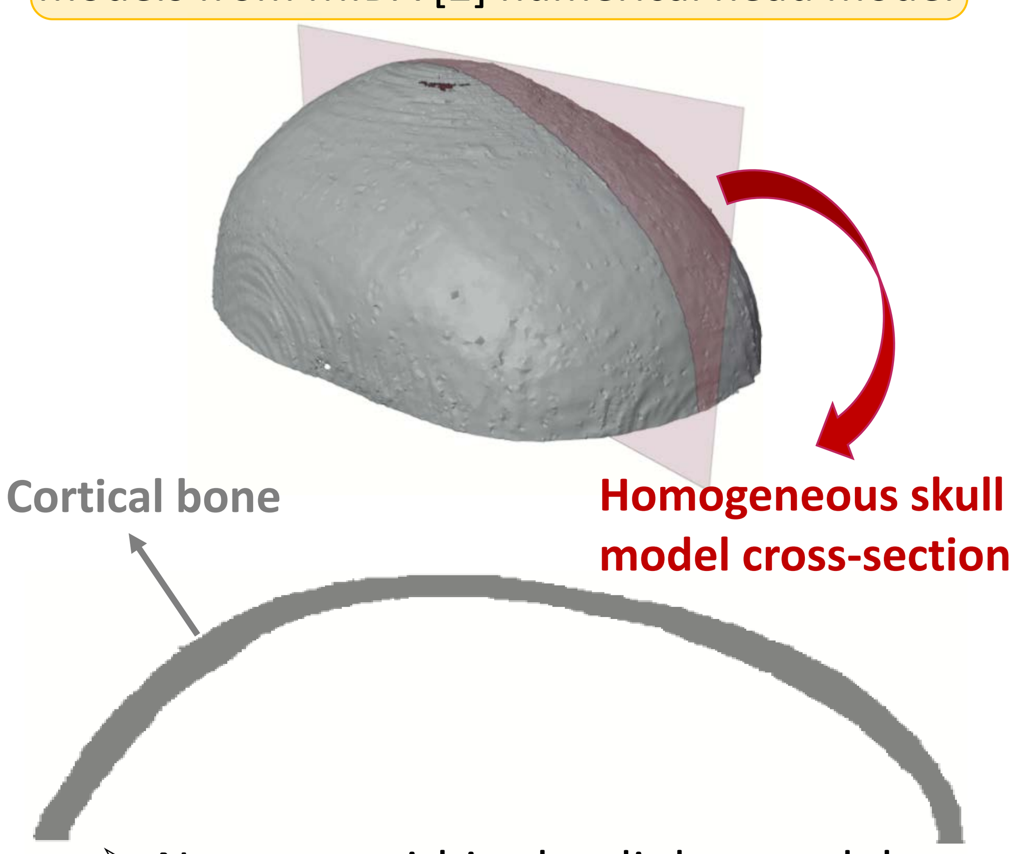
Aim of the work

We aim to draw attention to the importance of using a 3D numerical model of a realistic binary heterogeneous human skull (i.e., with porous diploe), instead of a homogeneous one, especially for tFUS applications where high spatial resolution and accuracy is required. We will show a comparison between 3D isosurface pressure maps of ultrasound wave propagation through binary heterogeneous and homogeneous diploe structures, using a single-element and a multi-element transducer, optimized through the time-reversal technique.

Methods

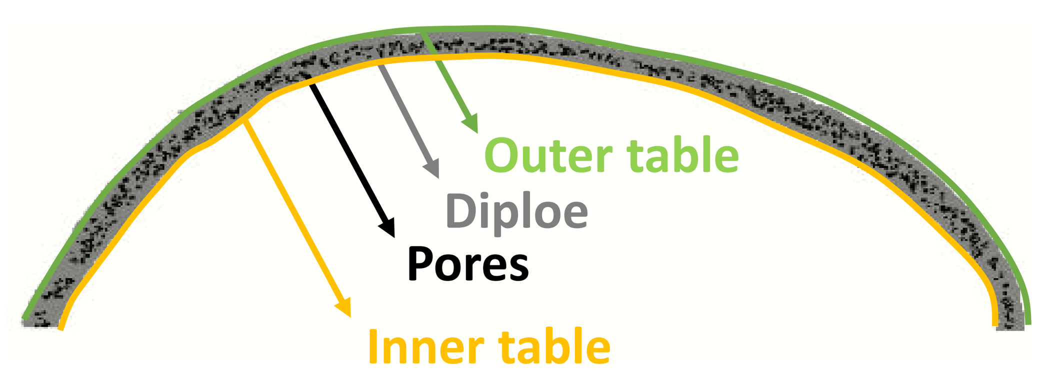
Homogeneous and heterogeneous numerical head models construction

Extraction of diploe, inner and outer table models from MIDA [2] numerical head model



- No pores within the diploe model

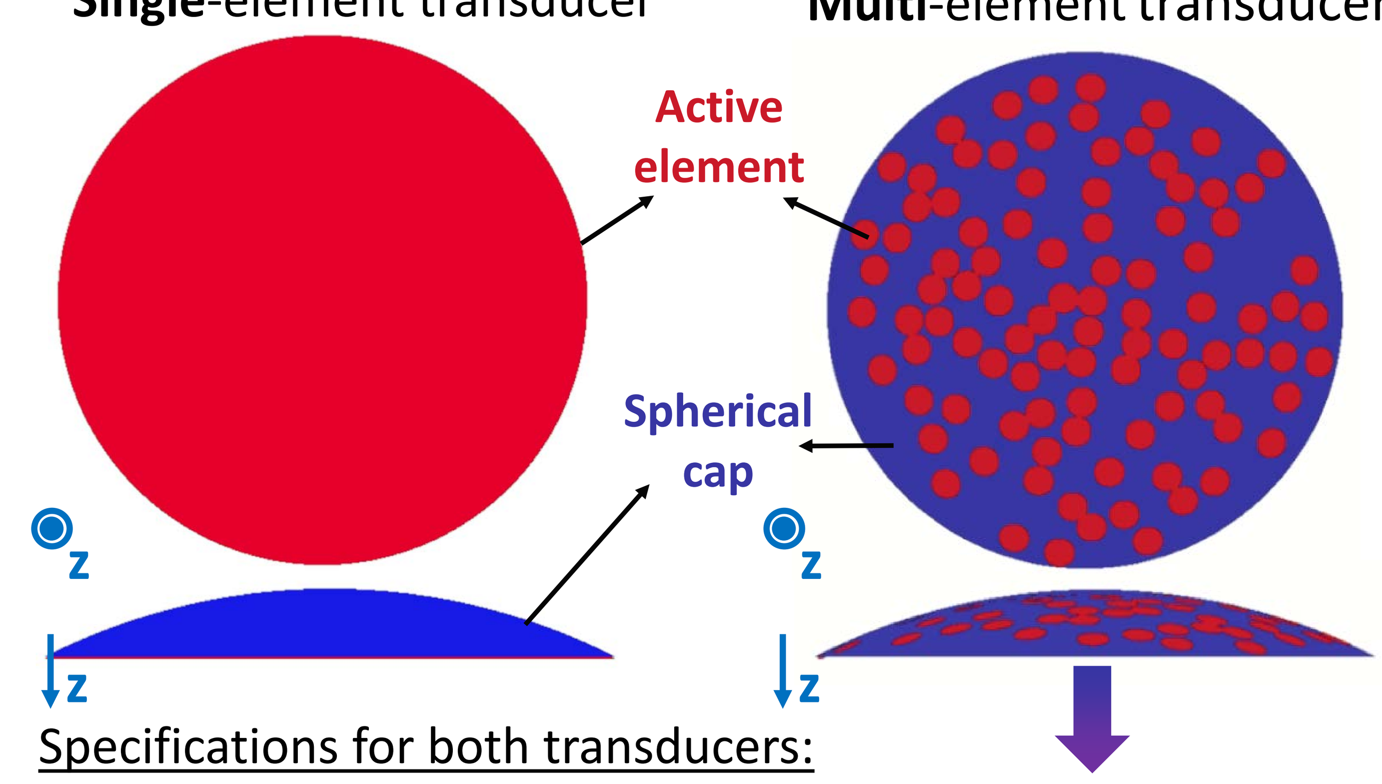
Creation of 50-55-60% [3] porosity diploe models (heterogeneous models)



- Pores have been generated in random positions within the diploe
- Pores have a random diameter ≤ 1.24 mm [3]

$$Porosity\ \% = \frac{\sum_i^{N\ pores} V_{pore}(i)}{V_{diploe}} \cdot 100$$

Transducers construction

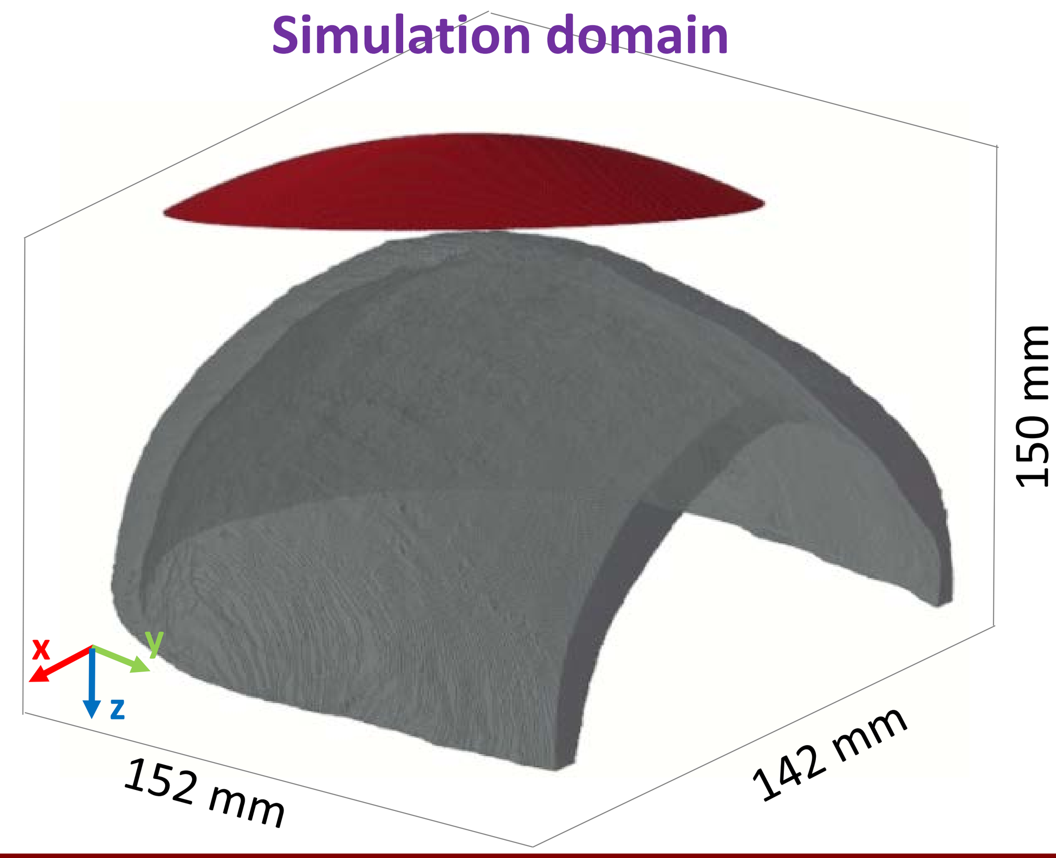


Specifications for both transducers:
- **Radius of curvature**: 125 mm
- **Aperture width**: 112.5 mm
- **f-number**: 1.1

Simulation setup

Acoustic simulations were performed using the MATLAB toolbox k-Wave [4]

Simulation domain



Materials acoustical properties

Item	Skull (diploe, inner & outer tables)	Pores	Transducer element(s)	Background
Color				
Material	Cortical bone	Bone marrow red	Water	Water
Speed of sound [m/s]	2813.7	1450	1500	1500
Density [kg/m³]	1908	1029	994	994
Absorption coefficient [dB/(cm*MHz^y)]	4.7385	1.0857	0.0022	0.0022
Source	[5]	[5]	[5]	[5]

Simulation parameters

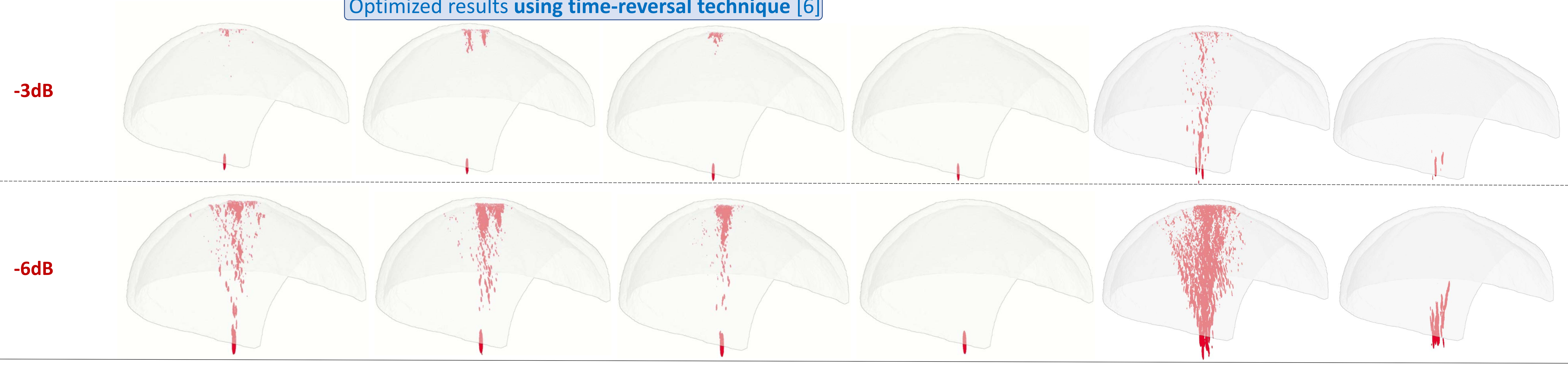
- Input signal frequency: 1 MHz
- Input signal amplitude: 0.1 Mpa
- Input signal wavelength in water: 1.5 mm
- Point per wavelength (PPW): 7
- Spatial discretization: 0.214 mm
- Spatial grid dimensions in number of voxels: 677x710x700 (Nx **x** Ny **x** Nz)
- Courant-Friedrichs-Lewy (**CFL**) number: 0.15
- Simulation time t: 200 μs

Results

Maximum pressure output data was collected after the **onset of the US wave stationary regime** (t ≥ 160 μs) and **normalized to the specific focus value**

Multi-element transducer — Optimized results **using time-reversal technique** [6]

Single-element transducer



	Multi-element				Single-element	
Porosity %	50	55	60	0	55	0
Specific focus distance from theorical (mm)	0.64	0.85	0.64	1.1	18.1	8.3

Conclusion & Discussion

The binary heterogeneous dipole model heavily impacts the propagation of tFUS in numerical simulations. Multi-element transducer -3dB and -6dB maps show how the US wave is scattered, resulting in distinct hotspots along the propagation path compared to the non-porous dipole model (0% porosity). This effect persist even when employing the time-reversal technique to correct for skull aberrations. Nevertheless, with time-reversal technique, the distance between the US wave specific and theorical foci is < 1 mm. Single-element performance results in higher US wave scattering, hotspot creation and specific focus shift compared to the multi-element. The latter results in a more precise and accurate system for tFUS sonication, which should be further optimized to achieve higher precision, accuracy and selectivity for neuromodulation/neuropsychiatry applications. This work also proposes a methodical approach for constructing *in-silico* skull models that could be used for testing and optimization of tFUS transducers, for both therapeutic and neuromodulation applications, without the need of high-resolution CT scans for a correct diploe model segmentation.

References

[1] Pinton, G. et al. "Attenuation, scattering, and absorption of ultrasound in the skull bone." *Medical physics* (2012).
[2] Iacono M.I. et al., "MIDA: A Multimodal Imaging-Based Detailed Anatomical Model of the Human Head and Neck" *PLoS One*, (2015).
[3] Stephen L.. A., et al., "Structural analysis of the frontal and parietal bones of the human skull", *Journal of the Mechanical Behavior of Biomedical Materials*, (2019).
[4] Treeby B. E., et al., "k-Wave: MATLAB toolbox for the simulation and reconstruction of photoacoustic wave-fields", *J. Biomed. Opt.,* (2010).
[5] Hasgall PA, et al., "IT'IS Database for thermal and electromagnetic parameters of biological tissues," Version 4.1, Feb 22, 2022
[6] Fink M., et al., "Time-reversal acoustics in biomedical engineering", *Annual Review of Biomedical Engineering,* (2003)