Acoustic Characterization of Two Pediatric Skull Phantoms

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Background

- Clinical trials for neurological disorders in adults are ongoing using MR guided Focused Ultrasound (MRgFUS).
- Although pediatric patients have thinner skulls and could benefit from MRgFUS, the acoustic properties of pediatric skulls have not been reported extensively in the literature.
- Acoustic characterization of *ex vivo* pediatric skulls is an ongoing effort in our lab but specimens are rare and do not represent the entire population range.
- Creating a library of skull phantoms based on computed tomography (CT) could offset the lack of *ex vivo* specimens.
- The aim of this study was to compare two pediatric skull phantoms to their corresponding *ex vivo* skulls to validate the material properties and manufacturing process.

The Neonate Skull Phantom

- Based on a micro-CT dataset of a real *ex vivo* neonate skull, a neonate skull phantom was manufactured out of a cortical bone mimicking phantom material [1].
- The fontanelle was made using a thin film of polyurethane.

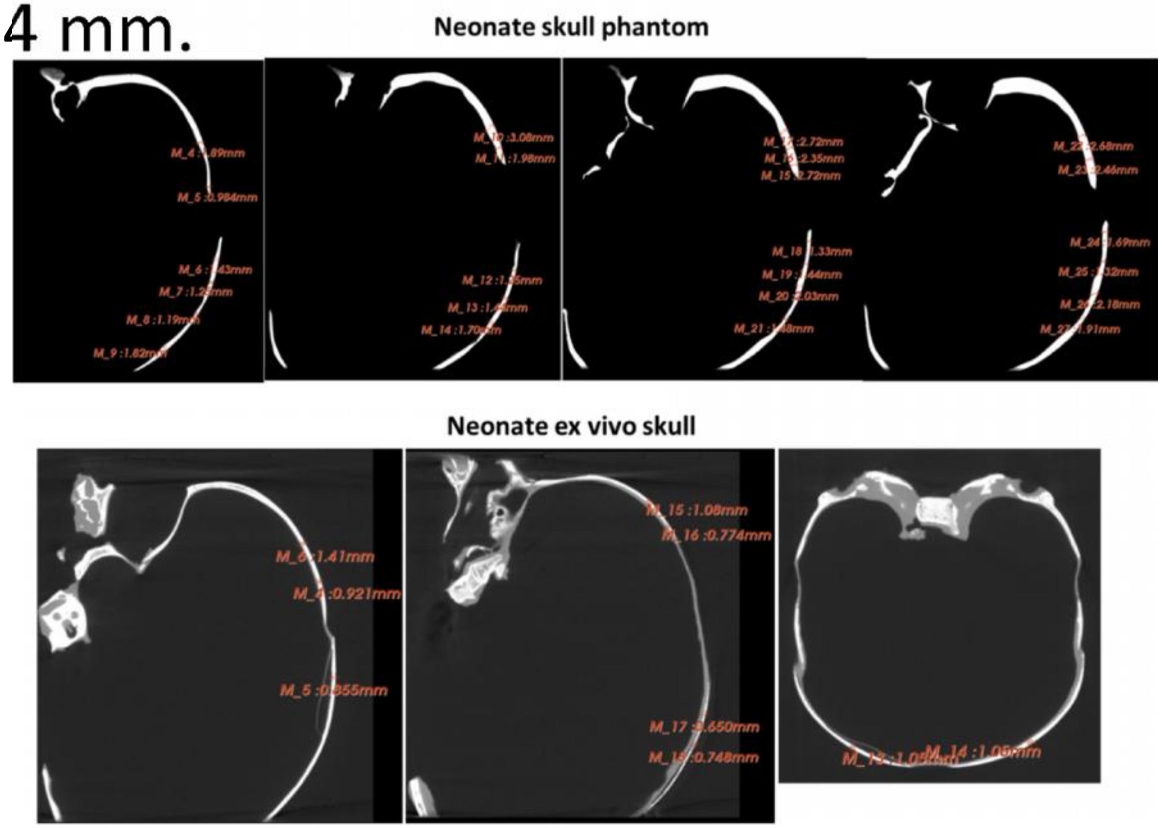
Cadaveric Specimen

Phantom Specimen

[1] A Wydra, RG Maev, Phys Med Biol, Vol 58(22), N303-19, 2013.

The Neonate Skull Phantom

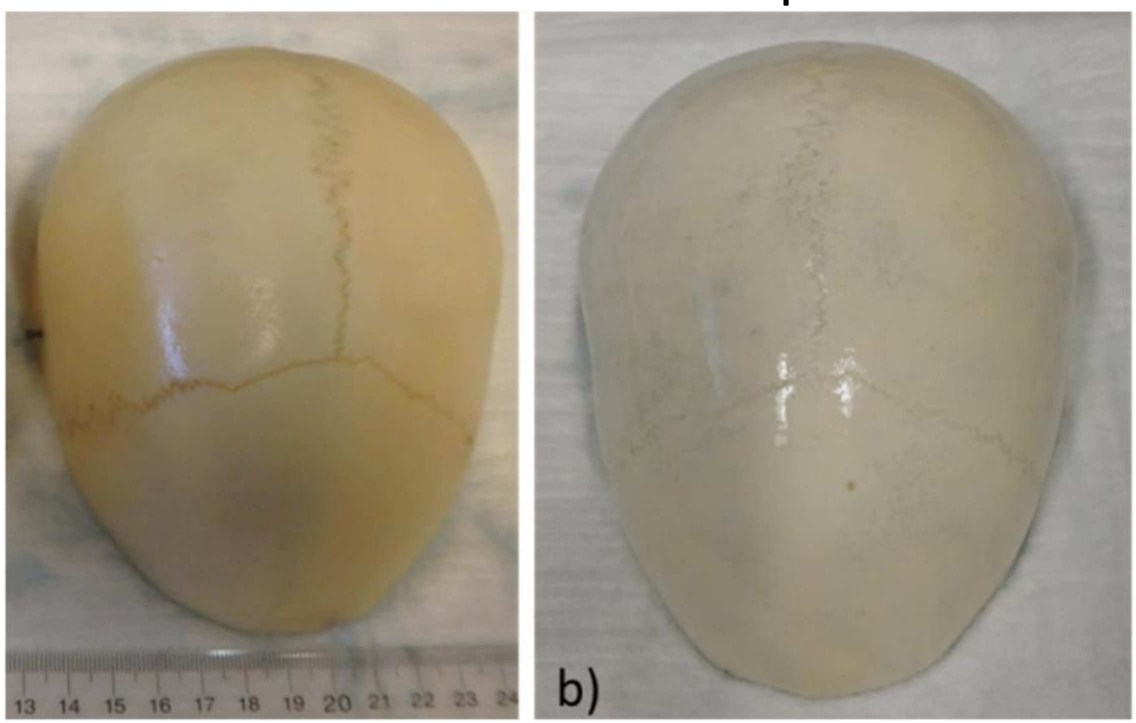
- Measurements of arbitrary phantom thicknesses close to the fontanelle ranged from 1.2 to 2.7 mm.
- For measurements of the *ex vivo* skull, results ranged from 0.65 to 1.4 mm.



The 8 Year Old Skull Phantom

- An 8-year old skull phantom was manufactured as a tri-layer laminate using the bone-mimicking material for cortical layers and a poppy seed / bone-mimicking composite to produce the trabecular layer.
- The suture structure was not yet fused in the cadaveric skull and was not fully reproduced in this iteration of the phantom.

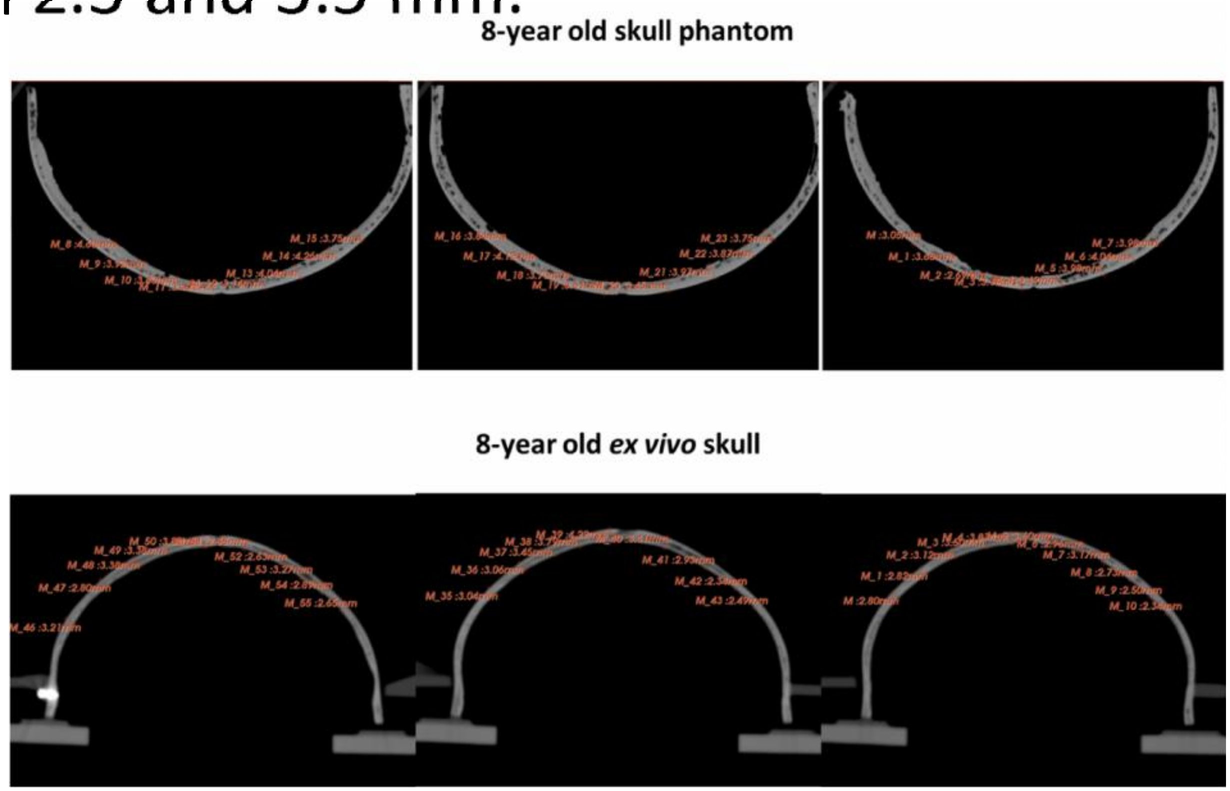
Cadaveric Specimen



Phantom Specimen

The 8 Year Old Skull Phantom

- Random measurements of the thickness of the phantom were between 3.4 and 4.3 mm.
- For the ex vivo skull, random thickness measurements were between 2.3 and 3.5 mm.



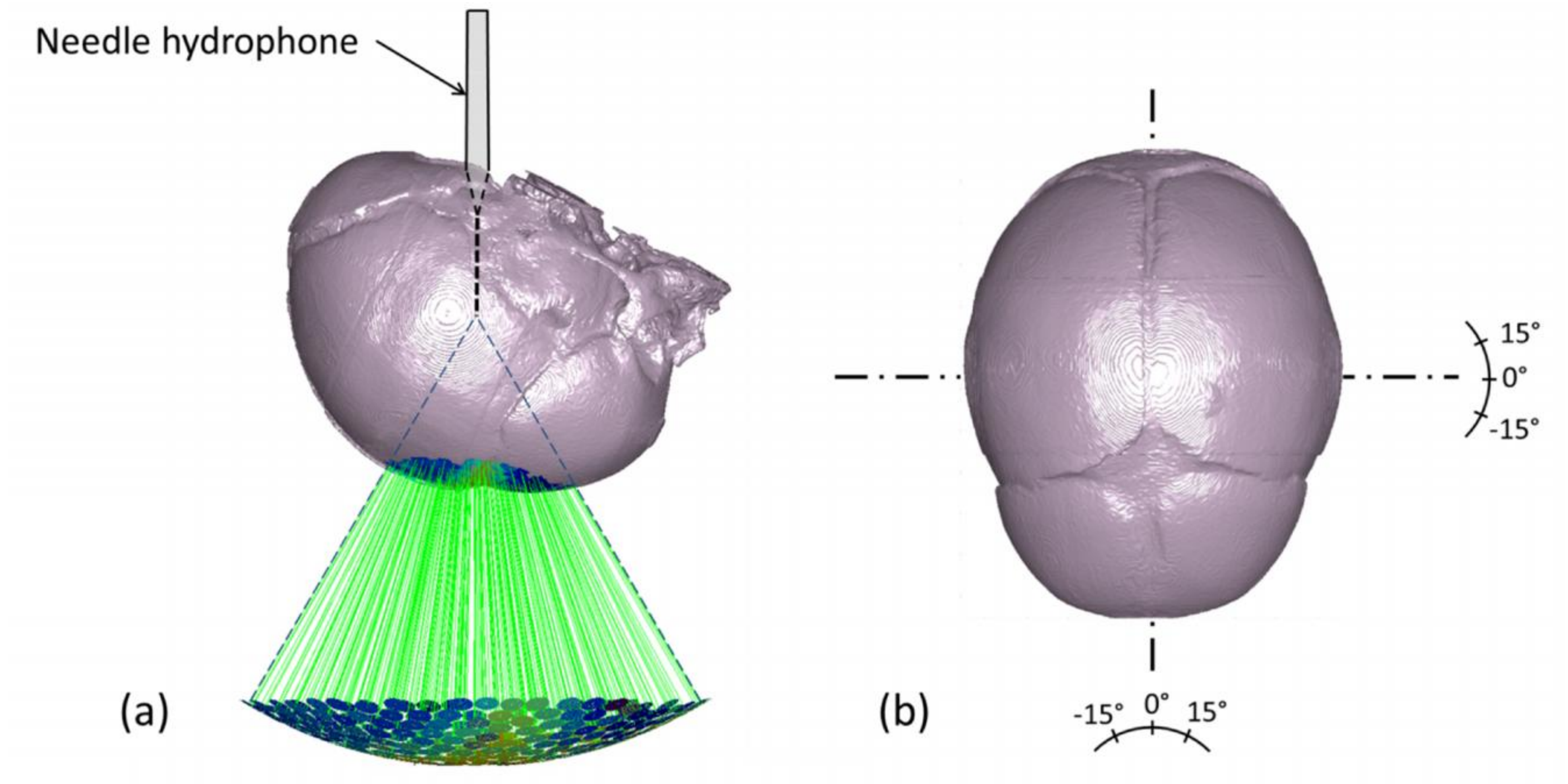
Skull Characterization Methods

- Transducer: 256-element Philips Sonalleve HIFU phased array transducer (ϕ = 130 mm, f = 120 mm, F = 1.2 MHz).
- 0.2 mm needle acoustic hydrophone, in a tank of degassed water, was aligned to the geometric focus of the transducer by measuring the time-of-flight (TOF) for the 256 elements and triangulating the TOF between 255 of the elements and an arbitrary reference element [2].
- A baseline measurement was performed by acquiring the signals of the 256 elements one by one without a skull.
- A degassed skull was placed in the tank between the hydrophone and transducer and measurements repeated.

[2] C. Mougenot et al., Med. Phys., 39 (4): 1936-1945, 2012.

Skull Characterization Methods

- Acquisitions were performed for different angular orientations of the skull according to the sagittal and coronal axes in the range of ± 15°.



Skull Characterization Methods

- Insertion losses (IL) and time-of-flight (TOF) delays due to the skull and the fontanelle are deducted from these measurements at 1.2 MHz.

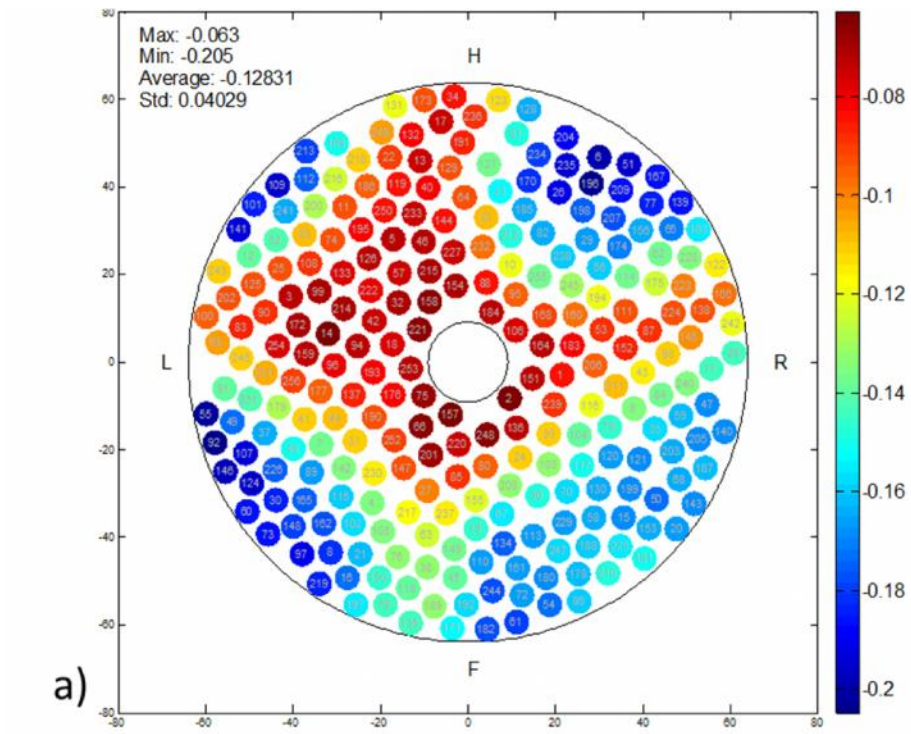
- Time-of-flight (TOF) delay due to the skull is obtained by calculating the difference between the skull and baseline TOF measurements for each orientation.

- The Insertion Loss (IL) is obtained by calculating the difference between the root mean square (RMS) amplitude of the skull signals and the baseline RMS amplitude for each orientation.

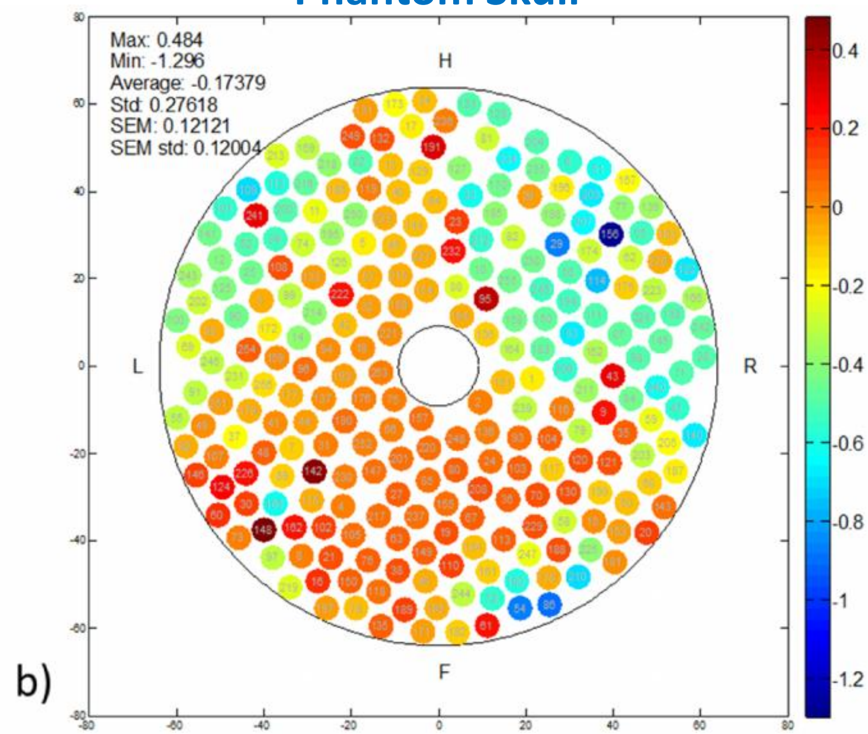
Results: Neonate TOF Delay

- TOF delays (in µs) obtained when positioning the skulls at 0° on the coronal axis. In this position, the acoustic beam mainly crosses the fontanelle.

Ex Vivo Skull



Phantom Skull



Results: Neonate TOF Delay

- The fontanelle of the *ex vivo* skull induces on average -0.06 µs of TOF delay and the fontanelle of the phantom induces no delay. The material used for the fontanelle in the phantom can be considered as a good fontanelle-mimicking material.

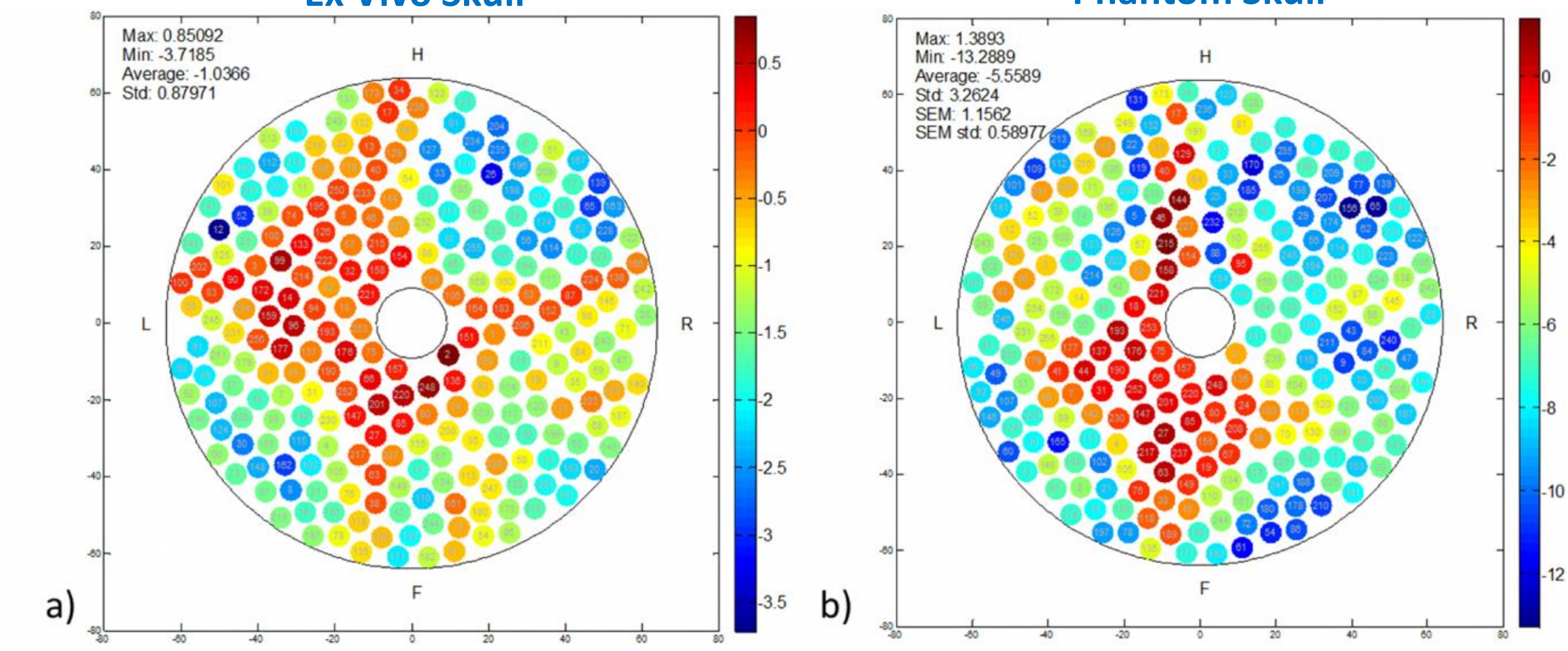
- The frontal bones of the *ex vivo* skull induce on average -0.18 µs of TOF delay and the parietal bones -0.15 µs of TOF delay. The bone-mimicking material of the phantom induces -0.4 µs of TOF delay in average with a few locations at -0.8/-1 µs of TOF delay.

Results: Neonate Insertion Loss

- IL (in dB) obtained when positioning the skulls at 0° on the coronal axis. In this position, the acoustic beam mainly crosses the fontanelle.

Ex Vivo Skull

Phantom Skull

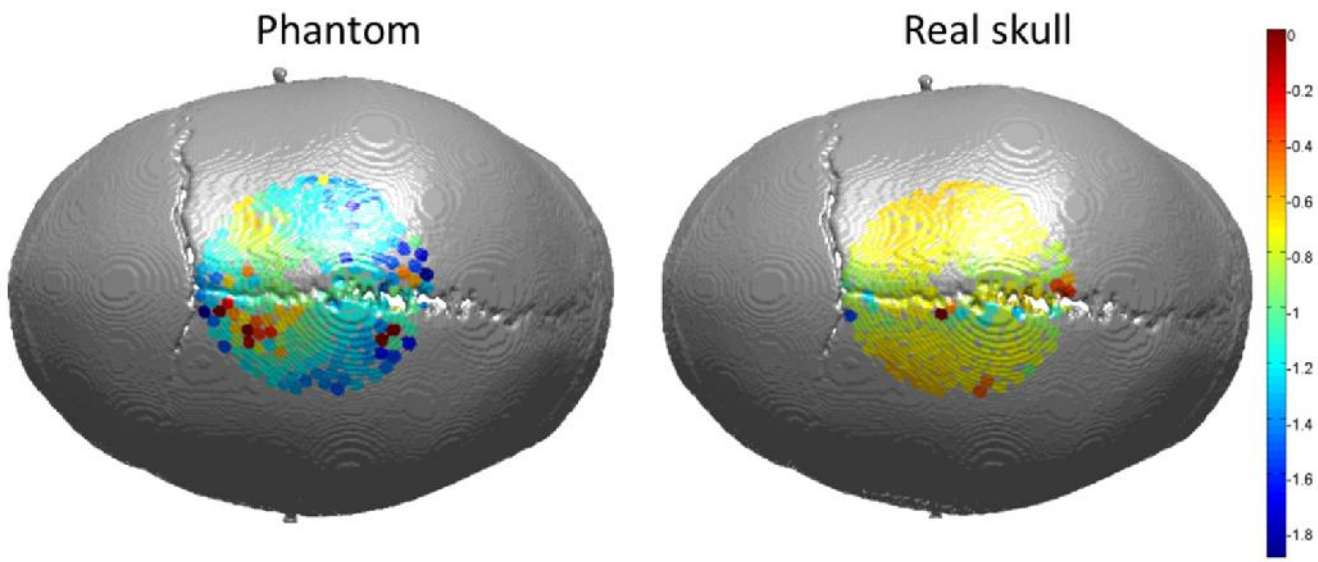


Results: Neonate Insertion Loss

- The fontanelle of the phantom induces an IL equivalent to the IL induced by the fontanelle of the *ex vivo* skull (0.5 dB on average).
- The frontal bones of the *ex vivo* skull induce on average 2.5 dB of IL and the parietal bones 1.5 dB of IL. The bone-mimicking material of the phantom induces 7 dB of IL on average but the IL maps are really heterogeneous ranging from 3 to 12 dB.
- This difference is significant and can be explained by the overall thickness of the phantom and also its heterogeneity of thickness through the trabecular layer.

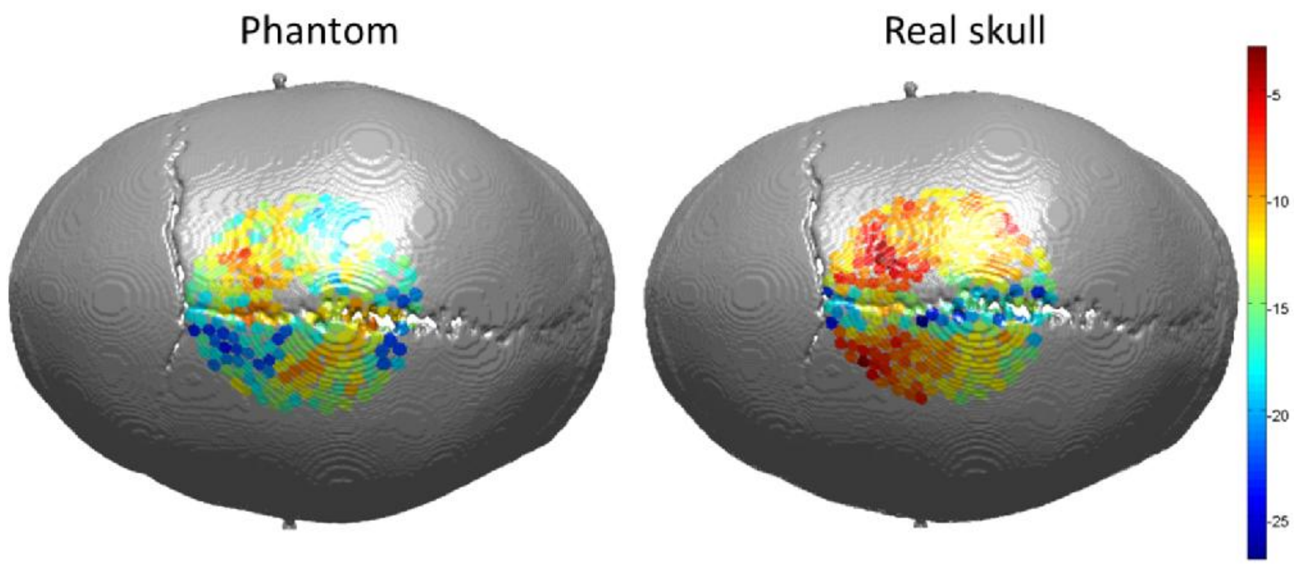
Results: 8 Yr Old TOF Delay

- The average TOF delay of the phantom is -1.1 ± 0.3 µs at 1.2 MHz versus -0.70 ± 0.08 µs for the real skull, resulting in a 57 % increase of the delay. However the TOF delay of a small area on the right parietal bone near the coronal suture matches well with the homogeneous TOF delay of the real skull.



Results: 8 Yr Old Insertion Loss

- The average IL of the phantom is 14.1 ± 2.6 dB at 1.2 MHz versus 9 dB for the real skull. But here again, the IL of a small area on the right parietal bone near the coronal suture but also of another area near the sagittal suture in the middle of the left parietal bone seem to match well with the average IL of the real skull.



Discussion

- Although phantoms and *ex vivo* skulls were visually similar, CT measurements showed a discrepancy between thicknesses.
- The neonate phantom was on average 100% thicker than the *ex vivo* skull due to manufacturing constraints.
- The 8-y.o. phantom was 50% thicker than the *ex vivo* skull.
- The TOF delays reflected these differences with an average of -0.4 µs for the neonate phantom vs -0.15 µs for the *ex vivo* skull and an average of -1.1 µs for the 8-y.o. skull phantom vs -0.7 µs for the *ex vivo* skull.
- The average speed of sound (SOS) of the neonate phantom was 2250 $m.s^{-1}$ vs 2080 $m.s^{-1}$ for the *ex vivo* skull. The average SOS of the 8-y.o. skull phantom was 2500 $m.s^{-1}$ vs 2300 $m.s^{-1}$ for the *ex vivo* skull.

Conclusions

- The bone-mimicking phantoms are an alternative to rarely available *ex vivo* pediatric skulls.
- Based on the CT scan of real pediatric skulls, two phantoms, representing a neonate skull and an 8-year old skull, were manufactured using bone-mimicking material, which was developed based on adult bone samples.
- TOF delay results suggests that comparable results would be obtained if the thickness of the bone layers were consistent between *ex vivo* and phantom skulls.
- IL values are not equivalent due to the thickness and the shape of the phantoms being not exactly the same.
- Future work will focus on quantifying the attenuation properties of the ex vivo and phantom skulls at multiple frequencies.

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