Characterization of longitudinal speed of sound in ex vivo human vertebral laminae.

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Background and Objective

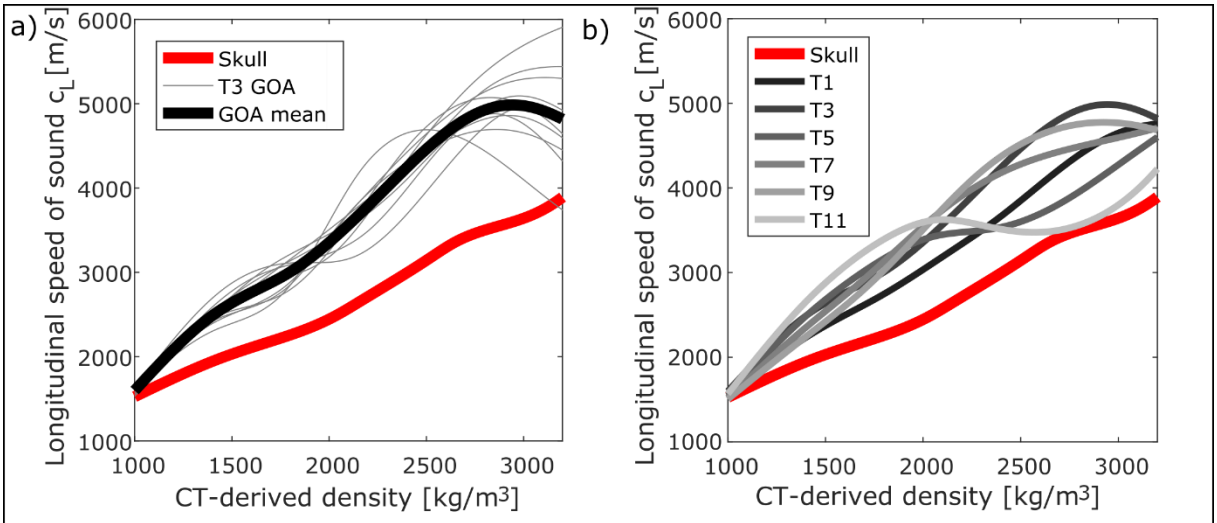
Pre-clinical studies in small animals have demonstrated safe focused ultrasound mediated blood-spinal cord barrier opening for therapeutic delivery. Clinical translation requires focusing through the highly aberrating human spine to the spinal cord; possible with a phased array and accurate phase corrections. Our prior work modelling sound propagation in the spine used longitudinal speed of sound (c_L) – CT-derived density relationships from skull bone. However, trabecular orientation affects c_L. While skull trabecular orientation is isotropic, the vertebral arch has anisotropic trabecular orientation due to tendon and ligament loading. Our objective is to characterize vertebral lamina-specific c_L-density relationships to improve the accuracy of our treatment planning models.

Methods

Ex vivo human vertebrae (T1, T3, T5, T7, T9, T11) were imaged with a clinical CT scanner (Aquilone One, Toshiba) at 0.5mm isotropic resolution, then sonicated with a spherically focused transducer at 514kHz, geometrically focused through the lamina to the canal center. Pressure waveforms were recorded in 8×8×8mm (0.5mm discretization) volumes within the canal with a 0.5mm needle hydrophone (Precision Acoustics). 5 repetitions (2.5mm vertical vertebra shifts) were performed with each vertebra. Voxel-wise cross-correlation between the canal and water-only waveforms was performed to extract vertebra-induced time shifts and corresponding phase differences, $\Delta\varphi$. Families of 10 random c_L – density spline functions were generated, ray acoustics simulation was used to evaluate phase error of each function, $\Delta\varphi_E$, the difference between experimentally measured and simulated $\Delta\varphi$. Genetic optimization was used to minimize $\Delta\varphi_E$ within the focal volume (convergence: minimum $\Delta\varphi_E$ unchanged for 5 consecutive generations). Optimization was repeated 10× per vertebra; each with a different random seed.

Results/Discussion

The optimized c_L–density functions of all vertebrae were 26 ± 7% (10% - 39%) faster than skull over the displayed density range. Intervertebral differences may be due to vertebra-specific trabecular orientation. Despite this intervertebral variation, this finding suggests that phase correction with lamina-specific c_L–density functions will improve phase correction accuracy.



A genetic optimization algorithm (GOA) was used to optimize c_L - CT derived density splines functions. a) 10 optimized functions for the third thoracic vertebra (T3), the 10 function average, and the 514kHz skull function. b) The averages of the optimized functions for odd-numbered vertebrae, relative to the skull function.