High frame rate ultrasound imaging of shear shock wave focusing in a human head phantom and the *in situ* porcine brain

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Background, Motivation and Objective

Impacts send shear waves into the brain which, due to tissue nonlinearity, develop into destructive shear shock waves. These shear shocks may be responsible for axonal damage and deaths from traumatic brain injuries. In this study we show that shear shock waves can be focused due to the spherical human skull morphology. We also show that shear shock wave focusing can be generated *in situ* in the porcine brain. Peak acceleration, strain rate, strain, and amplification are quantified using high frame-rate ultrasound imaging sequences and shear shock wave tracking methods that we have developed.

Statement of Contribution/Methods

First, a human skull phantom was 3D printed using a CT scan of a human head. It was subsequently filled with a gelatin-graphite phantom that was calibrated to have the same elastic and acoustic properties as brain tissue. The phantom was attached to a shaker and vibrated using a Gaussian-enveloped 10 cycle pulse within a frequency range of 30 to 150 Hz, consistent with the range observed in traumatic brain injury impacts. The resulting shear wave was imaged volumetrically with a mechanically translatable 5.2 MHz ultrasound array using a custom 16 focused transmit-receive ultrasound sequence at 6200 images/second. The beamformed images were processed with adaptive motion estimation algorithms that we designed for shear shock wave tracking. In a second series of experiments a craniectomy was performed on porcine heads and a plate was attached to the brain which was vibrated between 30 to 150 Hz. It is shown that focused shear shock waves were generated in both the phantom and fresh brain.

Results/Discussion

For a 20 G input at the brain surface, shear shock wave focusing was observed within the quasi-elliptical skull boundary with a peak acceleration of 300 G occurring at the natural geometric focus of the skull. In the fresh *in situ* porcine brain, shear shock wave focusing was also observed and quantified by the characteristic odd third and fifth harmonic amplitudes of the nonlinear shear waves (Fig 1d).

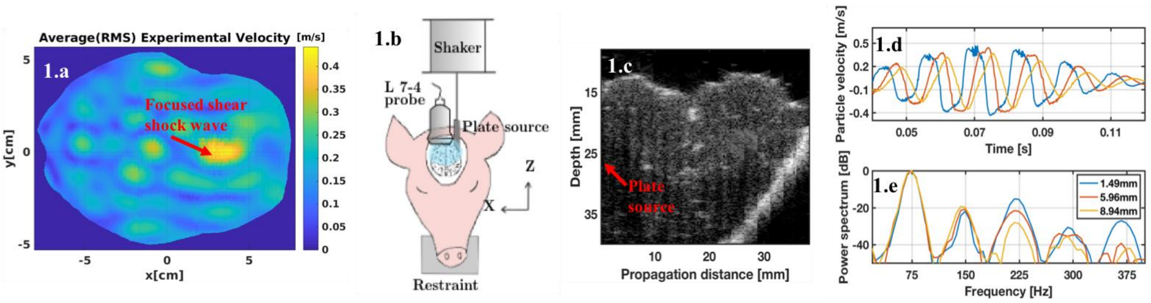

Fig.1. a) Strong geometric focusing of shear shock waves within the human skull boundary. Maximum velocity occurred at the focus of the ellipse-like boundary. b) Shear waves generated in *in situ* porcine brain using a focusing plate source attached to a shaker. Shear motion in brain was observed using a 5.2 MHz probe, using a sequence with 16 focused transmit-receive events. c) B-mode image of the *in situ* brain. d) Cubic nonlinear distortion of input shear waves observed within 3 mm of propagation. e) Characteristic odd harmonic spectrum of the shear shock was observed at 1.5 mm. Third and fifth harmonic amplitudes were higher than the second and fourth respectively, by 5 dB.