Transcranial Ultrasound Tomography for Imaging Traumatic Brain Injury

Trevor Mitcham†, Rehman Ali‡, Thomas Marini‡, Nebojsa Duric‡, Robert Haupt†

† MIT Lincoln Laboratory, Lexington, MA, USA   ‡ University of Rochester, Rochester, NY, USA

Motivation

- CT and MRI are effective for TBI detection, but SWaP requirements are impractical
- Medical ultrasound (US) has ideal SWaP, but struggles with transcranial imaging
- Ultrasound tomography (UST) addresses typical US limitations through:
  - < 1 MHz signals for reduced attenuation
  - Transmission mode to bypass reflections
  - Whole-head image coverage
- Goal: Develop a UST-based imaging system for whole-head TBI imaging at point of injury

Methods

Imaging Setup

In this work, UST data were collected on a Delphinus SoftVue clinical scanner [1] featuring:

- 1024 element ring array transducer
- Operational bandwidth: 200 kHz to 5 MHz
- Synthetic aperture acquisition

Figure 1. *A) The SoftVue clinical UST imaging system. B) Overview of the UST synthetic aperture data acquisition. The system transmits on one element at a time and receives on all 1024 elements before advancing to the next transmit element.*

Sample Preparation

- Cadaveric human head opened to provide access to the brain for UST studies [2]
  - Brain imaged with and without intact, degassed calvarium
- Repeat imaging performed after insertion of 40-cc hemorrhage-mimicking water inclusion
  - Sound speed (SS) contrast (~80 m/s) mimics hemorrhage vs. healthy brain tissue
- CT imaging (Philips Ingenuity 128) acquired of each sample as a ground truth assessment

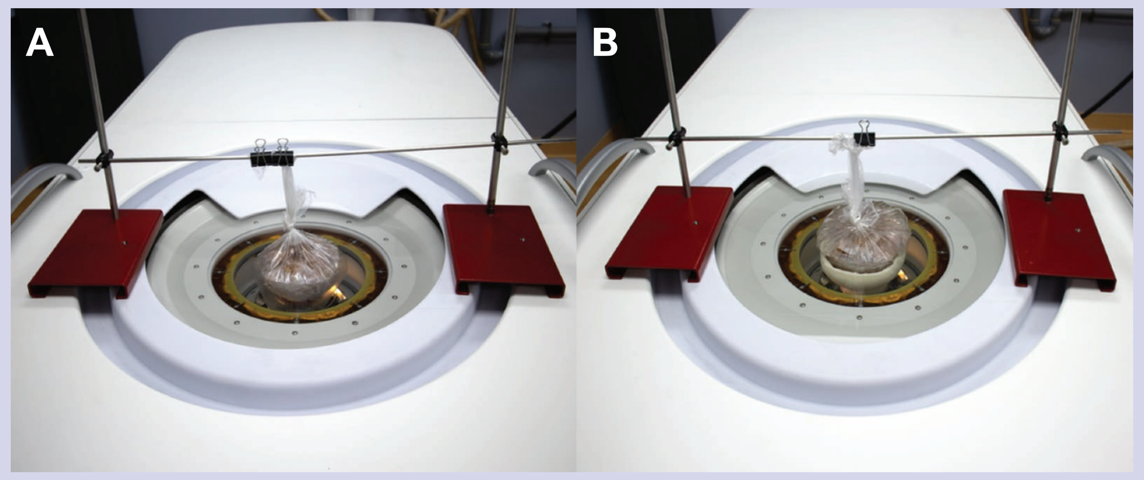

Figure 2. *Experimental setup on the SoftVue UST scanner. The brain sample is suspended from above while the ring transducer translates vertically to generate a full 3D volume. A) Standalone brain inside the scanner. B) Brain inside the removed calvarium, providing a realistic imaging environment.*

Image Reconstruction

Quantitative SS reconstruction with frequency-domain full-waveform inversion (FWI) was performed using a homogeneous initial model [3].

- Iterative nonlinear least-squares optimization minimizes mismatch between measured US data and forward model
- SS updates back-projection of residuals
- Frequency progression avoids cycle-skipping while improving resolution
  - 200 kHz to 1 MHz (standalone brain)
  - 200 to 800 kHz (transcranial imaging)

Results

Standalone Brain Imaging

- Healthy and irregular anatomy clearly visualized in both FWI SS maps and reflection images
- Measured SS values:
  - 1605 ± 1.5 m/s (healthy brain)
  - 1515 ± 2.3 m/s (inclusion)
  - 0.75 mm spatial resolution

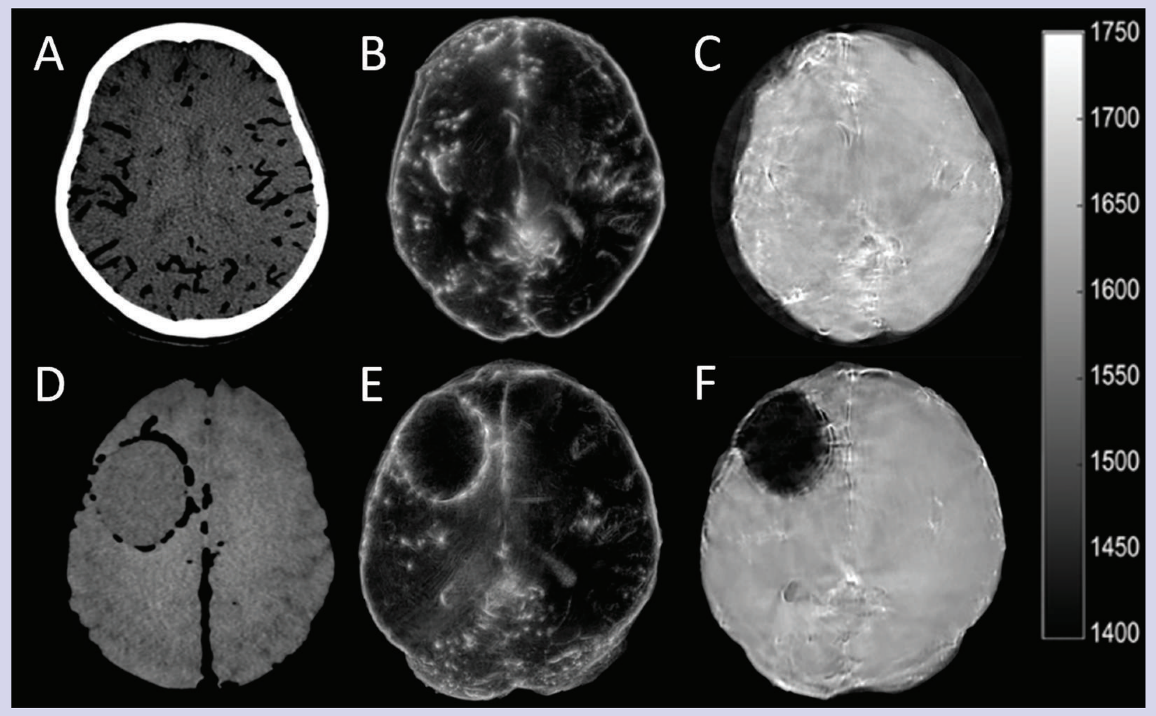

Figure 3. *Results from standalone brain imaging. A) CT image of intact head. B) Reflection and C) sound speed images of healthy cadaveric brain. D) CT image of brain with 40-cc hemorrhage-mimicking inclusion. E) Reflection and F) sound speed images of the brain with the 40-cc inclusion.*

Transcranial Imaging

- Healthy brain tissue clearly distinguishable from surrounding skull in SS images
  - Skull shape, thickness matches CT
  - Hemorrhage-mimicking inclusion easily visualized through skull
  - Presence and location of hemorrhage validated by three independent radiologists
- Measured SS values:
  - 1584 ± 4.3 m/s (healthy brain)
  - 1532 ± 1.0 m/s (inclusion)
  - 1 mm spatial resolution

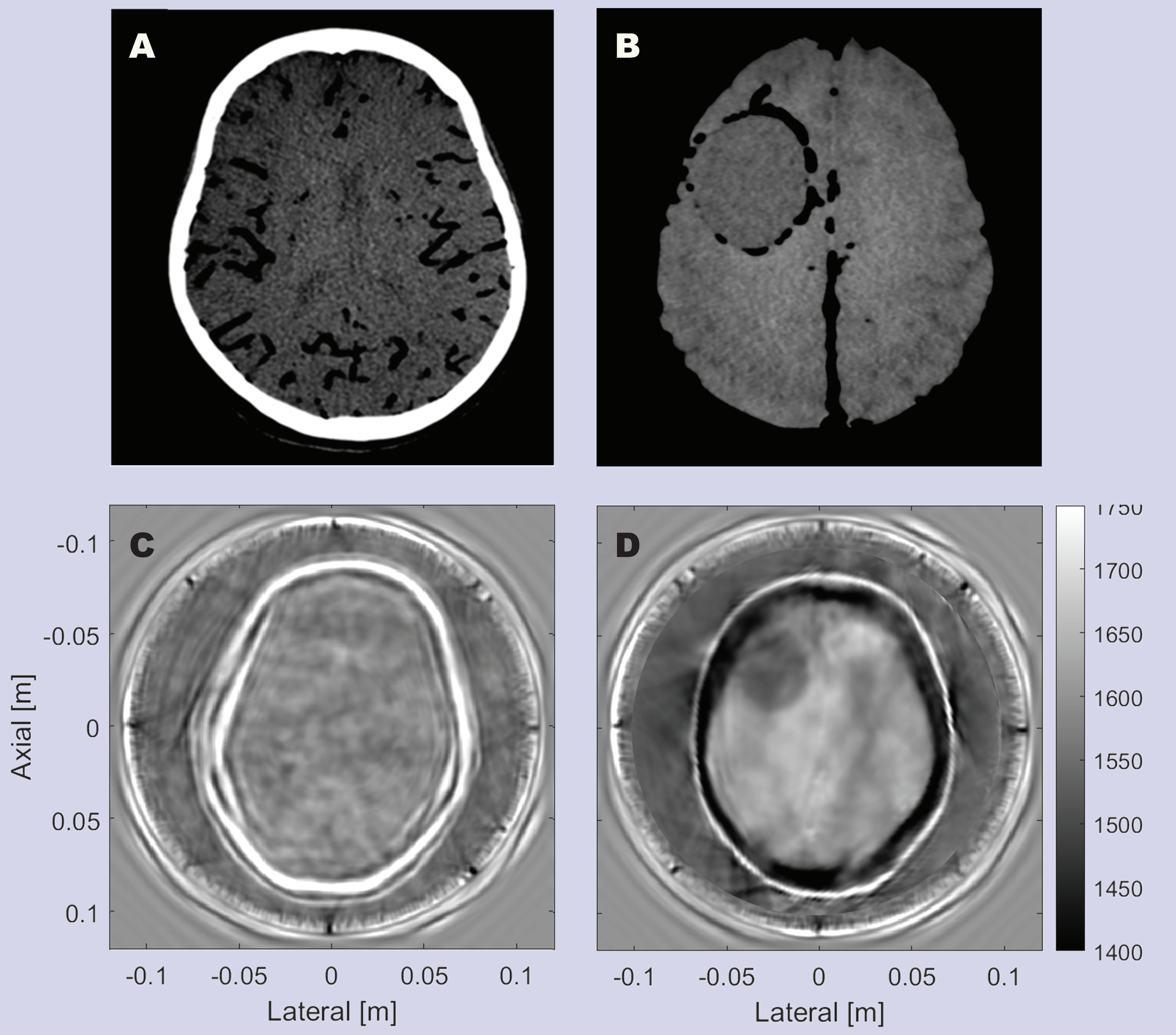

Figure 4. *Results from transcranial brain imaging. A) CT image of intact head. B) CT image of brain with 40-cc inclusion. C) UST image of intact cadaveric head showing skull and soft tissue contrast. D) UST image of the brain with inclusion within the degassed skull, clearly showing the hemorrhage-mimicking inclusion.*

Conclusions

- Healthy anatomy differentiated from irregular pathology when imaging through intact skull
- First-ever UST image of hemorrhage through human skull
- Demonstrates feasibility of UST for whole-head point-of-injury TBI detection
  - 40 cc hemorrhage detected (comparable to 30-cc evacuation threshold)

Future Work

- Improve image quality through reconstruction and hardware optimization
- Develop portable form factor suitable for field deployment in austere environments
- Evaluate multiple hemorrhage sizes and locations

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[1] Duric, Neb, et al. "Breast imaging with the SoftVue imaging system: First results." Proceedings of SPIE--the International Society for Optical Engineering. Vol. 8675. 2013
[2] Mitcham, Trevor, et al. "Transcranial ultrasound tomography for brain imaging: Ex vivo results and potential for stroke imaging." Medical physics 52.10 (2025): e18090
[3] Ali, Rehman, et al. "2-D slicewise waveform inversion of sound speed and acoustic attenuation for ring array ultrasound tomography based on a block LU solver." IEEE transactions on medical imaging 43.8 (2024): 2988-3000