JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

High-Rate Ultrasound Elastography for *In Situ* Characterization of Soft Tissue Mechanics During Ballistic Relevant Impact

MHSRS 2026 26-5773 Military Injury Biomechanics session

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Disclosure

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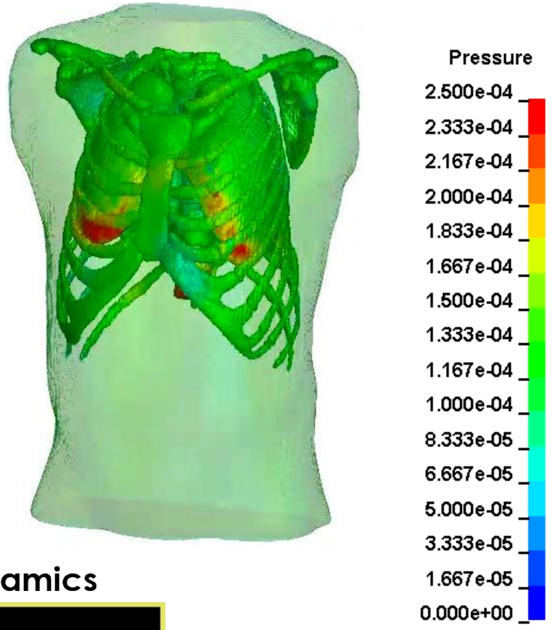
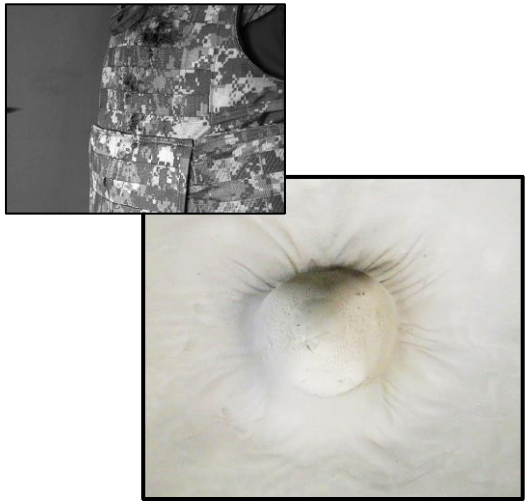
- A nonprovisional patent application covering aspects of this technology has been filed to USPTO as of July 25, 2026
- All authors have no conflicts of interest to report

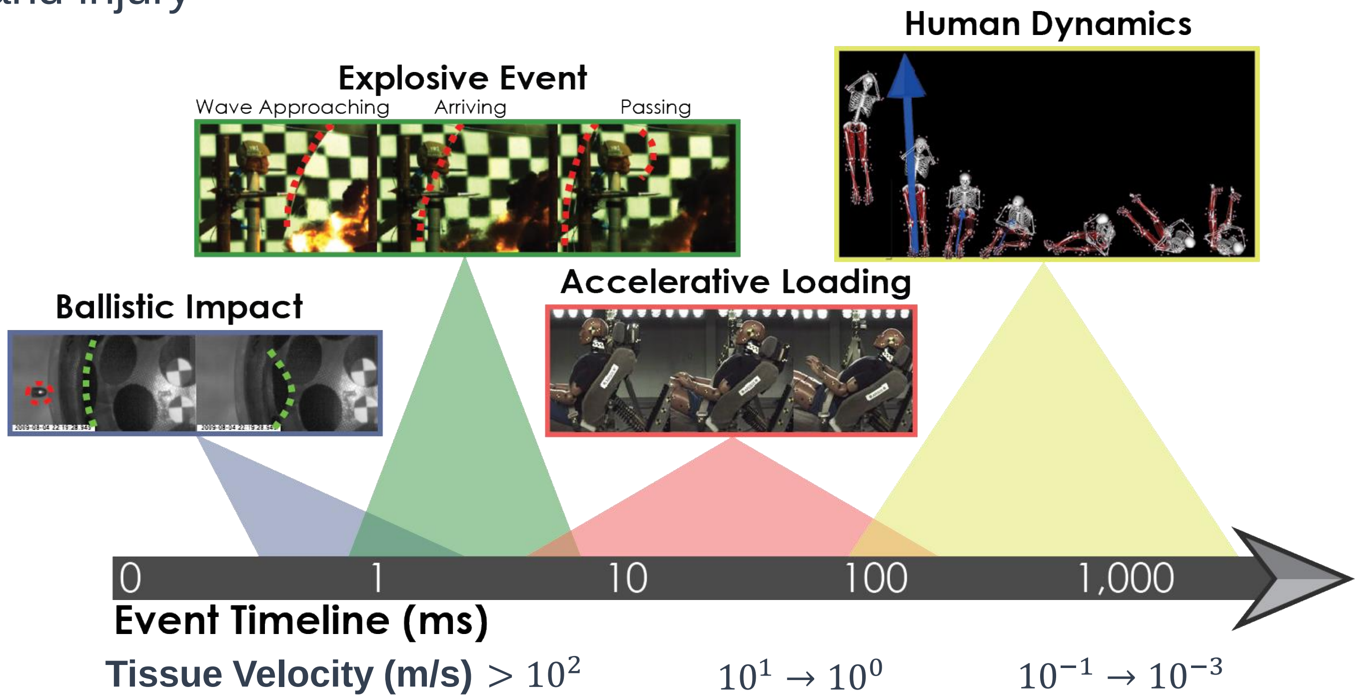
Motivation



Experimental test data to develop and validate human computational models for blast and ballistic impacts is challenging to collect due to:

- Rapid, large tissue deformations at high rates
- Complex internal tissue interfaces
- Tissue heterogeneity and accessibility
- Property dependence on rate and injury





Research Goals & Progressive Approach

- Combine high-frame-rate ultrasound plane wave compounding techniques and impact biomechanics
- Aim is to develop a novel method to characterize soft tissue deformation during military-relevant high-rate loading
- Use this to understand the effect of displacement rates on thoracic organ soft-tissue motion and material properties

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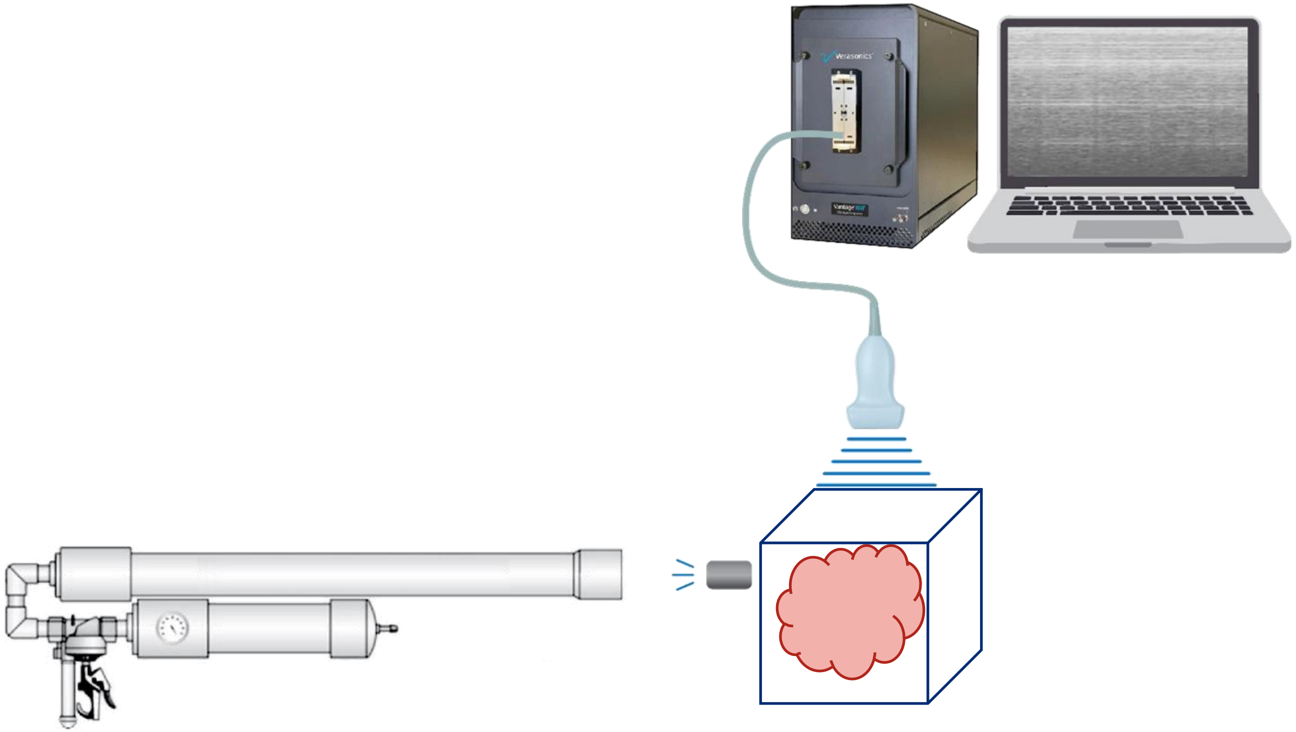
<u>Aim 1</u>: Medium velocity impacts (up to ~125 m/s) on phantom materials



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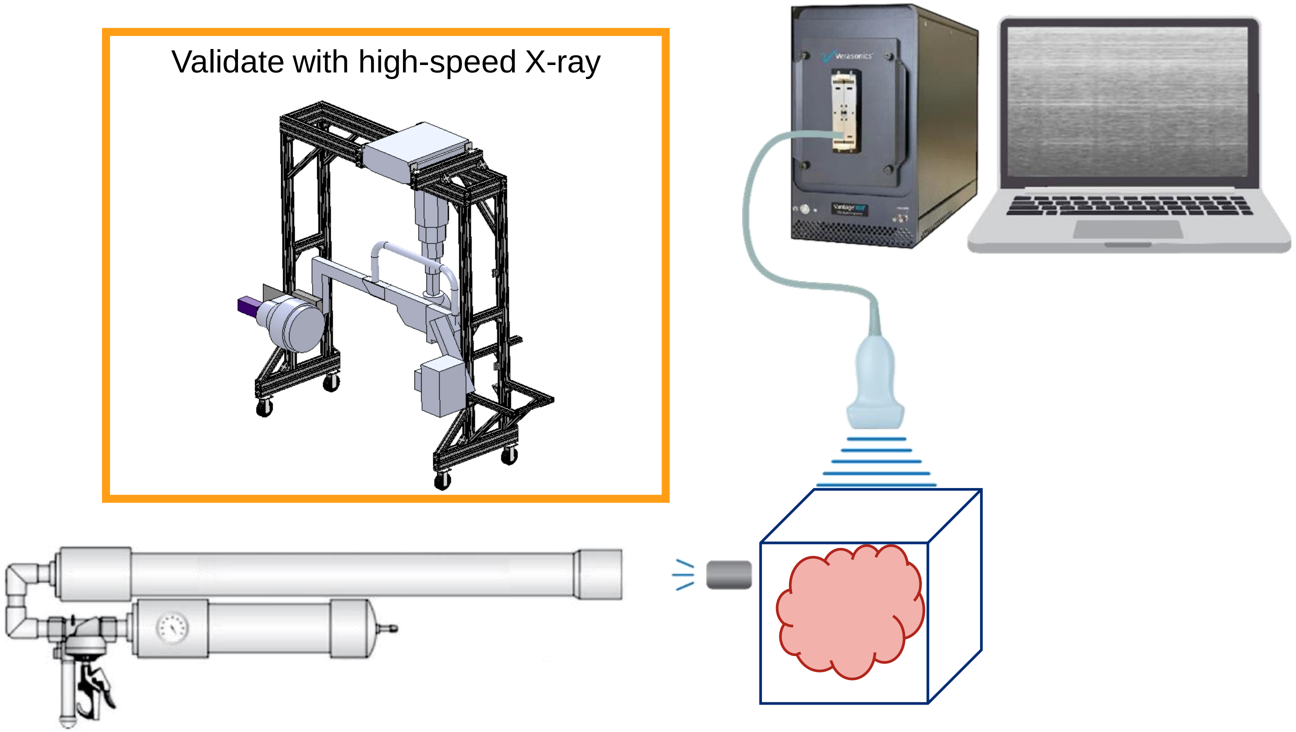

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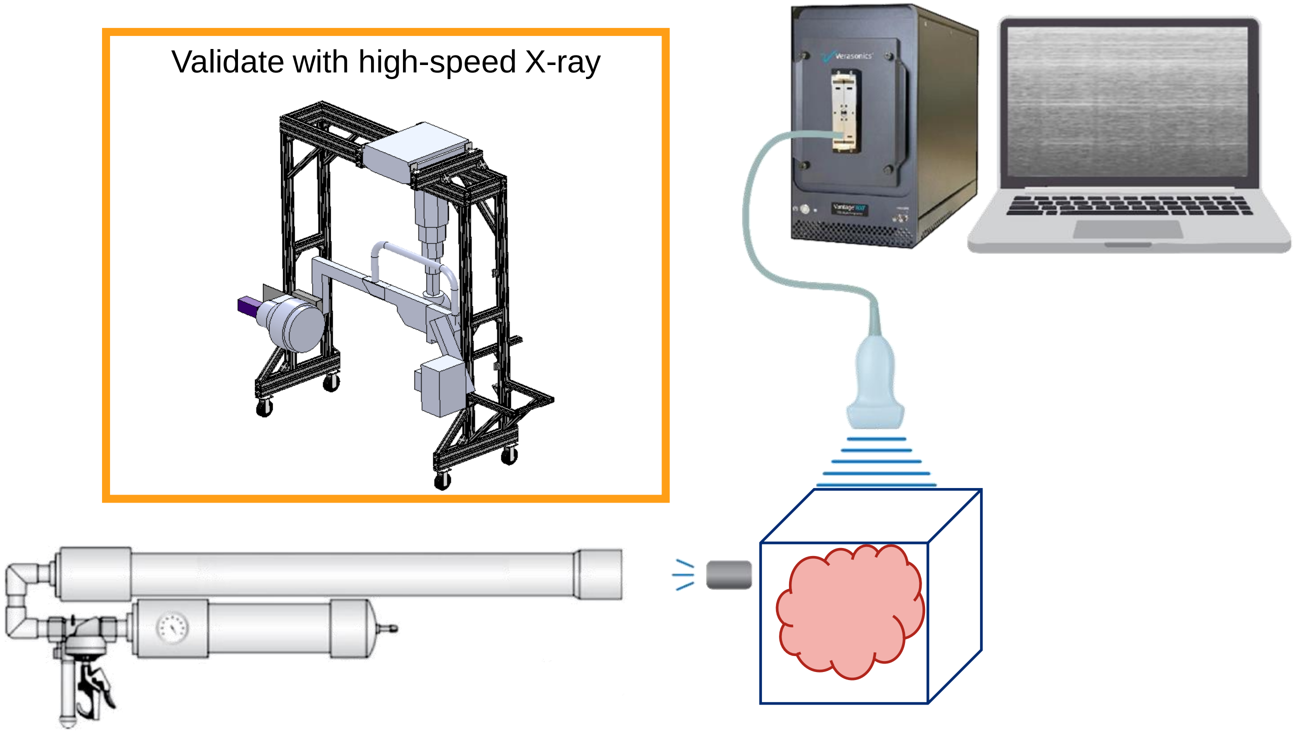

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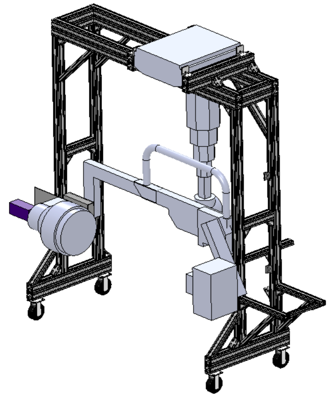
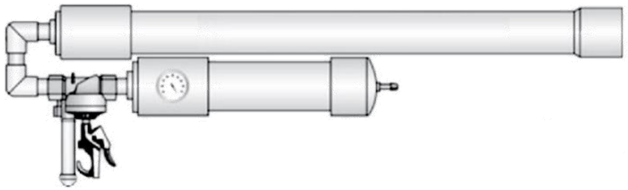
Aim 1: Medium velocity impacts (up to ~125 m/s) on phantom materials

Aim 2: Medium velocity impacts on cadaveric swine

Validate with high-speed X-ray

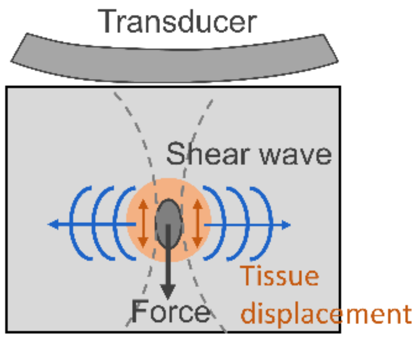


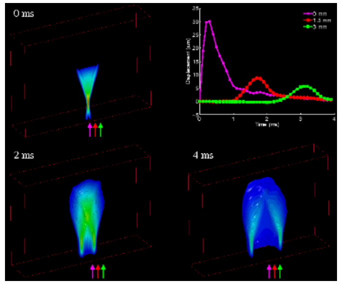


What is Ultrasound Elastography?

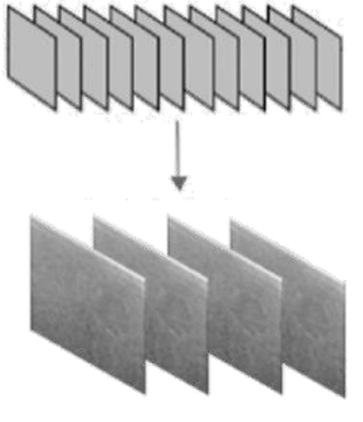
Non-invasive way to acoustically measure material stiffness (e.g., organs)

Excite tissue (acoustic radiation force or mechanical vibration)

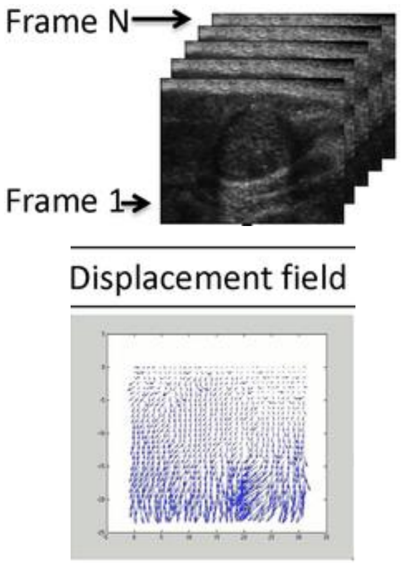




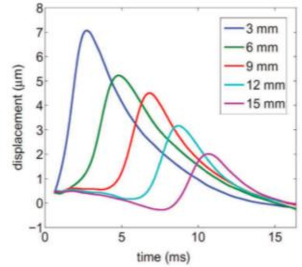
B-mode images as shear waves propagate

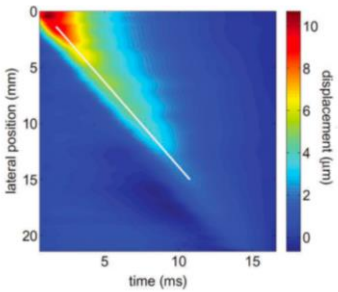


Displacement estimation via cross-correlation (similar to DIC)



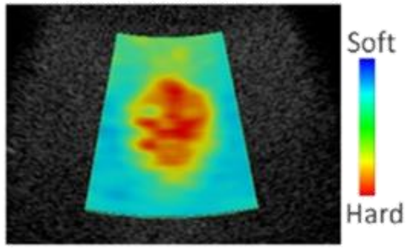
Displacement through time and space



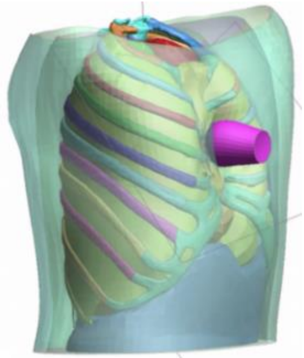


Slope of white line = SWS or c

Constitutive model to solve mechanical properties (e.g., if linear, elastic, isotropic, $E = 3\mu = 3\rho c^2$)



Selecting materials for finite element model (FEM)



Displacement data can be fit to higher order models

- **Viscoelastic**
- **Anisotropic**
- **Nonlinear**

Novelty of Approach

Uses high-frame-rate ultrasound to track rapid tissue displacement

What is Ultrasound Elastography?

Non-invasive way to acoustically measure material stiffness (e.g., organs)

Excite tissue (acoustic radiation force or mechanical vibration) → **B-mode images as shear waves propagate** → **Displacement estimation via cross-correlation (similar to DIC)** → **Displacement through time and space** →

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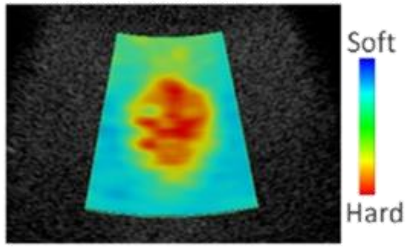
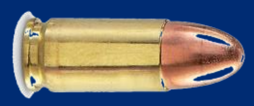


Uses high-rate loading as tissue excitation



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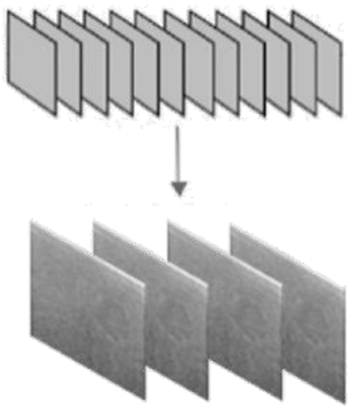
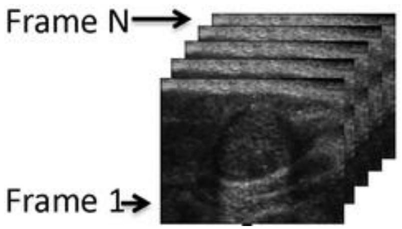
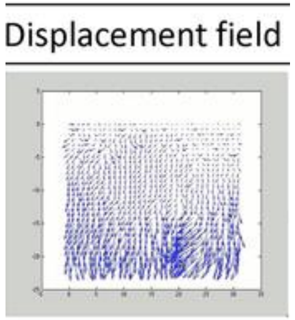
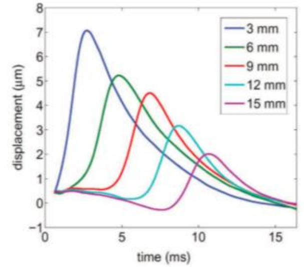
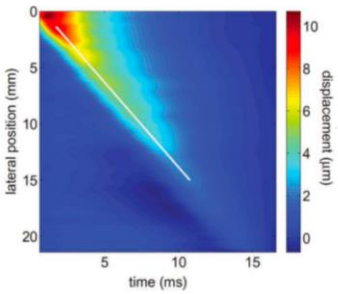


B-mode image reconstruction from raw RF data









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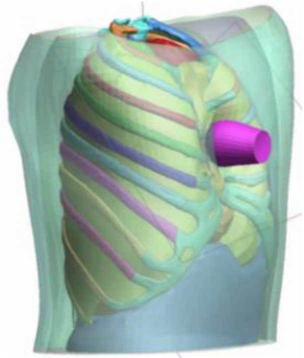

Displacement data can be fit to higher order models
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Novelty of Approach

Uses high-frame-rate ultrasound to track rapid tissue displacement

Research Ultrasound

Research ultrasound has recently expanded to high-rate imaging 10,000 fps starting in 2019

- Plane wave imaging allows for >10,000 fps
  - Coherent compounding to preserve resolution
- Individual control of transmit and receive timing
- Access to raw radiofrequency (RF) data allows for post-processing

Verasonics Vantage NXT

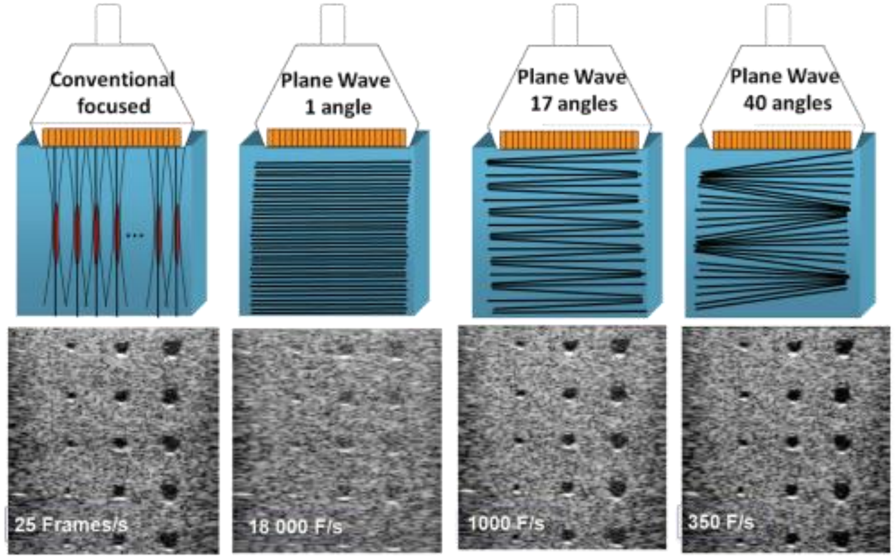
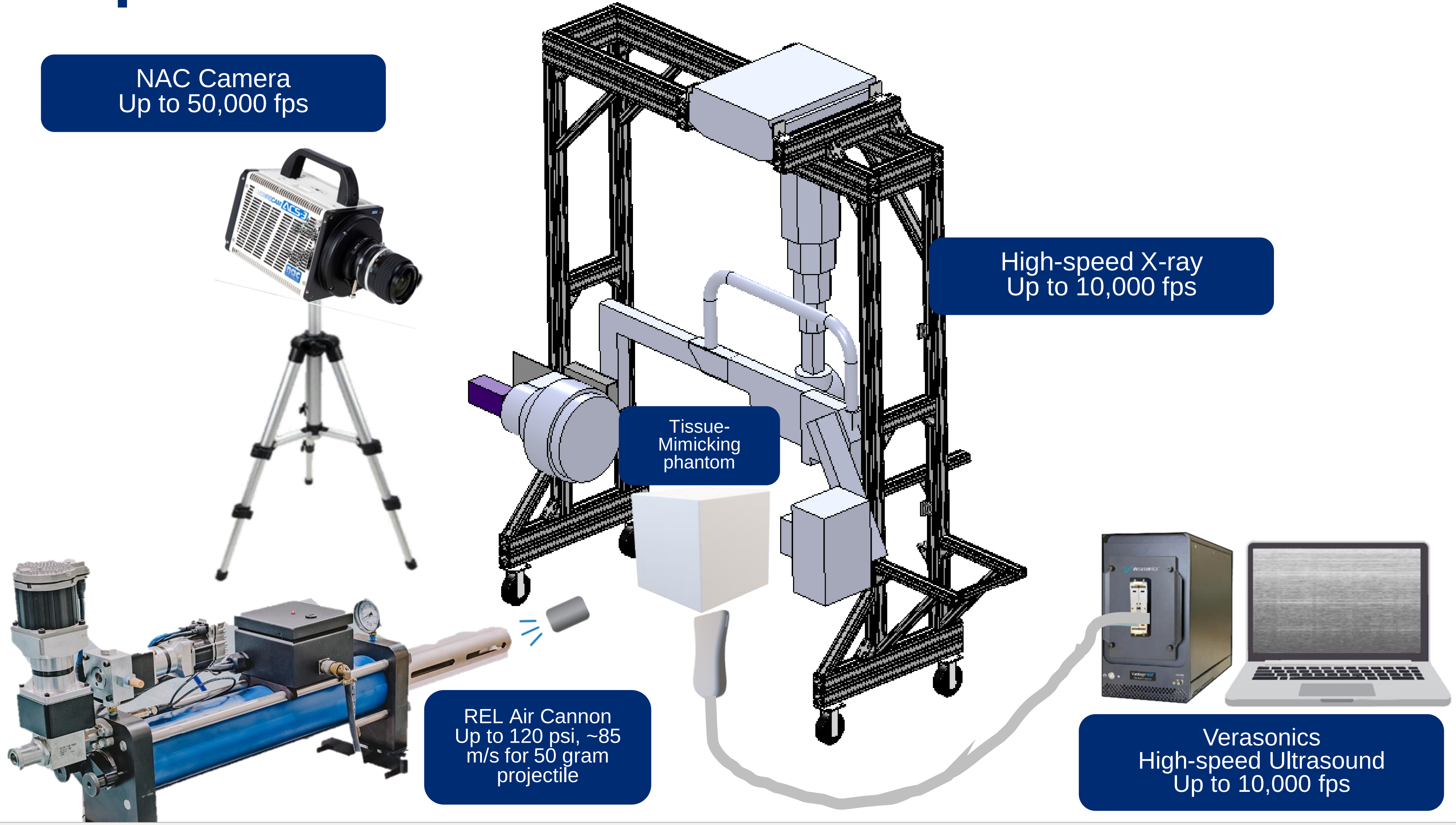
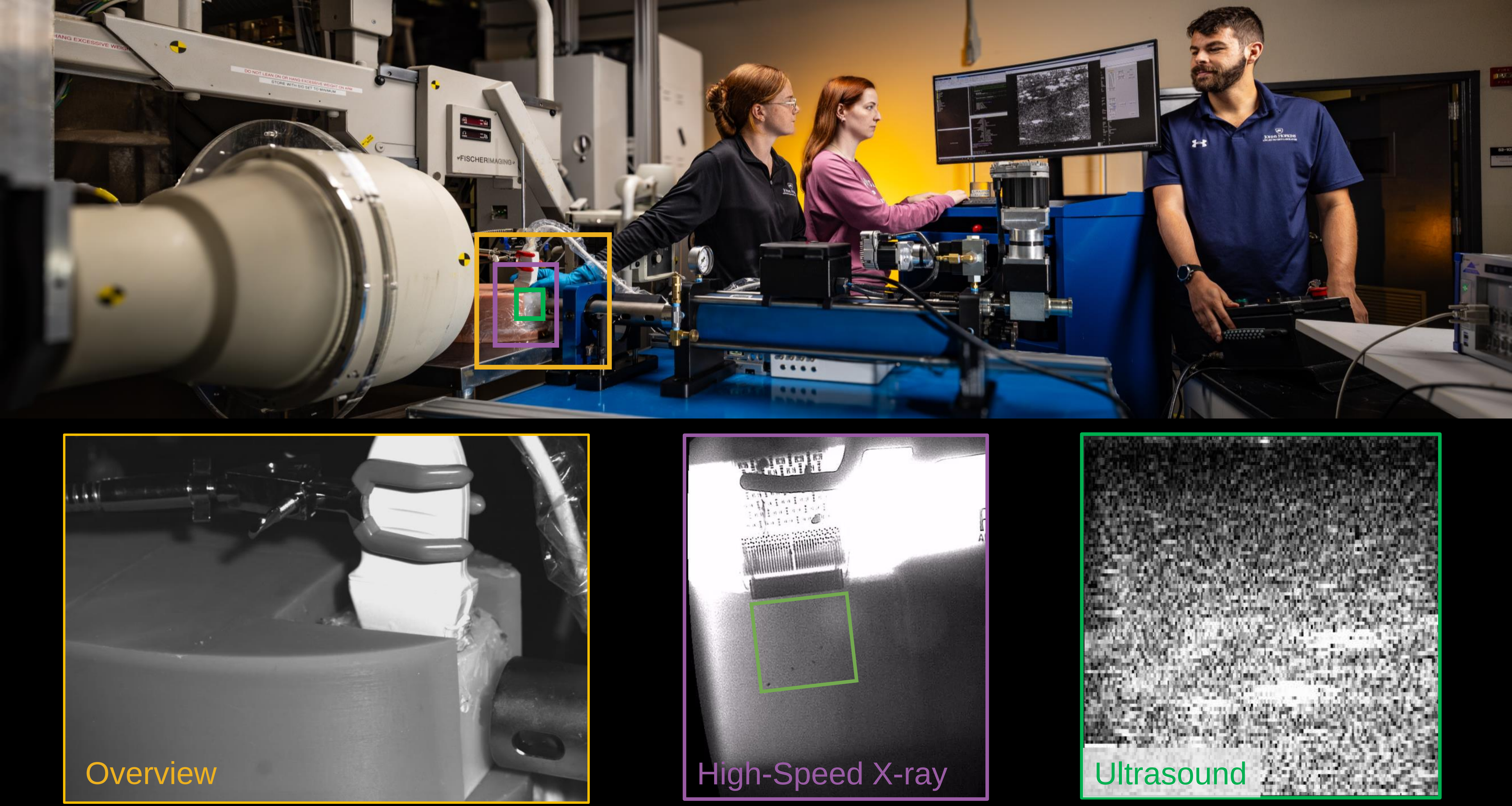


Fig. 2. Conventional focused and ultrafast ultrasound imaging sequences for a typical medical imaging setup (4-cm deep region of interest): (a) conventional focused imaging (128 focused beams and 4 focal depths leading to ~25 fps), (b) plane-wave imaging (~18000 fps), (c) plane-wave compounding with 17 angles (~1000 fps), and (d) plane-wave compounding with 40 angles (~350 fps).

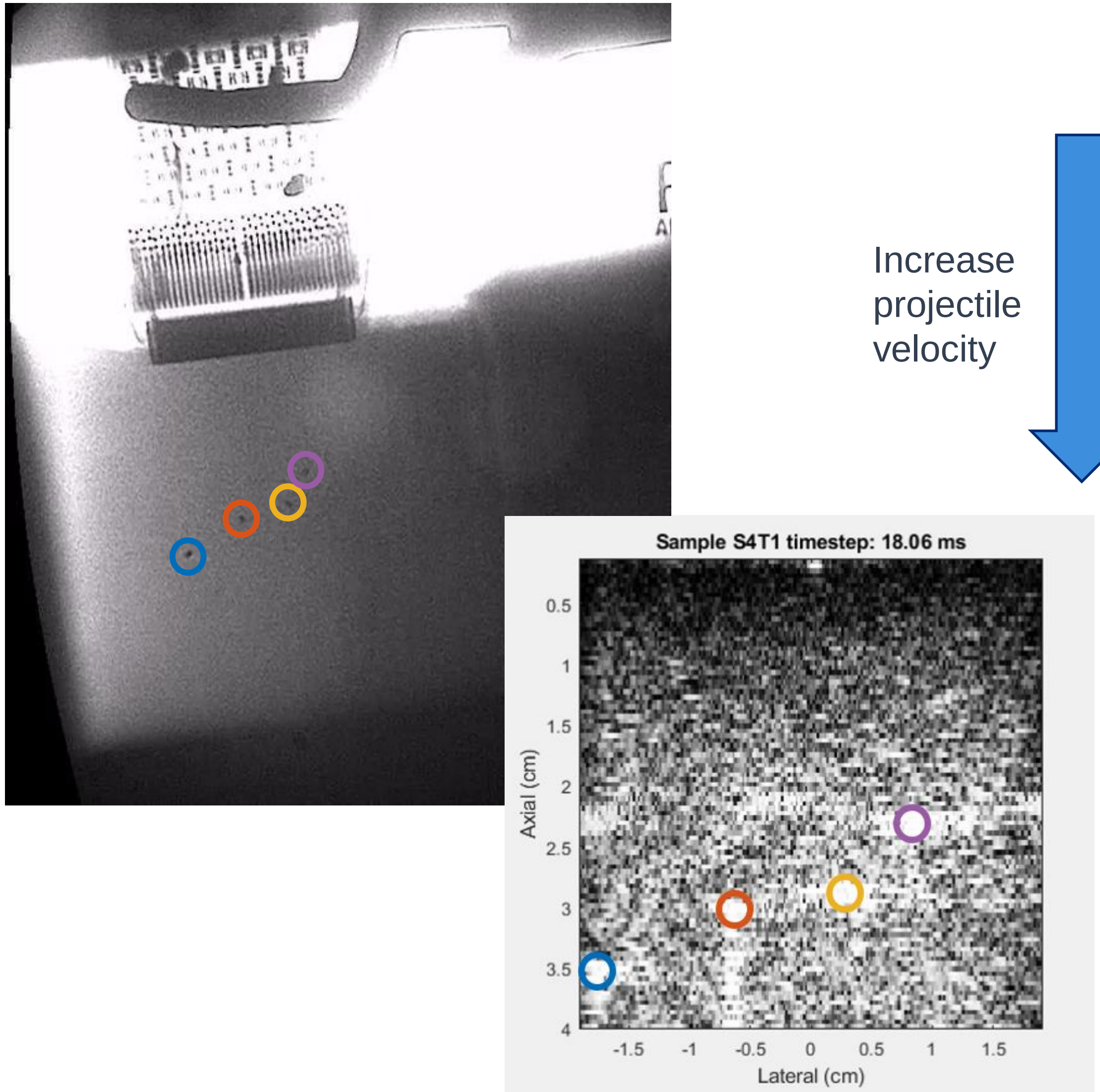
Tanter and Fink: Ultrafast Imaging in Biomedical Ultrasound
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6689779&tag=1

High-Speed Instrumentation for Validation

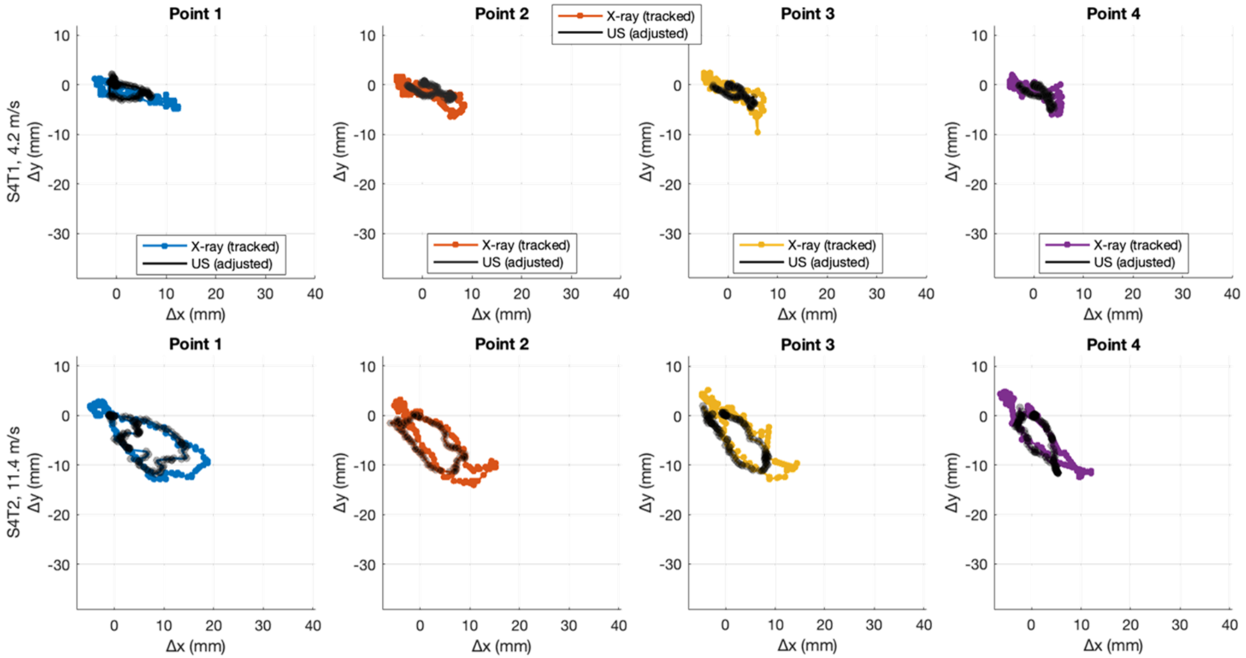



FISCHERIMAGING
Overview
High-Speed X-ray
Ultrasound

Ultrasound and High-Speed X-ray Validation

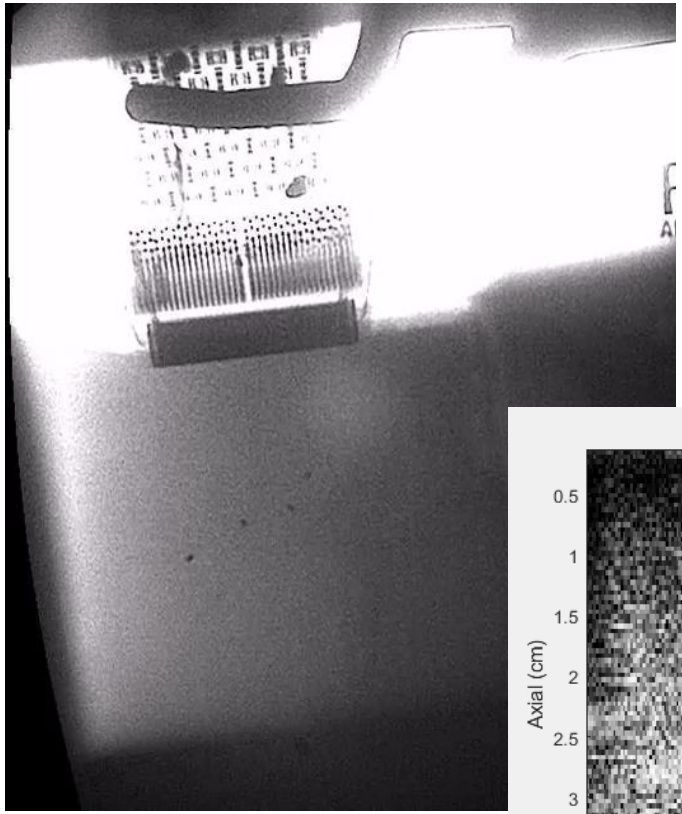


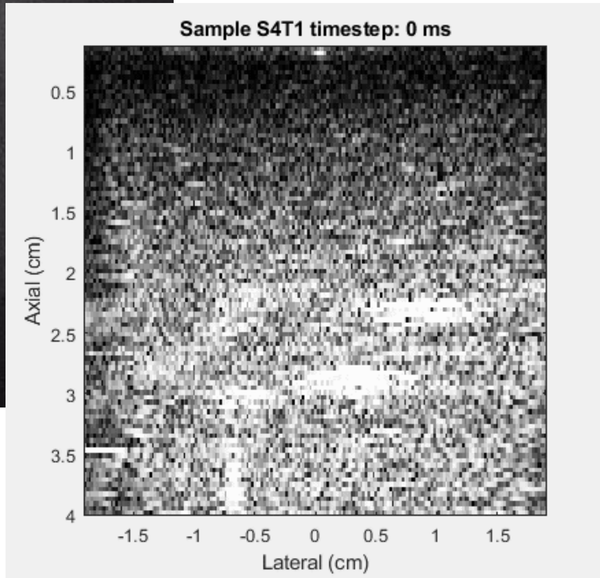
Increase projectile velocity

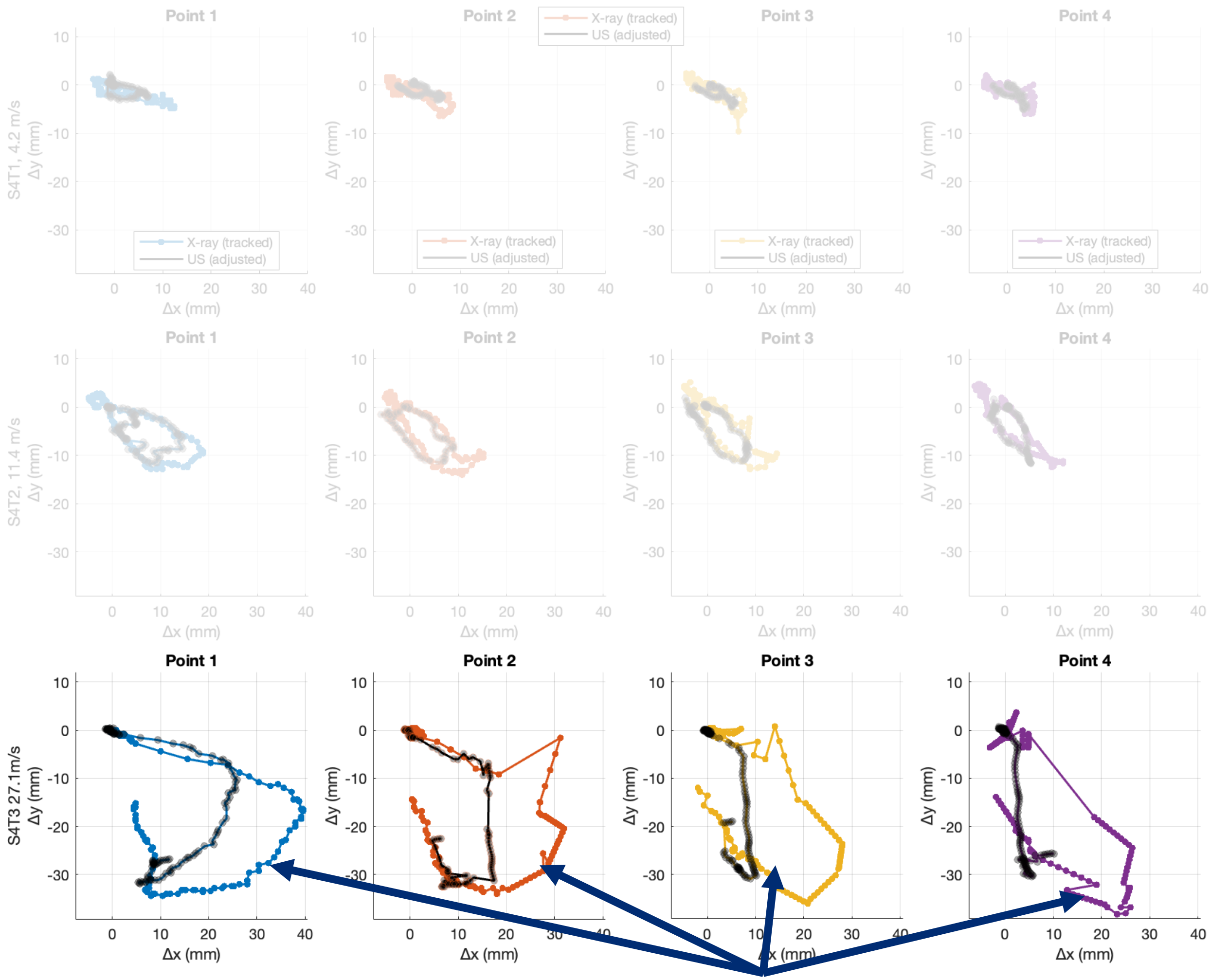


Solid agreements between ultrasound (US) and X-ray at lower impact speeds

Ultrasound and High-Speed X-ray Validation

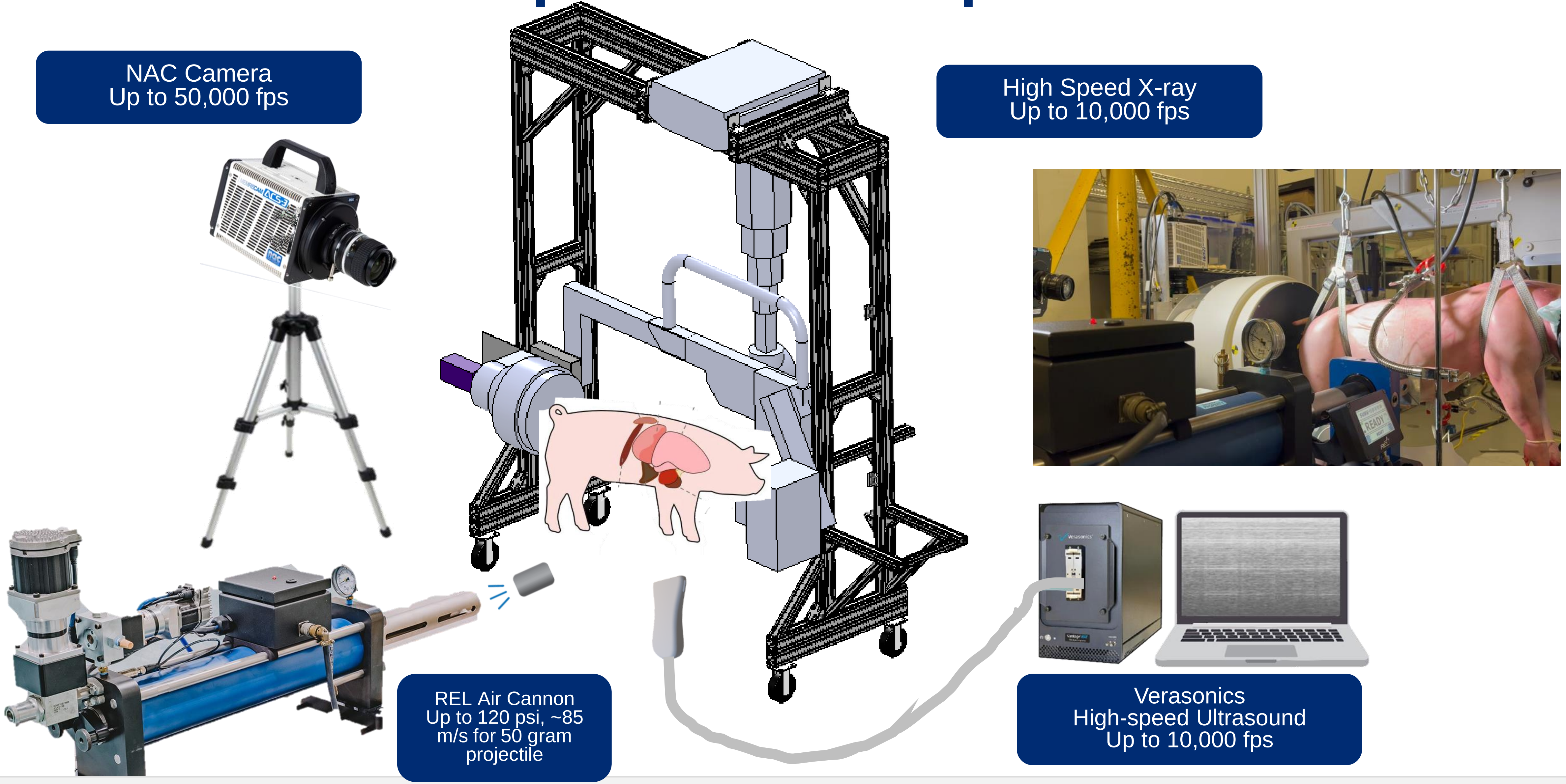






US and X-ray tracked points diverged for higher velocity impacts as beads moved out of view with greater displacement; but once back in US field of view agreed again

Porcine Model Impact Test Setup



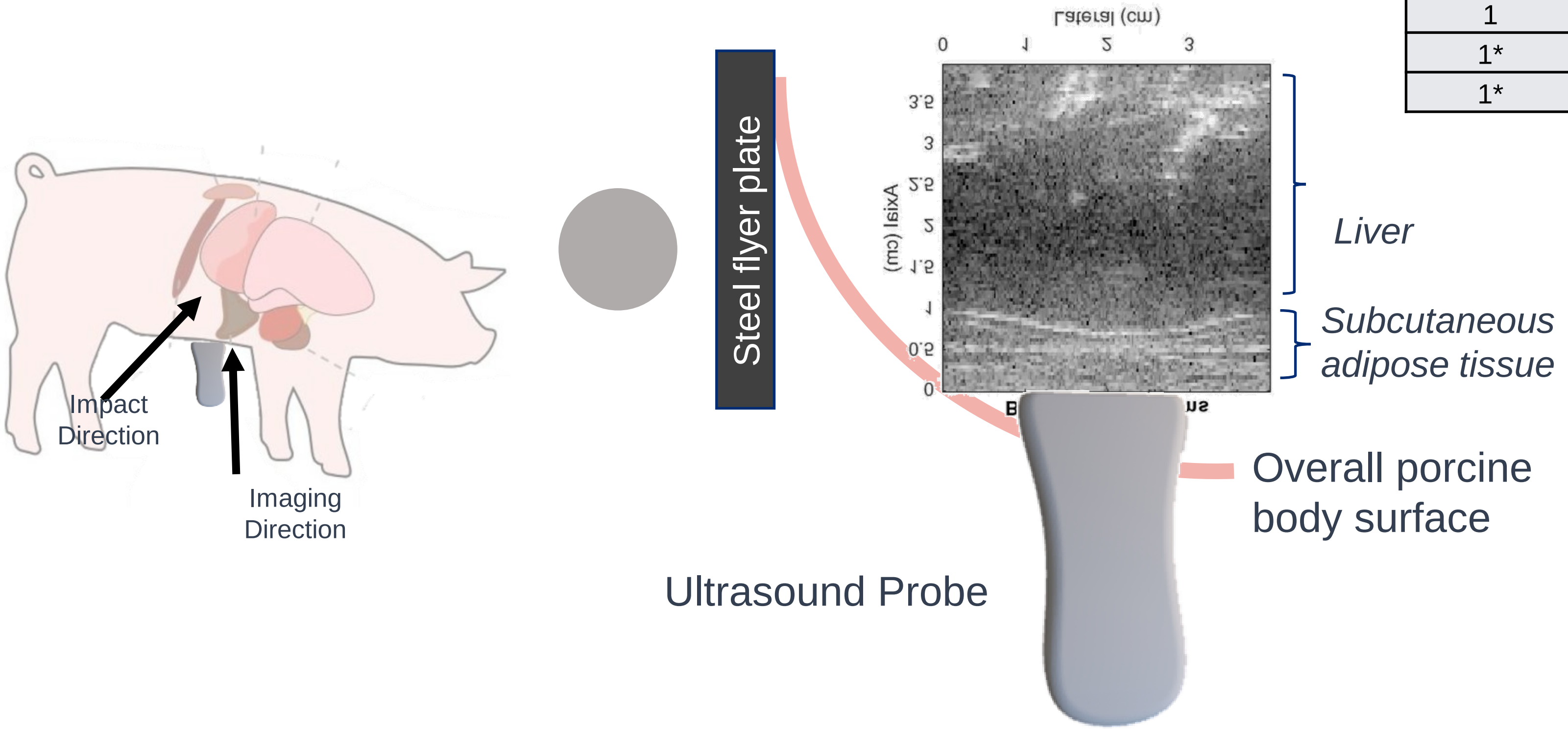
Porcine Impact Test Overview

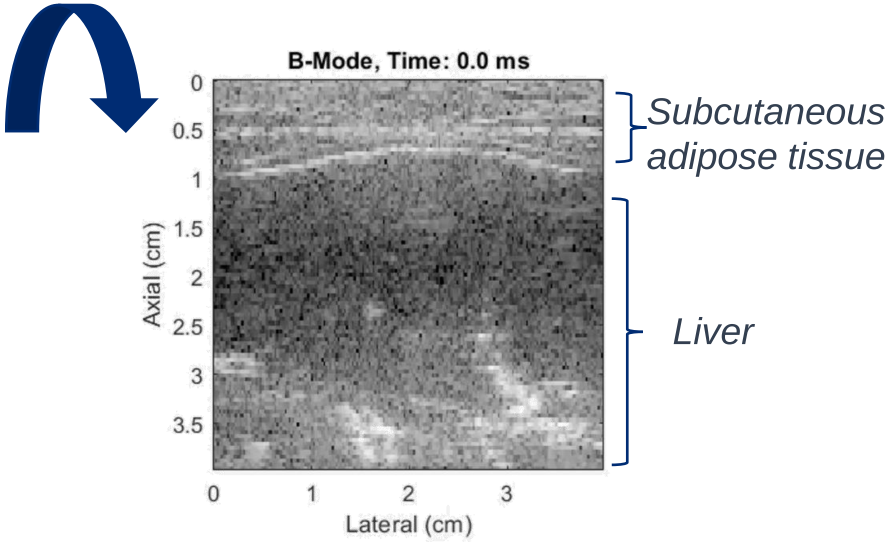
- 14 and 8 impacts respectively conducted on 2 different pig specimen with increasing projectile velocity
- Projectile impact velocities ranged from 19.4-85.5 m/s

Pig #	Air Cannon Pressure (psi)	Projectile Speed (m/s)
1	10.1	19.95
1	10	19.36
1	10.1	19.60
1	20.1	33.07
1	20	33.16
1	30.1	42.12
1	40	50.44
1	50.1	55.69
1	60	60.47
1	80	69.04
1	100	75.86
1	118.3	85.53
1*	20	30.93
1*	20	34.38

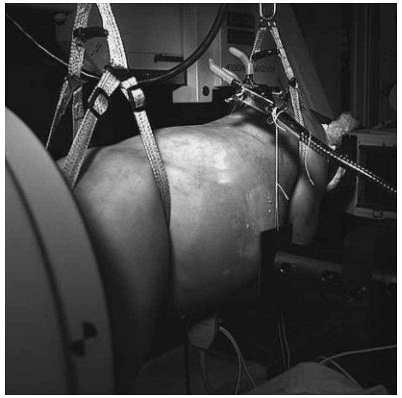
Pig #	Air Cannon Pressure (psi)	Projectile Speed (m/s)
2	10.1	19.58
2	20	32.03
2	30	43.68
2	40	50.38
2	50	68.24
2	60	66.14
2	10	15.97
2	20	31.06

- Pig at 45 degrees oblique angle

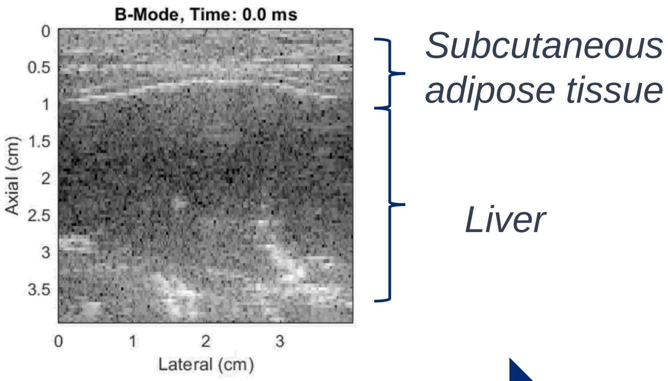




Increasing Projectile Speed



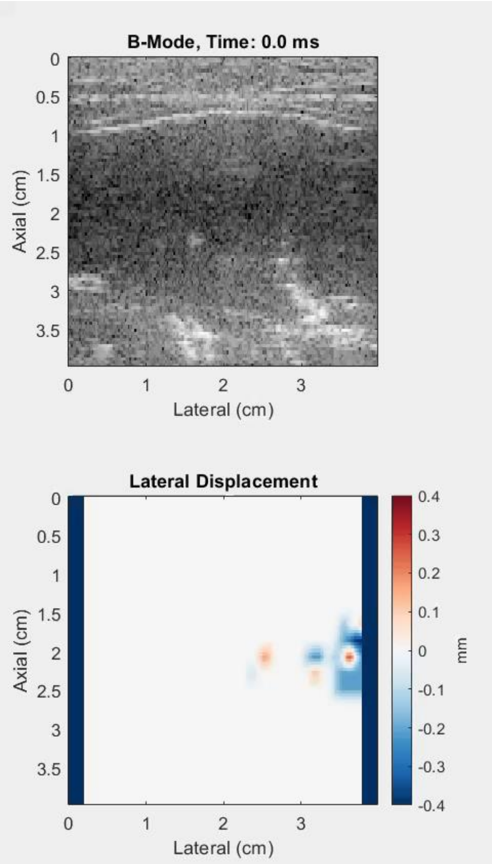
Exemplar video (120 psi)

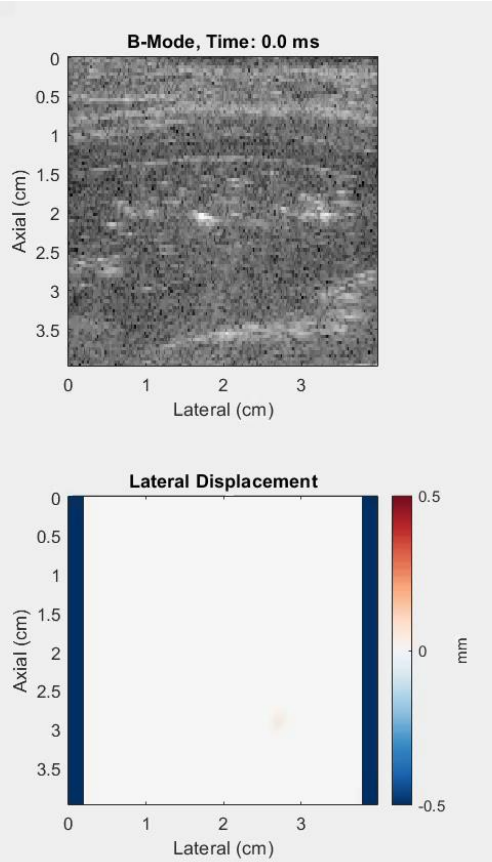


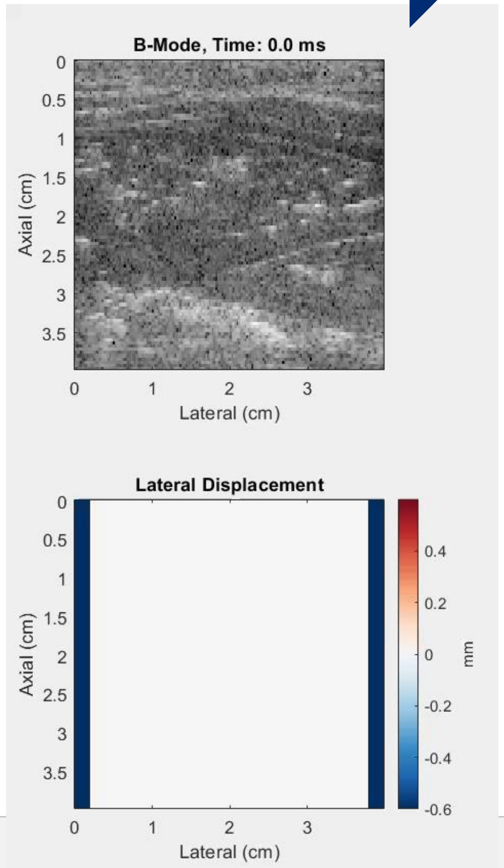
20 psi
33.2 m/s

50 psi
55.7 m/s

120 psi
85.5 m/s







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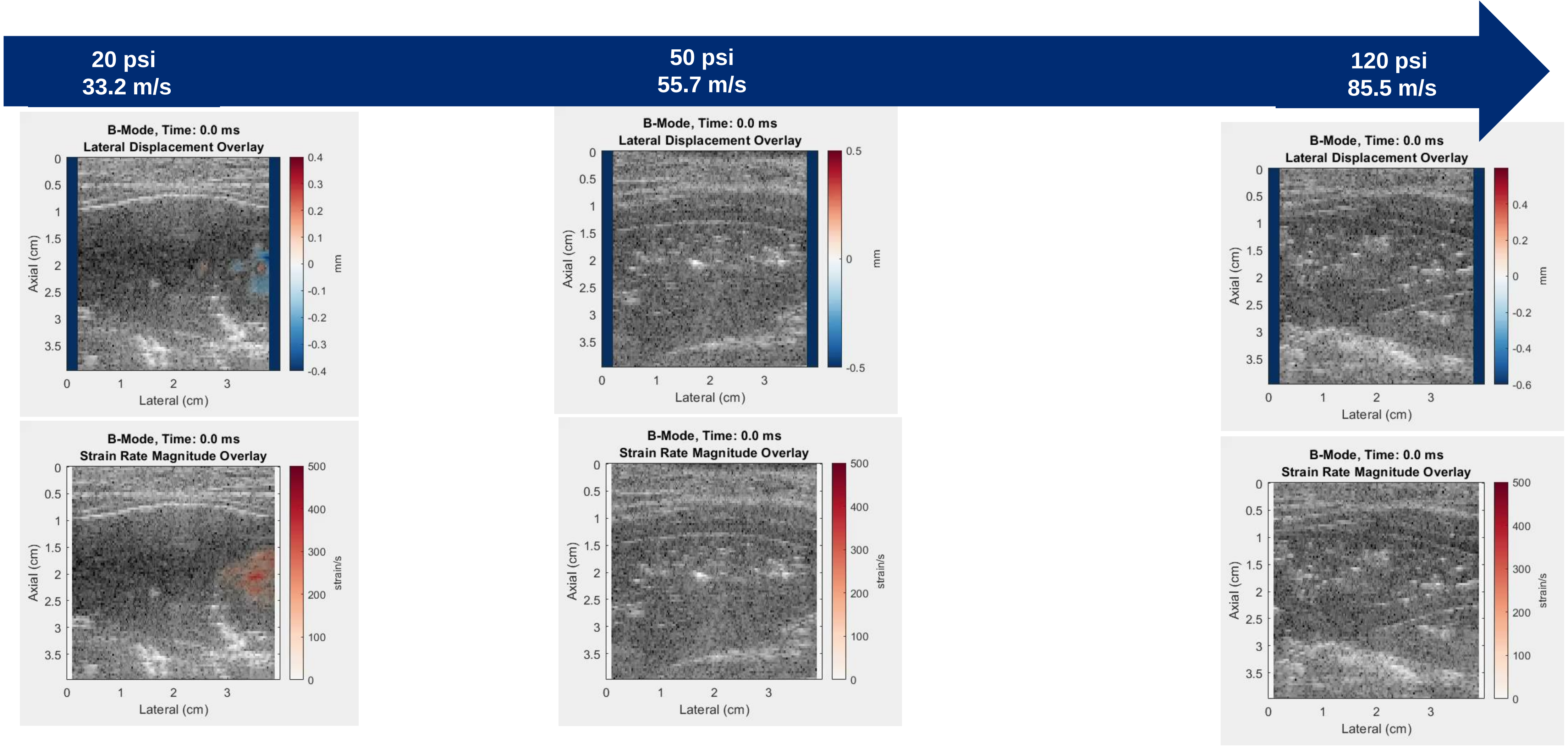


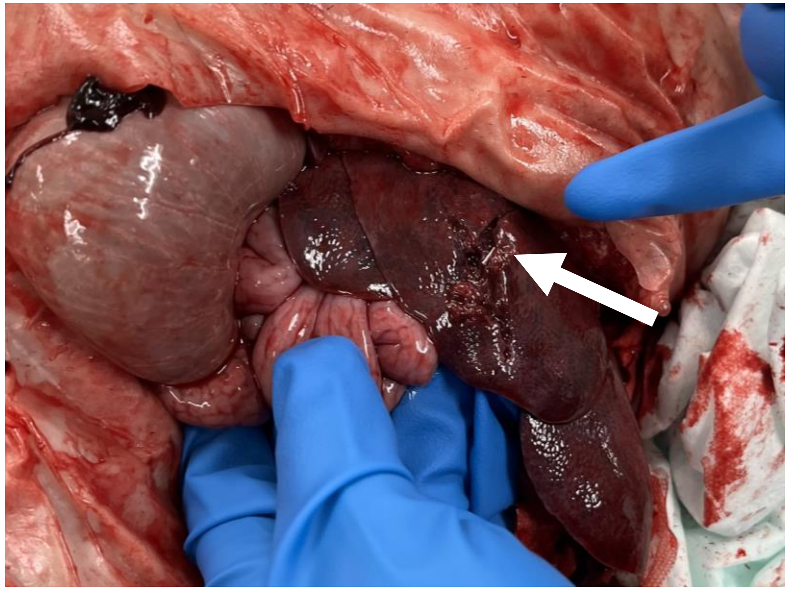
Novel finding: Organ slip boundary observed during loading
Confirms the ability of ultrasound to track displacement and strain during behind armor blunt trauma (BABT) relevant loadings

Impact-induced Liver Laceration Observed

- Post-test observation of Porcine #1 revealed liver laceration

- Specimen impacted multiple times, so injury timing and impact severity to induce injury is unclear (may be cumulative rather than single impact)

- Laceration appears similar to known BABT injuries, indicating that we’re likely in appropriate high-rate impact regime to study those dynamics



Impacts and Limitations

- **Project end state:**
  - New *in situ* high-rate acoustic tissue characterization methodology
  - Ability to directly measure organ motion during impact events
  - Ability to measure organ material properties during dynamic injury biomechanic and ballistic models
- **Limitations**
  - Only in 2 porcine specimen, 1 location (liver), ~5 cm from impact location to date
  - At current velocity capacity of air cannon, but BABT rates can be higher
- **Future research enabled by capability:**
  - Characterize organ tissue mechanics and injury during live fire blast and ballistic testing
  - Improved human FEM model organ interfaces and mechanical properties at high-rate loading

With thanks to our ARL Cooperative Agreement Partners:
- Karin Rafaels
- Kathryn Loftis
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- Sikhanda Satapathy
- Mike Kleinberger
- Tim Baumer
- Andrew Brown
- Tusit Weerisooriya
- Denise Ford (ARO)

Ultrasound as a monitoring platform for high-rate loading is applicable across injury biomechanics platforms (animal, PMHS, volunteers)

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