Numerical Characterization of Ultrasound Elastography for the Early Detection of Deep Tissue Injuries

by

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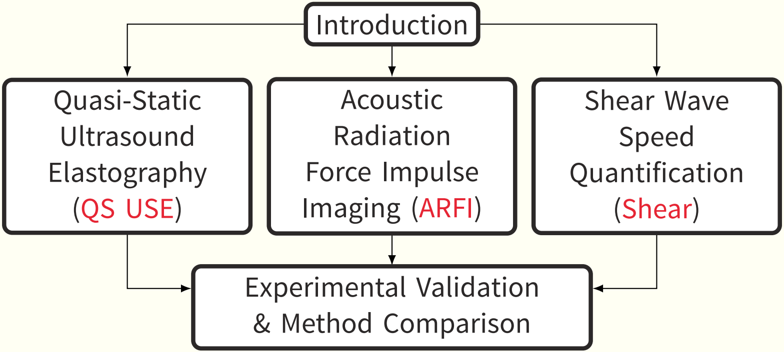
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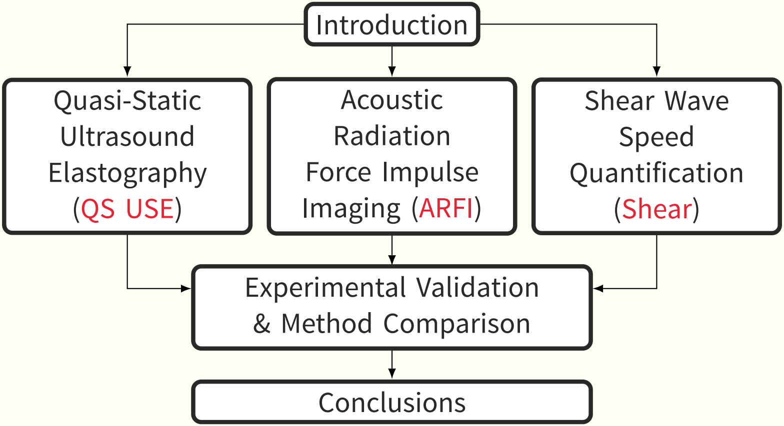
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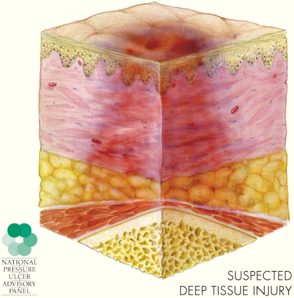
Introduction

Deep Tissue Injuries (DTI)

- Secondary injuries (limited mobility)
- Stage III – IV pressure ulcers
- Caused by pressure & deformation
- No clinical detection
- Severe health burdens [Russo et al., 2008]
  - 500,000 – 2,000,000 annually (USA)
  - Increased mortality, length of stay



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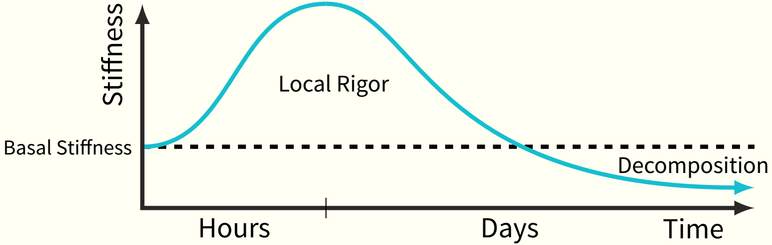
Current DTI Detection

- Clinical settings: risk assessment scales
  - Norton, Braden, and Risk Assessment Pressure Sore scales
  - No actual detection, only risk assessment
- Research settings: MRI
  - Not clinically feasible
- New research:
  - B-mode imaging [Aoi et al., 2009]
  - Blood / urine markers [Makhsous et al., 2010]
  - Ultrasound elastography [Deprez et al., 2011]

Ultrasound Elastography

- Mechanical stiffness changes with injury formation and progression



Adapted from [Gefen, 2009], used with permission

- Ultrasound elastography is a technology which measures tissue stiffness

Literature Review

- The purpose of this research was to gain understanding of and characterize the use of ultrasound elastography toward DTI detection

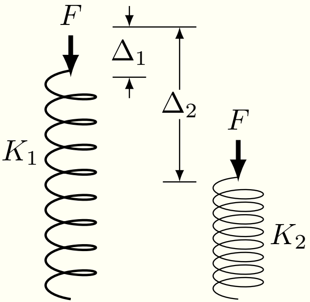
	DTI	B-Mode US	QS USE	ARFI	Shear	FE Models	Gel Phantoms	Animals	Humans	Characterized	Clinical
PU Risk scales	✗	—	—	—	—	✗	✗	✗	✓	✓	✓
MRI	✓	—	—	—	—	✓	✓	✓	✓	✗	✗
Aoi, 2009	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	?
Makhsous, 2010	✓	—	—	—	—	—	—	✓	✗	✗	✓
Deprez, 2011	✓	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓
➜ This work	✓	✗	✓	✓	✓	✓	✓	?	?	✓	✓

Quasi-Static Ultrasound Elastography*

* Accepted for publication as: K. Hamaluik, W. Moussa, and M. Ferguson-Pell, “Numerical Characterization of Quasi-Static Ultrasound Elastography for the Detection of Deep Tissue Injuries.” *IEEE Transactions on Medical Imaging*

Theory of Operation

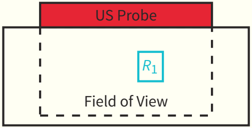
- Manual deformation
- Magnitude of deformation related to stiffness
  - $\downarrow$ deformation
    $\approx \uparrow$ stiffness
    $\approx \uparrow$ damage magnitude



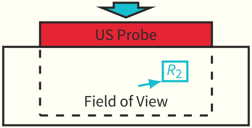
$$\Delta_1 < \Delta_2$$
$$\therefore \; K_1 > K_2$$

Theory of Operation

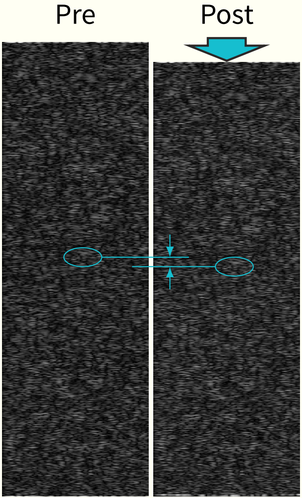
- Manual deformation
- Magnitude of deformation related to stiffness
  - $$\begin{aligned} &\downarrow \text{deformation} \\ \approx &\uparrow \text{stiffness} \\ \approx &\uparrow \text{damage magnitude} \end{aligned}$$
- Track scattering centres
  - Assumptions of motion [Brusseau et al., 2008]



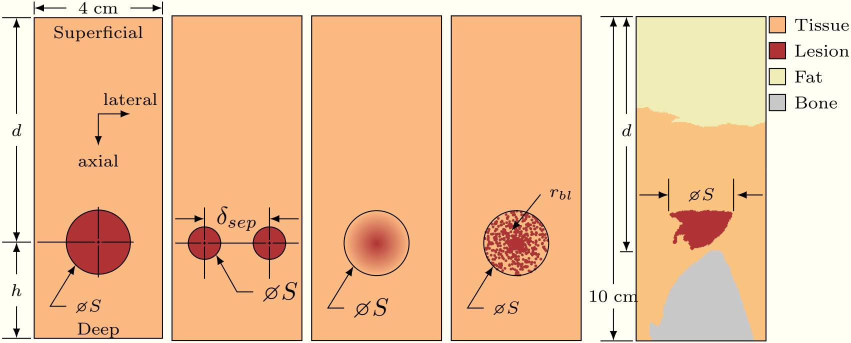
Pre-compression image



Post-compression image

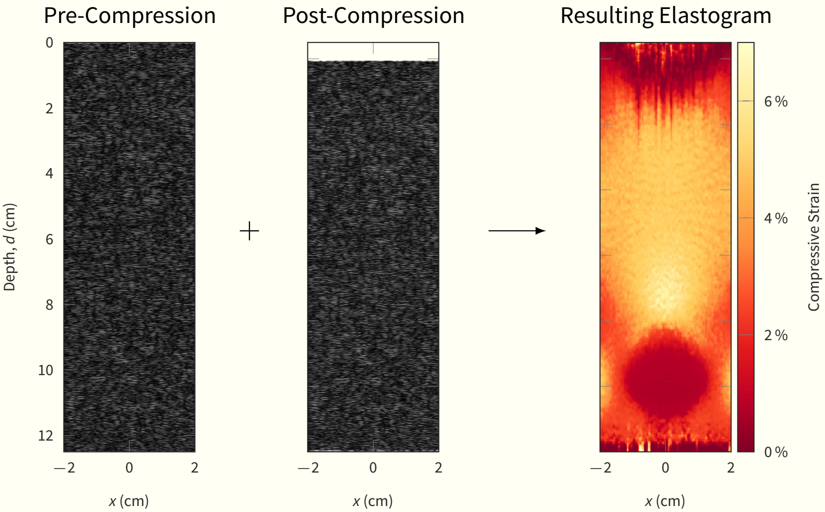


Investigated Models

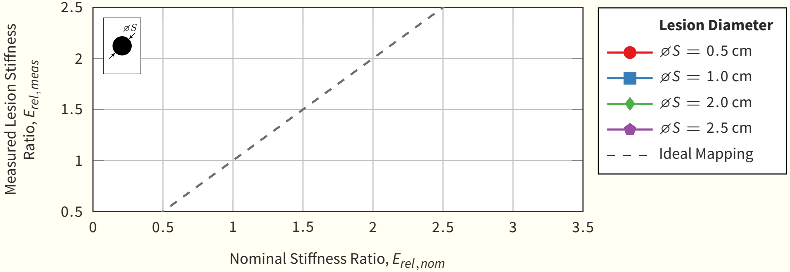


d:	lesion depth	δ_{sep}:	separation distance
h:	lesion altitude	b_r:	blur radius
$\varnothing S$:	lesion size	b_ρ :	cluster density
f:	interrogation frequency	r_{bl}:	cluster radii
ε_{app}:	applied strain		

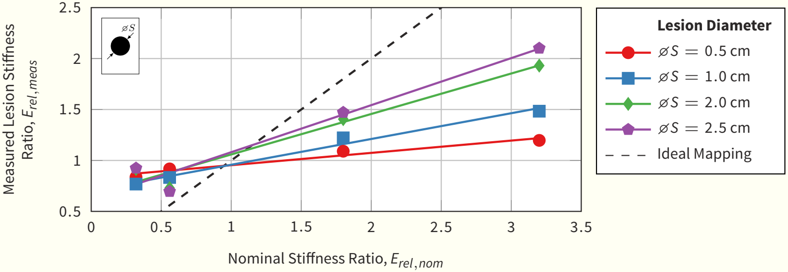
Sample Resultant Elastogram



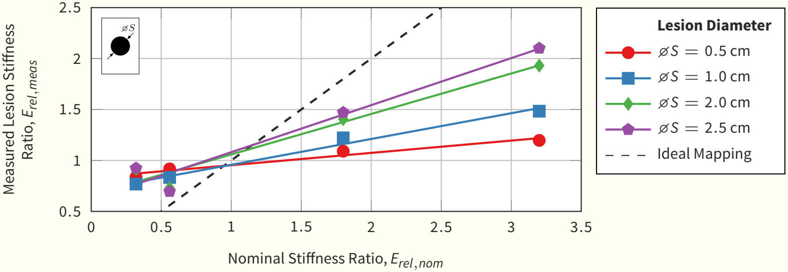
Sample Quasi-Static Results

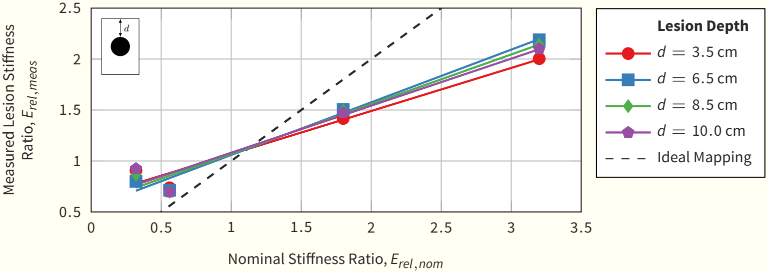


Sample Quasi-Static Results

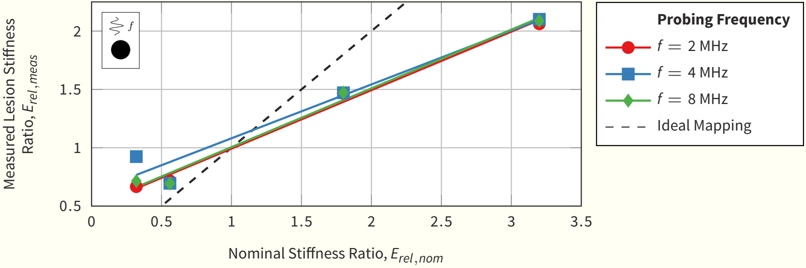


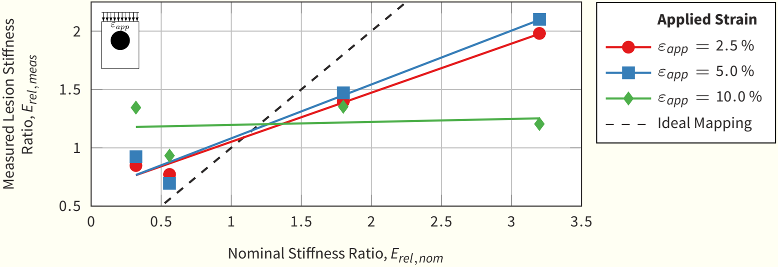
Sample Quasi-Static Results





Sample Quasi-Static Results





Quasi-Static USE Outcomes

- Small lesions undetectable
  - Larger $\rightarrow$ more accurate
- Not reliant on:
  - Depth
  - Interrogation frequency
- Apply $\lesssim 5\,\%$ strain
- Complicated geometry can affect results
- Manual palpation not reliable
  - ARFI imaging as an alternative
- Can detect DTI
- Not ideally sensitive

Acoustic Radiation Force Impulse Imaging

Introduction

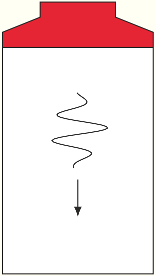
- QS USE has low detection sensitivity, unreliable
- ARFI imaging similar to QS USE
  - Transducer-generated force instead of manual
- $\uparrow$ repeatability, $\uparrow$ inter-operator reliability
- Absorbed energy generates force:

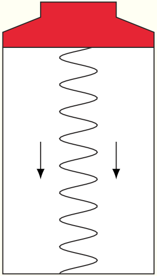
$$\left|\vec{F}\right| = \frac{2\alpha I}{c}$$

$\vec{F}$: ARFI force
α: Absorption coefficient
I: Intensity
c: Longitudinal wave speed

How ARFI Imaging Works

- Normal ultrasound is only a couple periods long ($\approx$ 2 ms)
- ARFI imaging uses continuous beams ($\approx$ 100 ms)

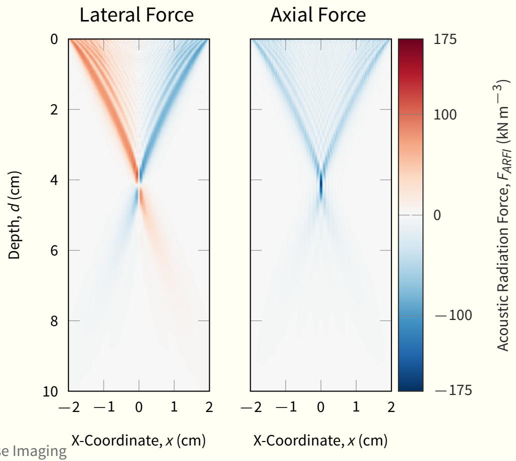




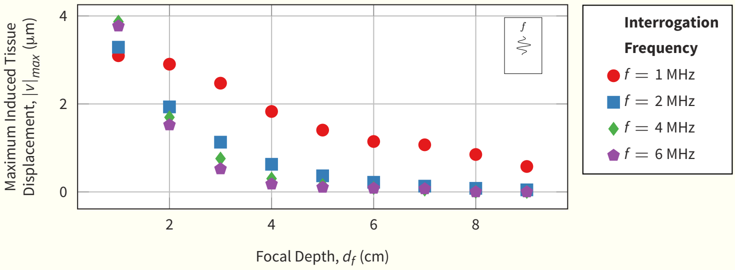
- Acoustic energy is absorbed by tissue and causes deformation

Simulating ARFI Loads

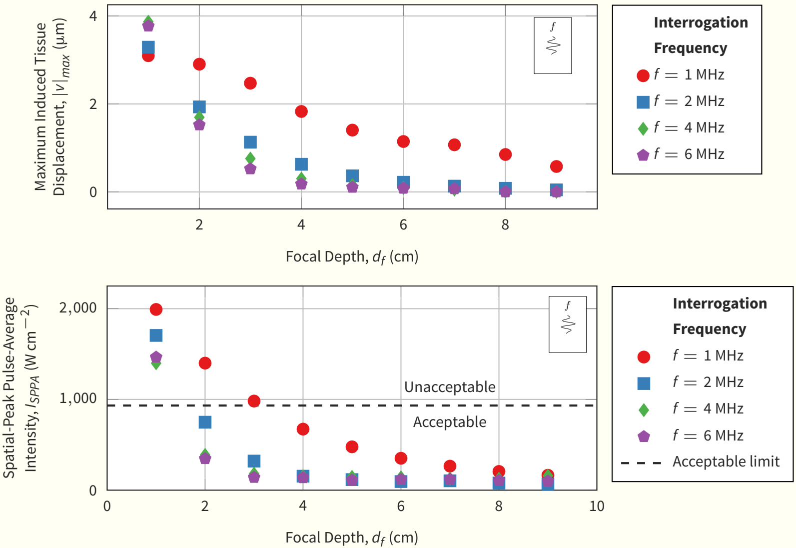
- Use k-space pseudo-spectral method to solve the wave equation
  - k-Wave MATLAB® toolbox



Sample ARFI Results



Sample ARFI Results



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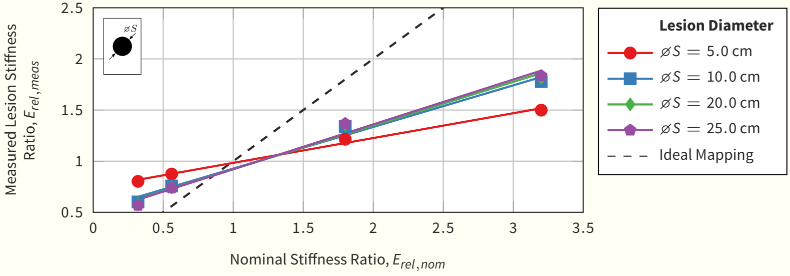

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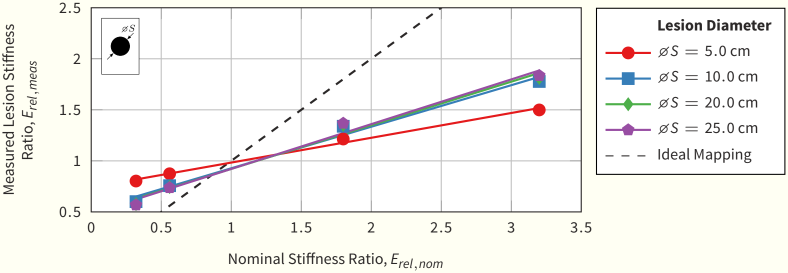
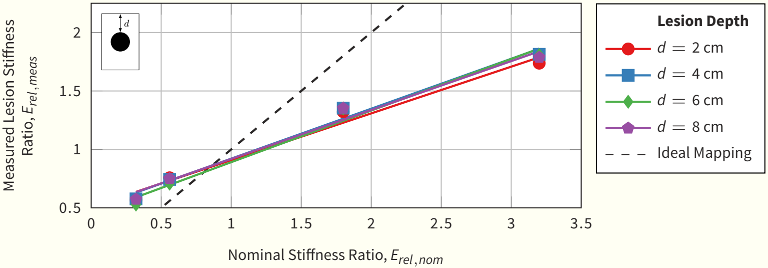




ARFI Imaging Outcomes

- ARFI sensitivity $\approx$ QS USE sensitivity
- ARFI not as dependent on lesion size as QS USE
- Not reliant on depth
- Complicated geometry can affect results
- Significant safety considerations
- ARFI more reliable than QS USE
- ARFI has limited penetration depth

Shear Wave Speed Quantification

Introduction

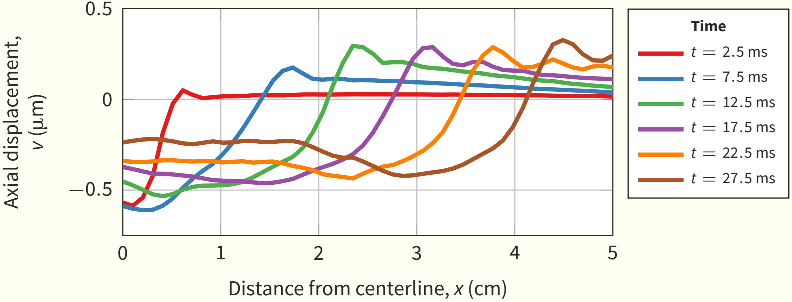
- QS USE and ARFI provide qualitative measures
- Shear wave speed quantification is quantitative
  - Absolute values
  - Track over time
- Uses ARFI pulses to generate shear wavess
  - Measure shear wave speed $\rightarrow$ calculate stiffness:

$$\mu = c_T^2 \rho$$

μ:	Shear modulus
c_T:	Shear wave speed
ρ:	Tissue density

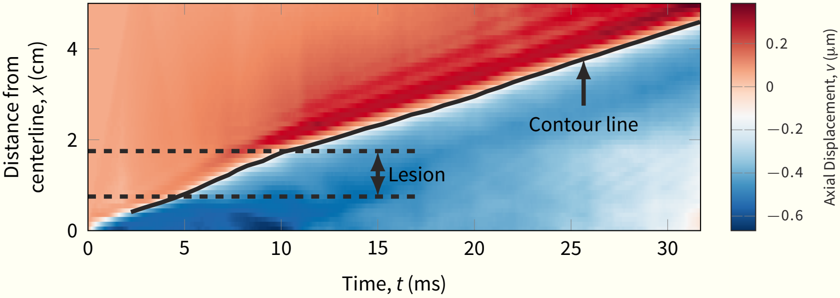
Measuring Shear Wave Speed

1. Induce ARFI at desired depth
   - Shear waves radiate outward, like “ripples in a pond”



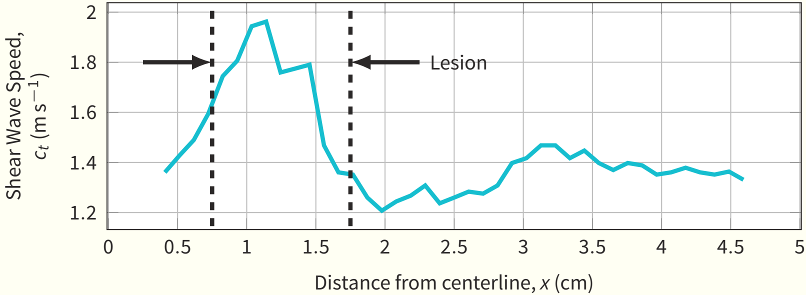
Measuring Shear Wave Speed

1. Induce ARFI at desired depth
   - Shear waves radiate outward, like “ripples in a pond”
2. Monitor deformation along a line extending from the focal point using B-mode ultrasound

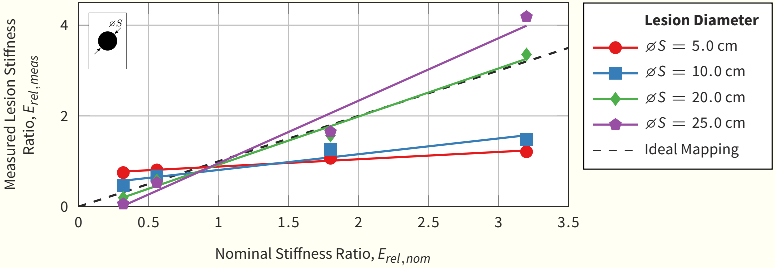


Measuring Shear Wave Speed

1. Induce ARFI at desired depth
   - Shear waves radiate outward, like “ripples in a pond”
2. Monitor deformation along a line extending from the focal point using B-mode ultrasound
   - Calculate speed of shear wave along this line



Sample Shear Results



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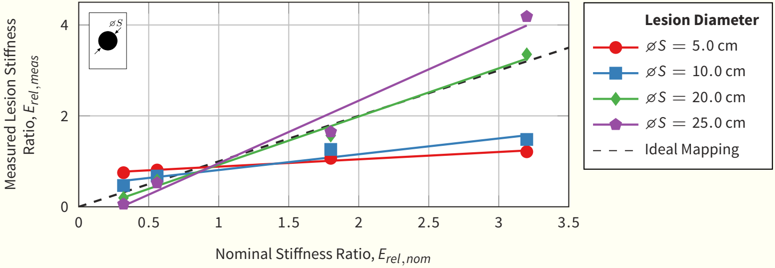
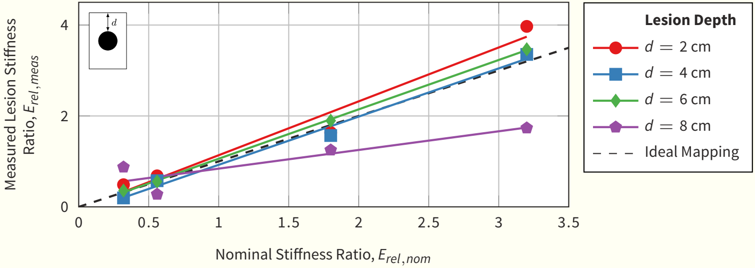
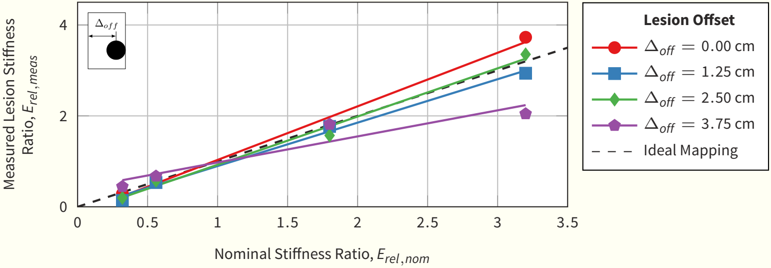




Sample Shear Results



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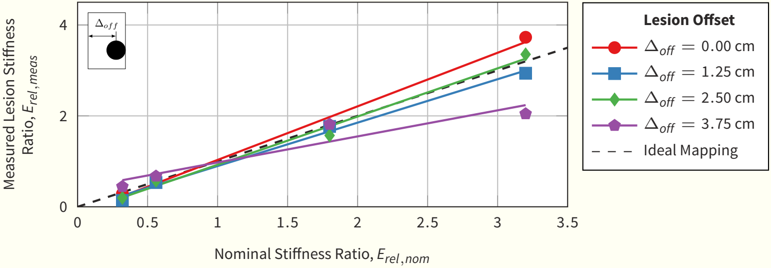
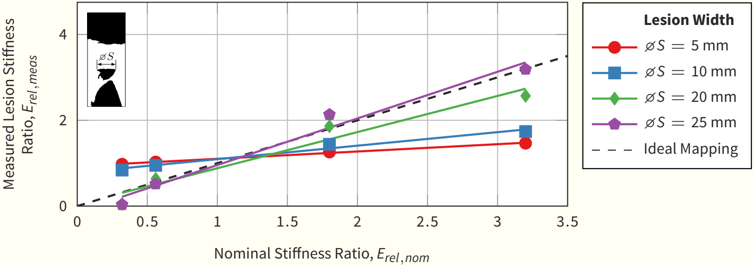


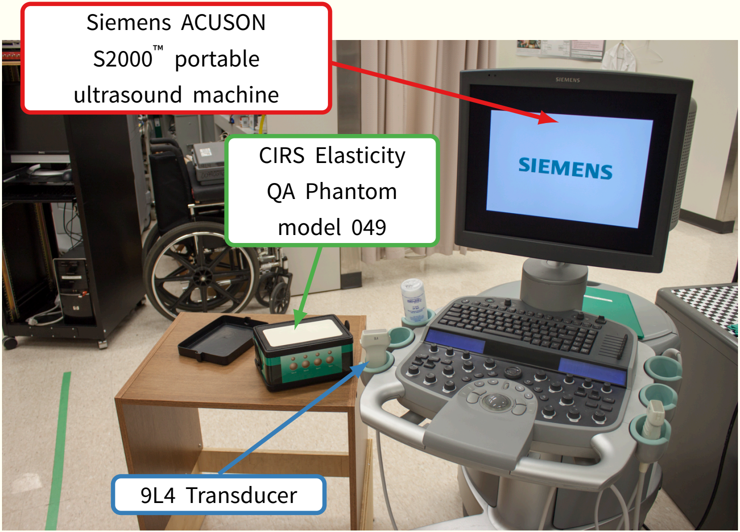


Shear Wave Speed Outcomes

- Similar reliability to ARFI
- Difficult to detect:
  - Small lesions
  - Deep lesions
- Localized measures only
  - QS USE and ARFI provide domain interrogation
- More sensitive than ARFI and QS USE
- Quantifiable
  - Can monitor injury over time

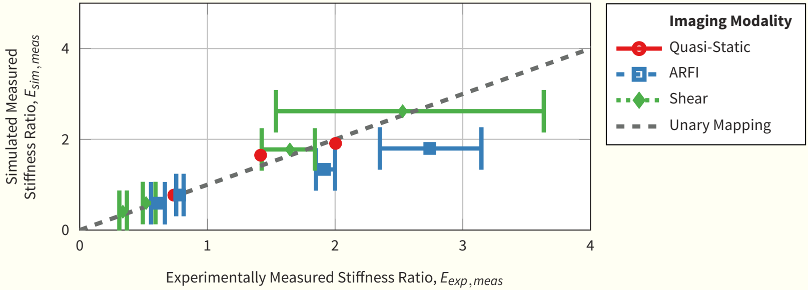
Experimental Validation & Method Comparisons

Experimental Setup

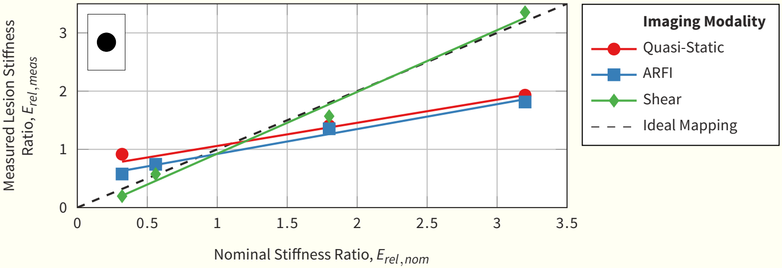


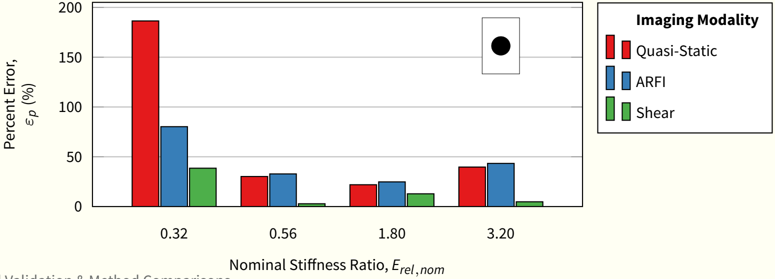
Experimental Validations

- Siemens ACUSON S2000™ ultrasound machine with a Siemens 9L4 transducer and a CIRS QA Phantom 049 gel phantom
- Compared parametrically-identical experimental results to simulation



Comparing Methods





Conclusions

Recommendations

- Shear wave speed quantification yields best results
  - Use when possible
- ARFI more reliable than QS USE
  - Lacks penetration depth
- Small lesions ($r \lesssim 0.5\,\mathrm{cm}$) difficult to detect
  - MRI'd lesions: $r \gtrsim 1.0\,\mathrm{cm}$
- Future work: animal and human studies
  - Toward eventual clinical implementation

Conclusions

- DTI are a major health concern
  - No early detection
- Ultrasound elastography can detect DTI
  - Within limits
  - Clinically feasible
- Numerically characterized 3 modalities
  - Quasi-Static Ultrasound Elastography
  - Acoustic Radiation Force Impulse Imaging
  - Shear Wave Speed Quantification ←

Thank You

- Supervisors:
  - Dr. W. Moussa
  - Dr. M. Ferguson-Pell
- Lab-mates

Project
SMART
Sensory Motor Adaptive Rehabilitation Technology

Additional Slides

- References
- Derivation of ARFI
- Quasi-Static Parameters
- ARFI Parameters
- Shear Parameters
- Phantom Properties
- Quasi-Static Finite-Element Details
- Quasi-Static Mesh Dependency
- ARFI / Shear Finite-Element Details
- ARFI / Shear Mesh Dependency

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Derivation of Acoustic Force

$$\sigma_{ij,j} + \rho b_i = \rho f_i$$

$$\vec{F} = \nabla p_2 - \mu_{tissue} \nabla^2 \vec{v_2}$$

$$\vec{F} = \rho \langle \vec{v_1} \nabla \cdot \vec{v_1} + \vec{v_1} \nabla \vec{v_1} \rangle$$

$$\vec{F} = 2\rho \langle \vec{v}\vec{v}_{,x} \rangle$$

$$\vec{v} = i\omega A e^{-\alpha x + i(\omega t - kx)} \hat{x}$$

$$\left|\vec{F}\right| = A^2 e^{-2\alpha x} \rho \alpha$$

$$\boxed{\left|\vec{F}\right| = \frac{2\alpha I}{c}}$$

$\langle\rangle$: Time-average
$\vec{F}$: Acoustic Force
$\vec{v}$: Particle velocity
ρ: Tissue density
α: Absorption coefficient
I: Acoustic intensity
c: Speed of sound

QS USE Parameters

QS USE Parametric Study Parameters

Parameter	Symbol	Values	Units
Lesion depth	d	3.5, 6.5, 8.5 and 10.0	cm
Lesion altitude	h	1.25, 2.50 and 3.75	cm
Lesion diameter	$\varnothing S$	0.5, 1.0, 2.0 and 2.5	cm
Lesion stiffness ratio	E_{rel}	0.32, 0.56, 1.80 and 3.20	–
Ultrasound frequency	f	2, 4 and 8	MHz
Transducer-applied strain	ε_{app}	2.5, 5.0 and 10.0	%
Co-located separation distance	δ_{sep}	1.25, 1.50, 1.75 and 2.00	cm
Blurred lesion blur radius	b_r	1.0, 2.5, 5.0 and 7.5	mm
Clustered lesion density	b_ρ	10, 20, 30 and 40	cm^{-2}
Clustered lesion radius	r_{bl}	0.5, 1.0 and 1.5	mm
Visible human lesion width	$\varnothing L$	0.5, 1.0, 2.0 and 2.5	cm
Visible human lesion depth	d	6.25, 6.75 and 7.25	cm

ARFI Parameters

K-Space Psuedospectral Model Parameters

Property	Symbol	Value	Units
Nonlinearity parameter	B/A	8	–
Power law prefactor	α_0	0.7	$\mathrm{Np}\,(\mathrm{rad/s})^{-y}\,\mathrm{m}^{-1}$
Power law exponent	y	0.95	–
Density	ρ_0	1060	$\mathrm{kg\,m^{-3}}$

ARFI Parameters

Simulated Material Parameters

Property	Symbol	Value	Units
Bulk Modulus	K	515.7	kPa
Shear Modulus	μ_{tissue}	1.0	kPa
Density	ρ	1060	$\mathrm{kg\,m^{-3}}$

Generalized Maxwell Viscoelastic Material Model Parameters

Branch	Shear Modulus (Pa)	Relaxation Time (s)
1	791.0	2
2	66.5	40
3	0.6	80

ARFI Parameters

ARFI Parametric Study Parameters

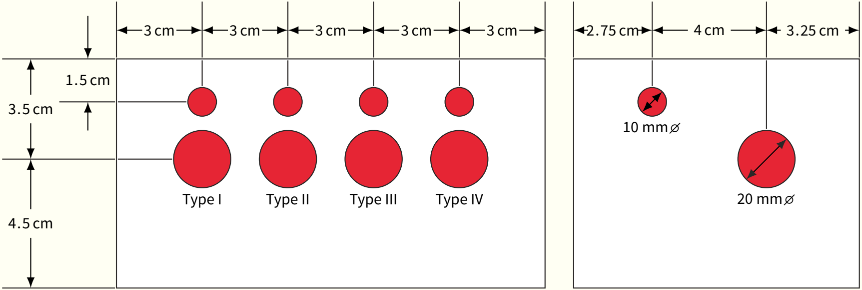
Parameter	Symbol	Values	Units
ARFI interrogation frequency	f	1, 2, 4 and 6	MHz
Transducer width	w_{trans}	4, 8 and 10	cm
ARFI pulse cycles	n_c	3, 100, 300, 500 and 700	–
ARFI source pressure	P_{source}	4, 5, 6, 7 and 8	MPa
Lesion depth	d	1, 2, 3, 4, 5, 6, 7, 8 and 9	cm
Lesion diameter	$\varnothing S$	0.5, 1.0, 2.0 and 2.5	cm
Lesion stiffness ratio	E_{rel}	0.32, 0.56, 1.80 and 3.20	–
Blurred lesion blur radius	b_r	1.0, 2.5, 5.0 and 7.5	mm
Clustered lesion density	b_ρ	10, 20, 30 and 40	cm^{-2}
Clustered lesion radius	r_{bl}	0.5, 1.0 and 1.5	mm
Visible human lesion width	$\varnothing L$	0.5, 1.0, 2.0 and 2.5	cm

Shear Parameters

Shear Parametric Study Parameters

Parameter	Symbol	Values	Units
Lesion depth	d	1, 2, 3, 4, 5, 6, 7, 8 and 9	cm
Lesion diameter	$\varnothing S$	0.5, 1.0, 2.0 and 2.5	cm
Lesion offset	d_{off}	0.00, 1.25, 2.50 and 3.75	cm
Lesion stiffness ratio	E_{rel}	0.32, 0.56, 1.80 and 3.20	
Blurred lesion blur radius	b_r	1.0, 2.5, 5.0 and 7.5	mm
Clustered lesion density	b_ρ	10, 20, 30 and 40	cm^{-2}
Clustered lesion radius	r_{bl}	0.5, 1.0 and 1.5	mm
Visible human lesion width	$\varnothing L$	0.5, 1.0, 2.0 and 2.5	cm

CIRS Phantom Properties

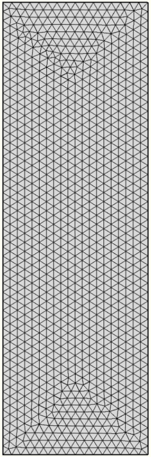


CIRS Phantom Material Properties and Geometry

Property	Symbol	Value	Units
Nominal basal elastic modulus	E_{tissue}	25	kPa
Lesion elastic modulii	E_{tissue}		
Type I		4	kPa
Type II		14	kPa
Type III		45	kPa
Type IV		80	kPa
Speed of sound	c_0	1540	$\mathrm{m\,s^{-1}}$
Acoustic attenuation	α	0.5	$\mathrm{dB\,cm^{-1}\,MHz^{-1}}$

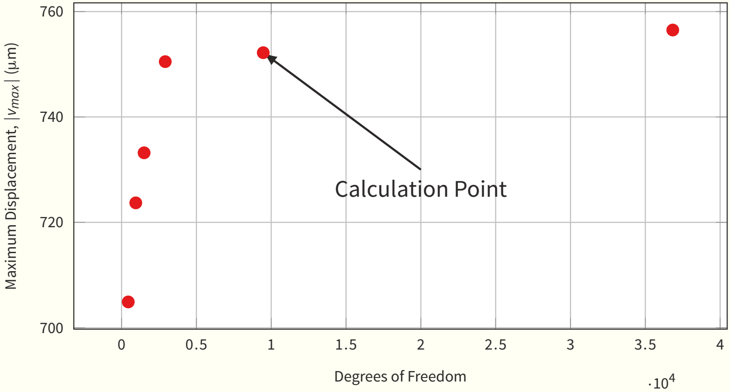
Quasi-Static FEA Details

- Quadratic Lagrangian triangular elements
- 9,468 degrees of freedom
- Solved using COMSOL Multiphysics



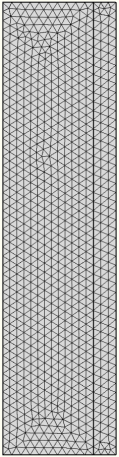
The Quasi-Static Mesh

Quasi-Static Mesh Dependency



ARFI / Shear FEA Details

- Quadratic Lagrangian triangular elements
- 51,096 degrees of freedom
- 25 ns constant time stepping
- Simulation stopped after focal displacement reached 1 % of maximal value
- Solved using COMSOL Multiphysics



The ARFI / Shear Mesh

ARFI / Shear Mesh Dependency