

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

by

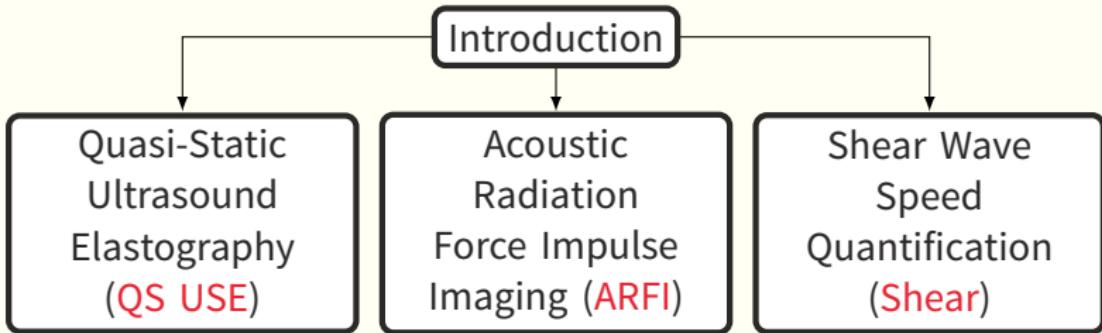
Kenton David Hamaluik

Supervisors: Dr. W. Moussa and Dr. M. Ferguson-Pell
Examiner: Dr. R. Burrell
Chair: Dr. M. Zuo

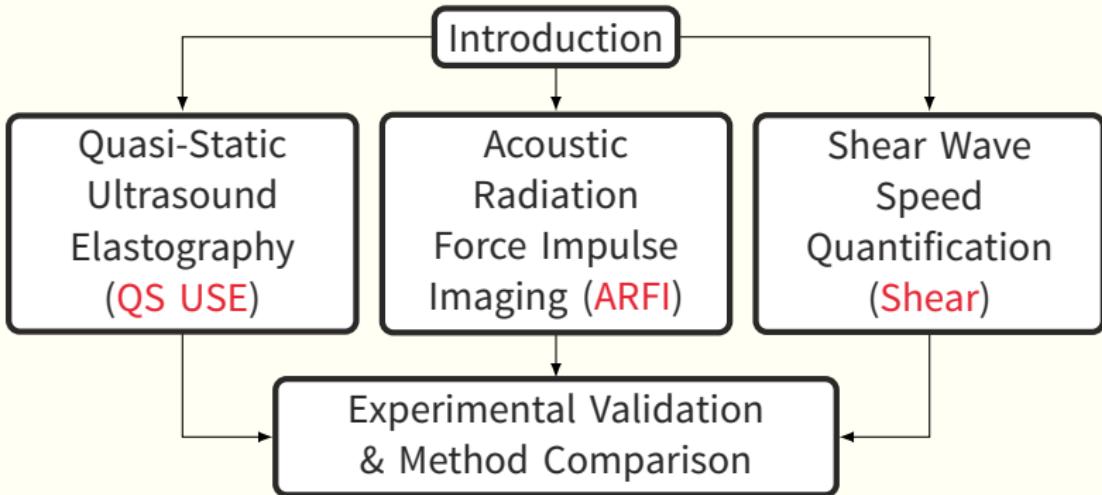
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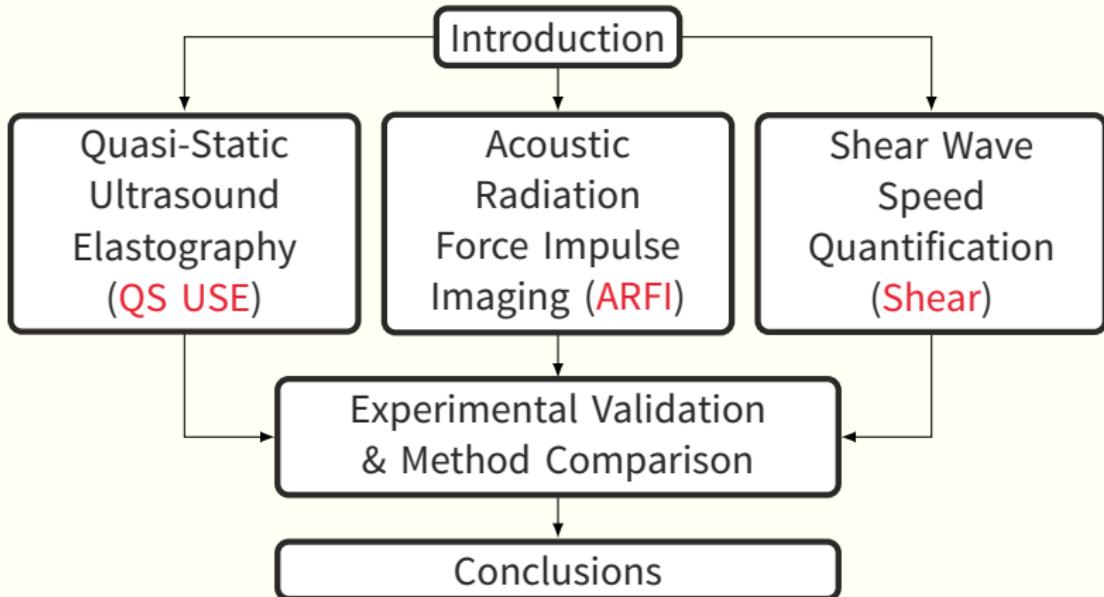
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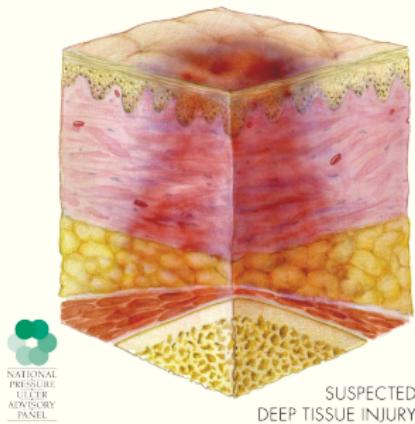
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Introduction

Deep Tissue Injuries (DTI)

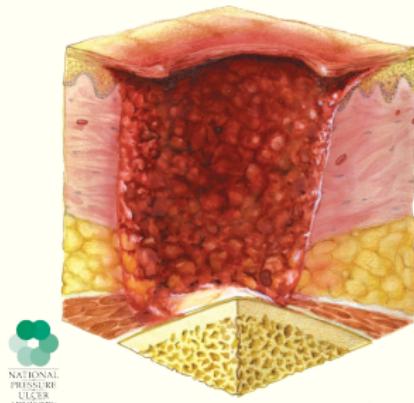
- ✚ Secondary injuries (limited mobility)
- ✚ Caused by pressure & deformation
- ✚ Stage III – IV pressure ulcers
- ✚ No clinical detection
- ✚ Severe health burdens
[Russo et al., 2008]
 - 500,000 – 2,000,000 annually (USA)
 - Increased mortality, length of stay



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Deep Tissue Injuries (DTI)

- ✚ Secondary injuries (limited mobility)
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STAGE 4

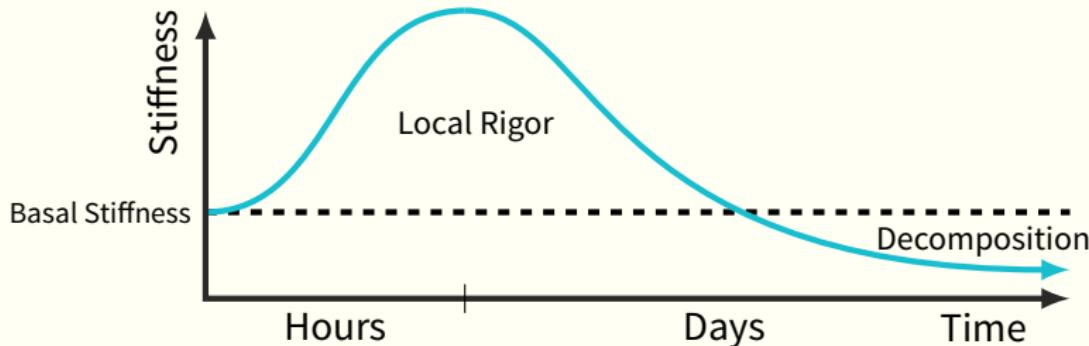
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Current DTI Detection

- 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

- Ultrasound elastography is a technology which measures tissue **stiffness**



Adapted from [Gefen, 2009], used with permission

- Mechanical **stiffness changes** with injury formation and progression

Literature Review

- The purpose of this research was understand ultrasound elastography for DTI detection

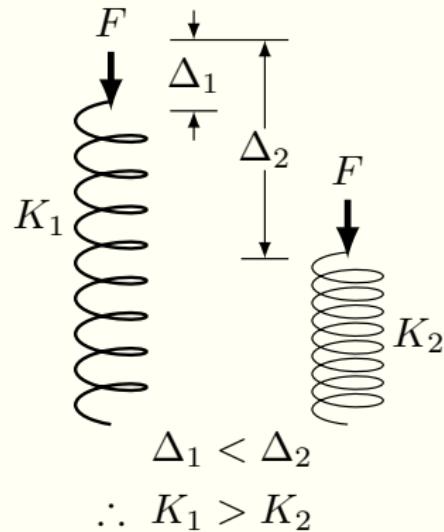
	DTI	B-Mode US	QS USE	ARFI	Shear	FE Models	Gel Phantoms	Animals	Humans	Characterized	Clinical
PU Risk scales	X	—	—	—	—	X	X	X	✓	✓	✓
MRI	✓	—	—	—	—	✓	✓	✓	✓	X	X
Aoi, 2009	✓	✓	X	X	X	X	X	X	✓	X	?
Makhsous, 2010	✓	—	—	—	—	—	—	✓	?	X	✓
Deprez, 2011	✓	X	✓	X	X	✓	✓	✓	?	X	✓
→ This work	✓	X	✓	✓	✓	✓	✓	?	?	✓	✓

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*, vol. 33, no. 7, pp. 1410–1421, July 2014.

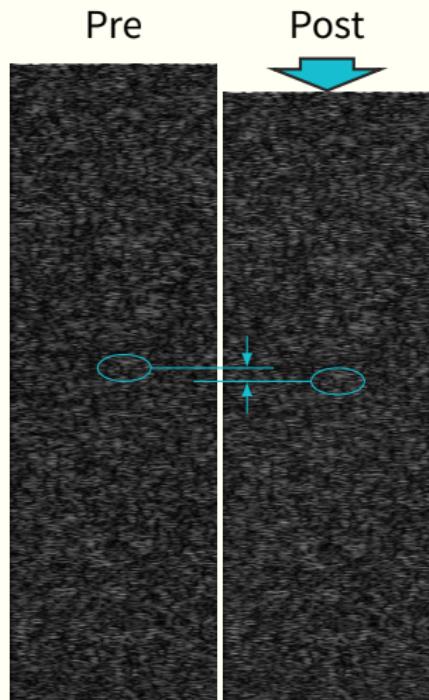
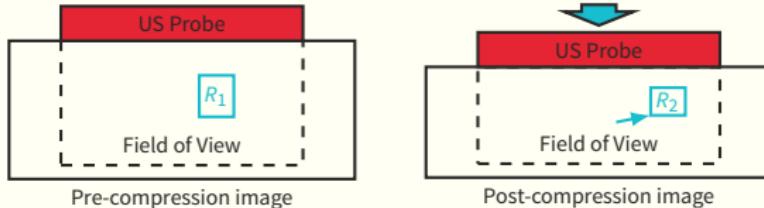
Theory of Operation

- Manual deformation
- Magnitude of deformation related to stiffness
 - ↓ deformation
≈ ↑ stiffness
≈ ↑ damage magnitude

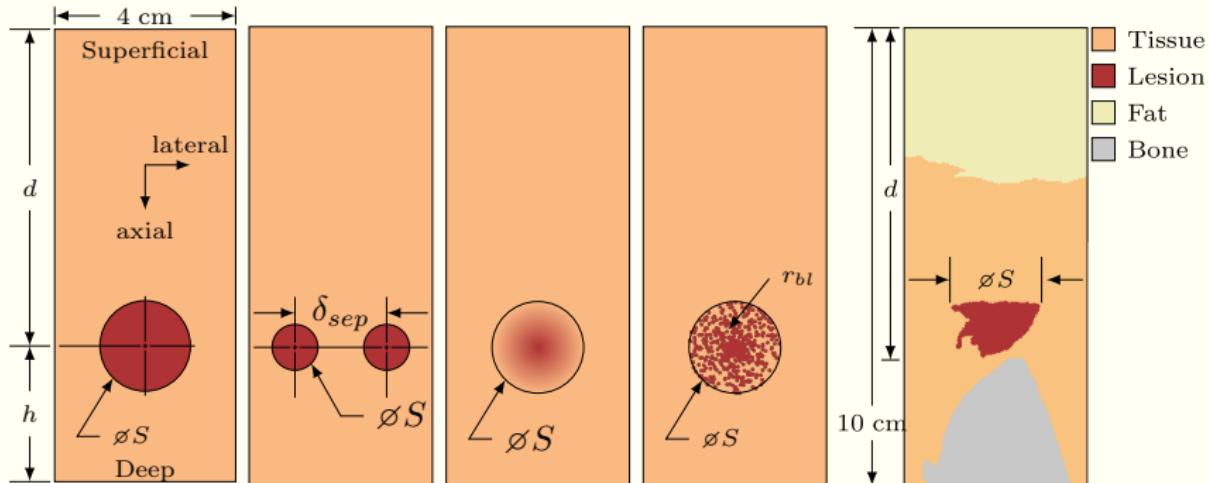


Theory of Operation

- Manual deformation
- Magnitude of deformation related to stiffness
 - ↓ deformation
 - ≈ ↑ stiffness
 - ≈ ↑ damage magnitude
- Track scattering centres
 - Assumptions of motion [Brusseau et al., 2008]



Investigated Models



d : lesion depth

h : lesion altitude

ϕS : lesion size

f : interrogation frequency

ε_{app} : applied strain

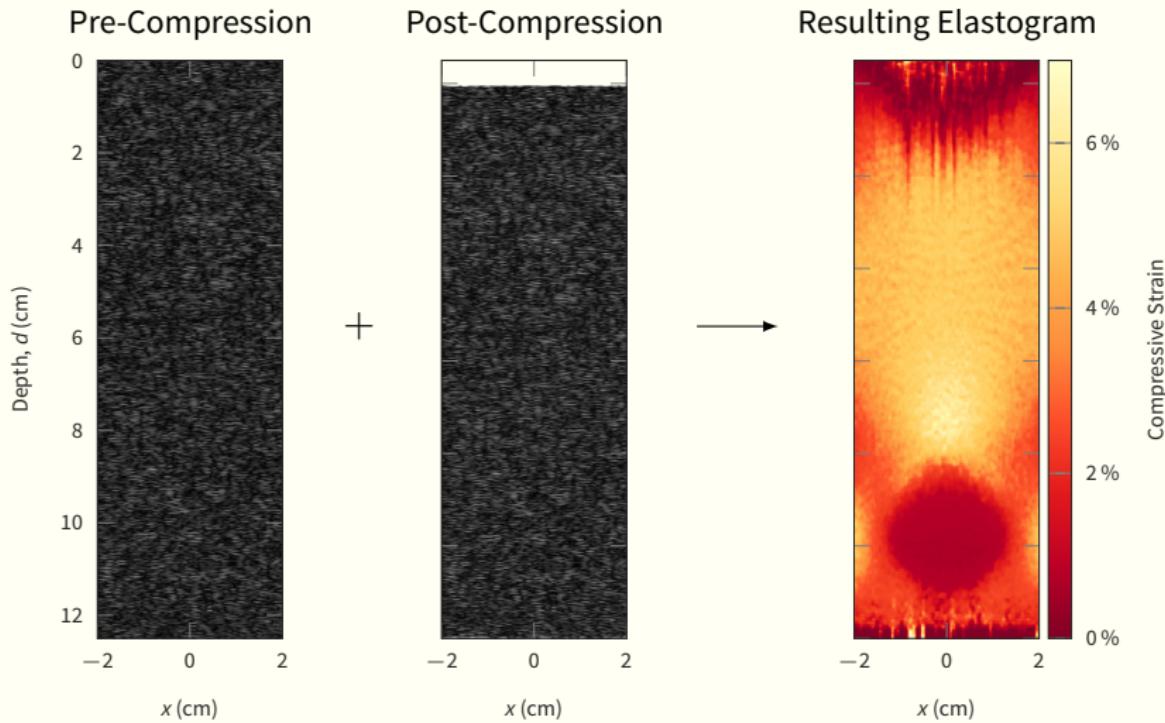
δ_{sep} : separation distance

b_r : blur radius

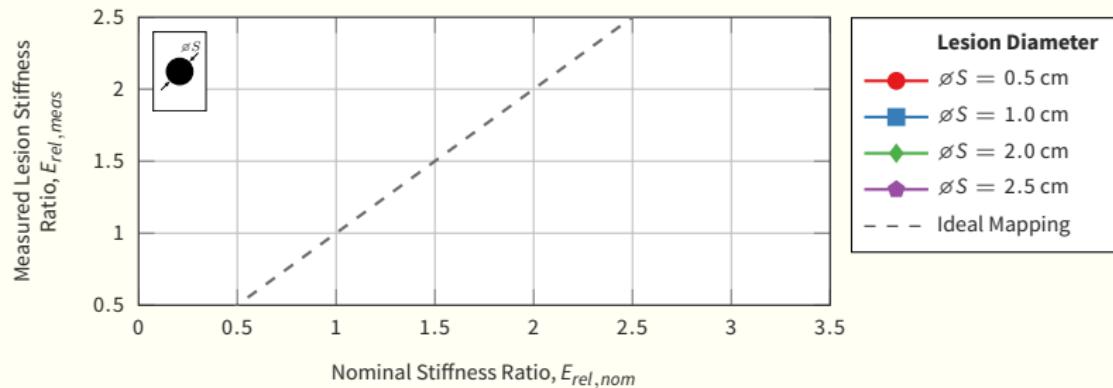
b_ρ : cluster density

r_{bl} : cluster radii

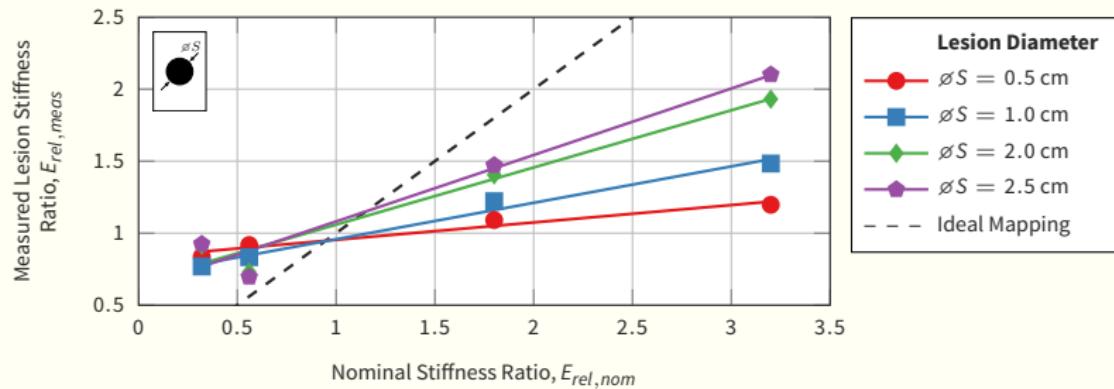
Sample Simulated Elastogram



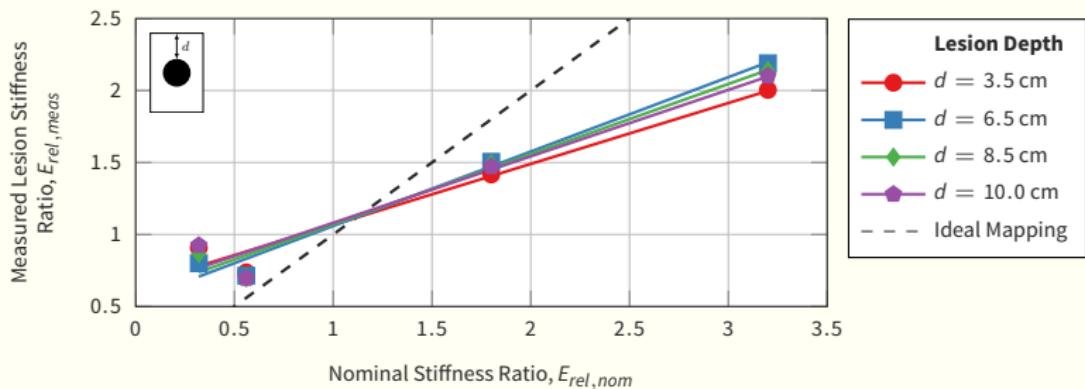
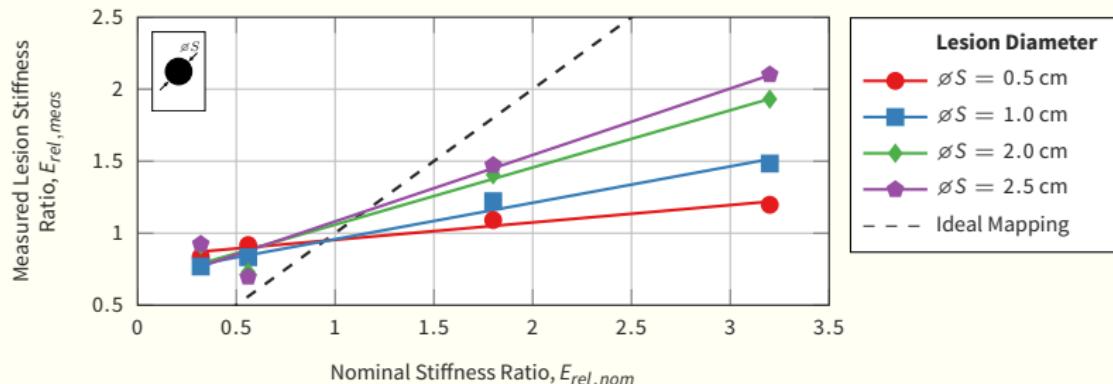
Sample Quasi-Static Results



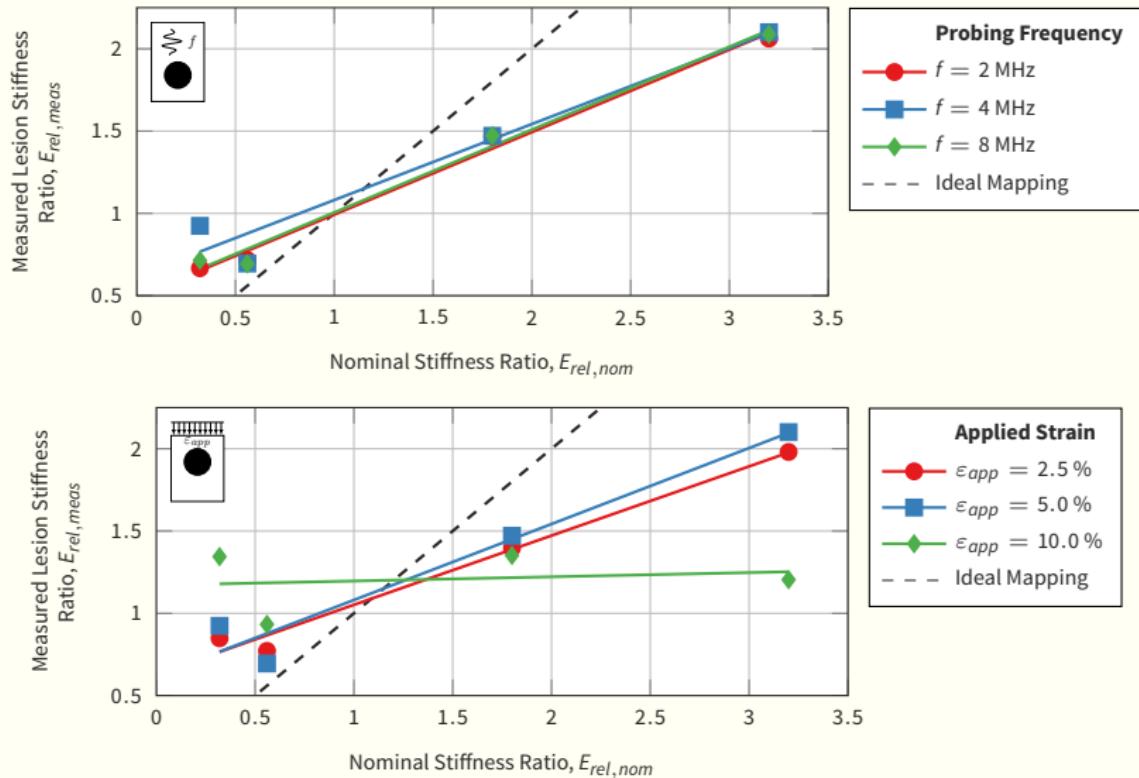
Sample Quasi-Static Results



Sample Quasi-Static Results



Sample Quasi-Static Results



Quasi-Static USE Outcomes

- ❖ Small lesions undetectable
 - Larger → 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
- ❖ Not ideally sensitive
- ❖ Can detect DTI

Acoustic Radiation Force Impulse Imaging

Introduction

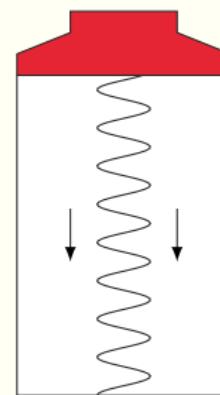
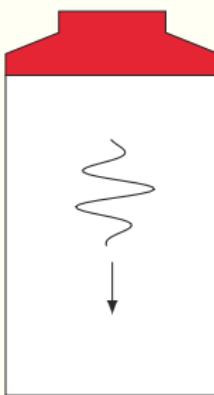
- QS USE has low detection sensitivity, unreliable
- Acoustic Radiation Force Impulse (**ARFI**) imaging similar to QS USE
 - Transducer-generated force instead of manual
- ↑ repeatability, ↑ inter-operator reliability
- Absorbed energy generates force:

$$|\vec{F}| = \frac{2\alpha l}{c}$$

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

How ARFI Imaging Works

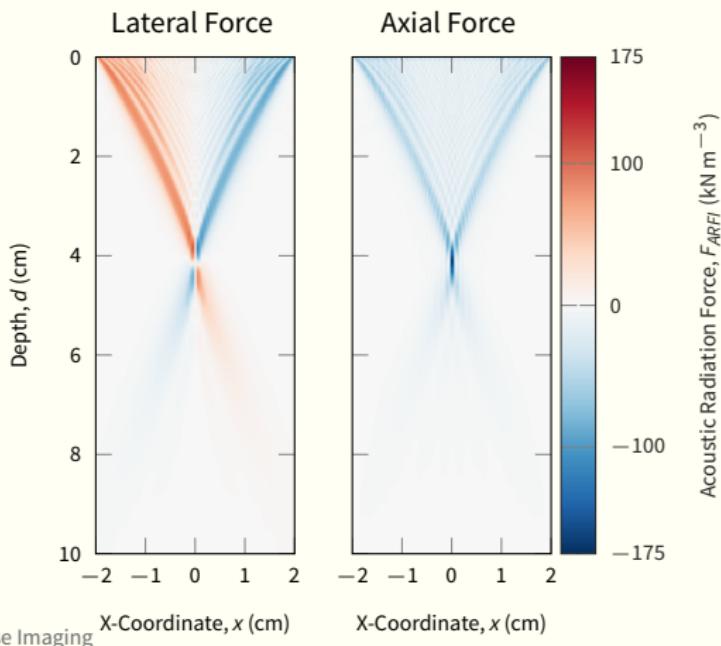
- Normal ultrasound is only a couple periods long (≈ 2 ms)
- ARFI imaging uses continuous beams (≈ 100 ms)



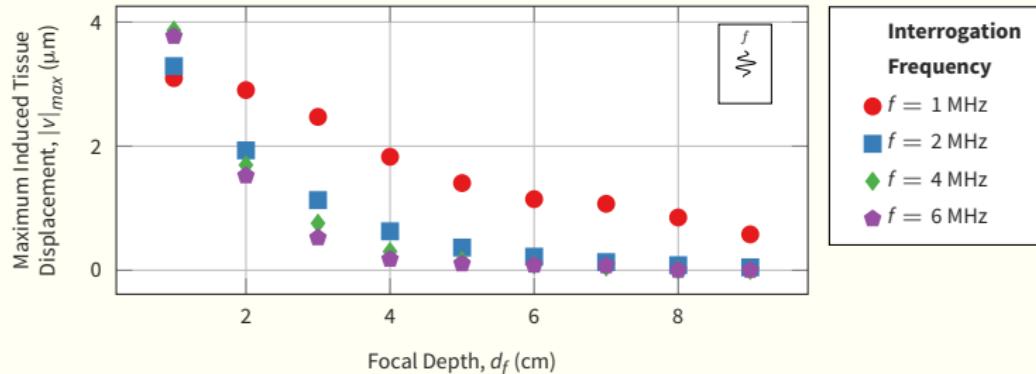
- Acoustic energy is absorbed by tissue and causes deformation

Simulating ARFI Loads

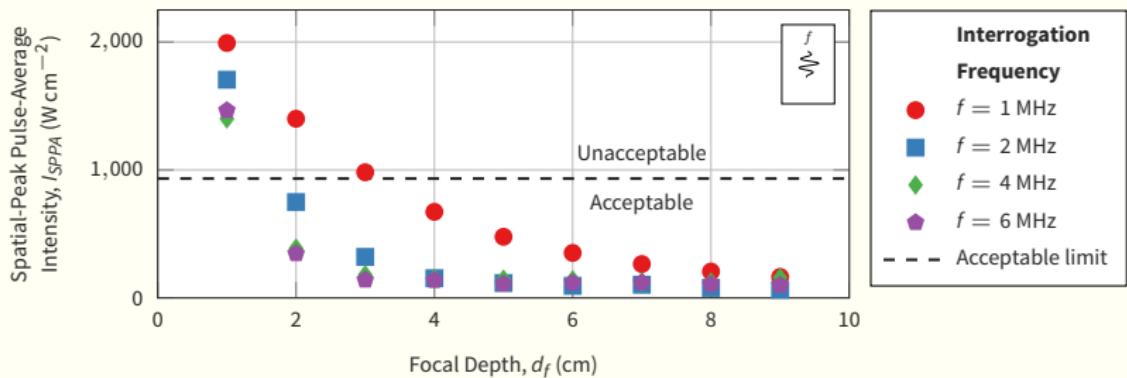
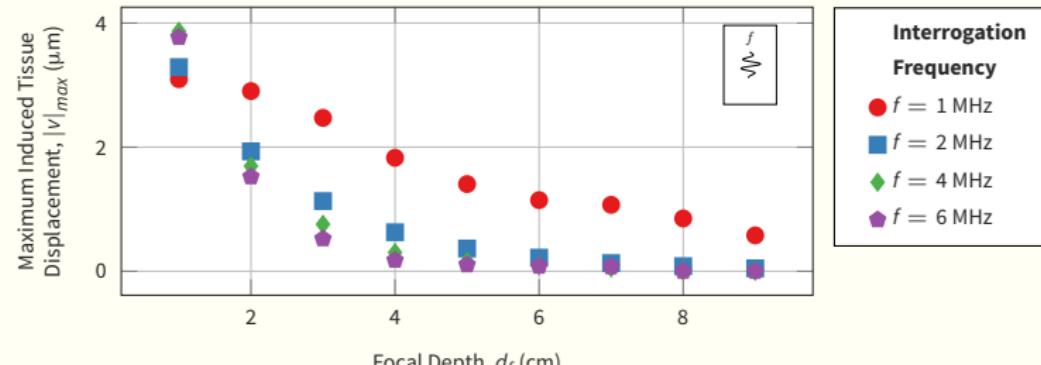
- Use k-space pseudo-spectral method to solve the wave equation
 - k-Wave MATLAB[®] toolbox



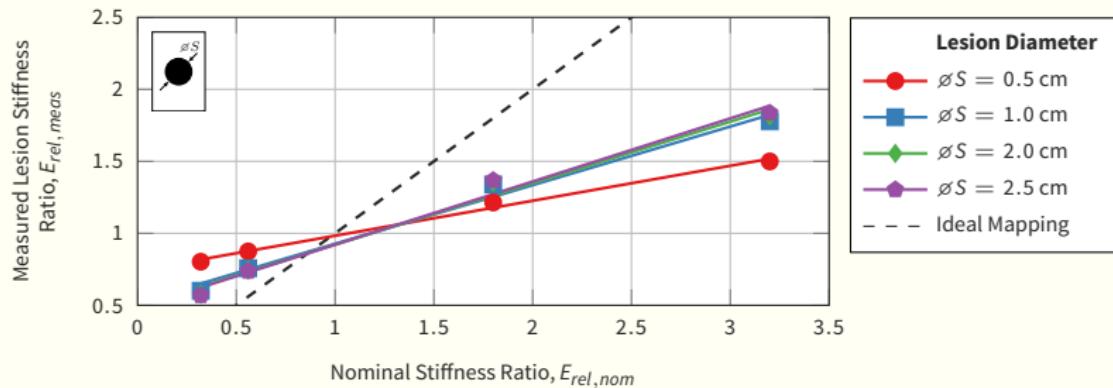
Sample ARFI Results



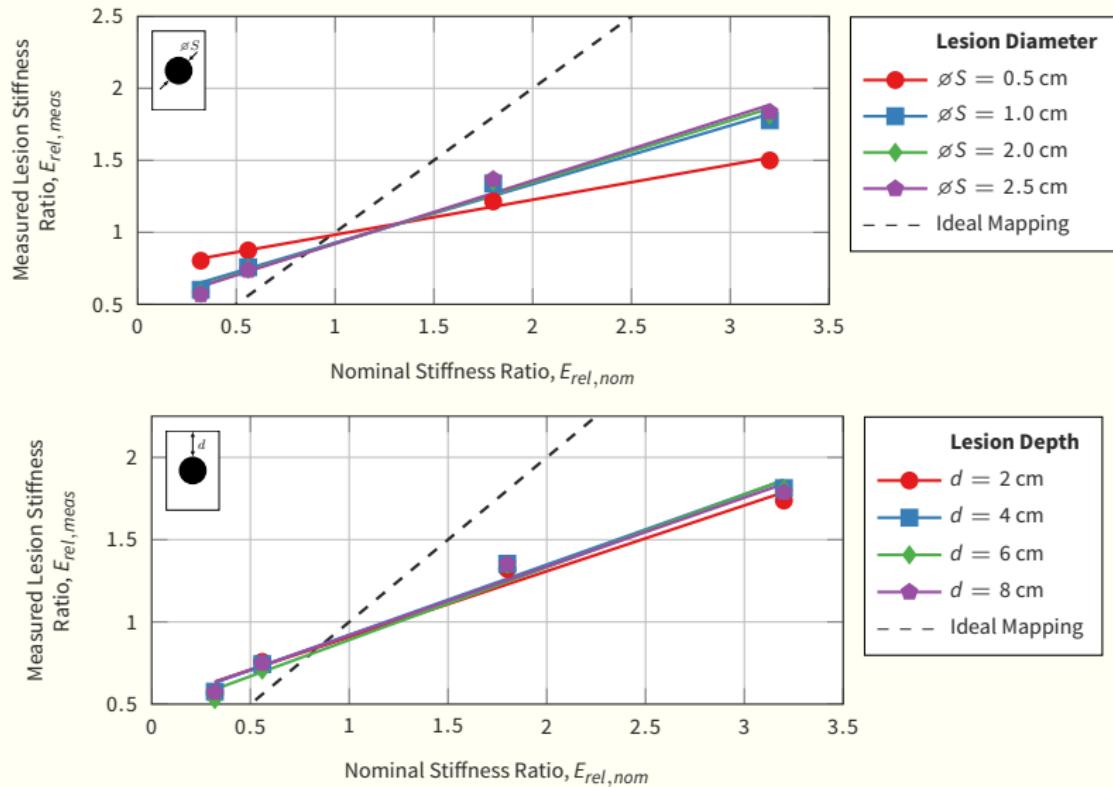
Sample ARFI Results



Sample ARFI Results



Sample ARFI Results



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

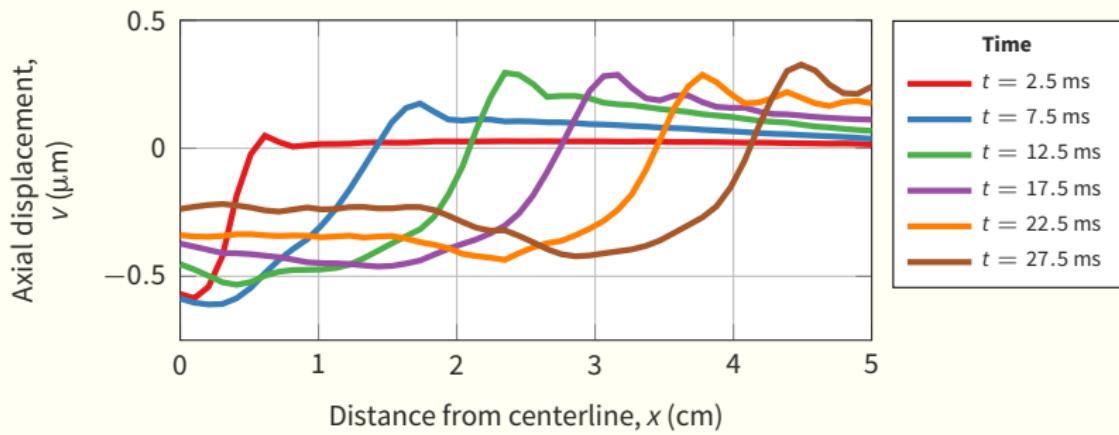
- QS USE and ARFI provide **qualitative** measures
- Shear wave speed quantification is **quantitative**
 - ▶ Absolute values
 - ▶ Track over time
- Uses ARFI pulses to generate shear waves
 - ▶ Measure shear wave speed → calculate stiffness:

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

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

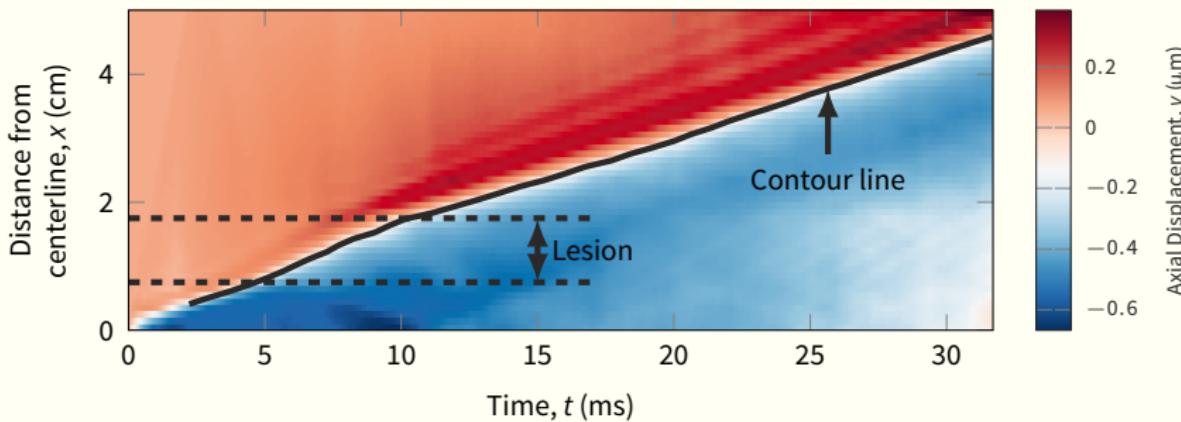
Measuring Shear Wave Speed

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



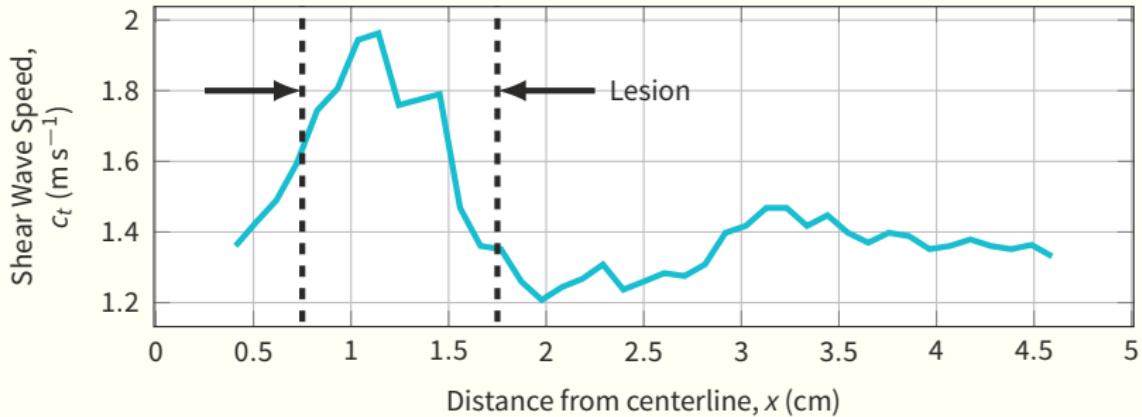
Measuring Shear Wave Speed

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

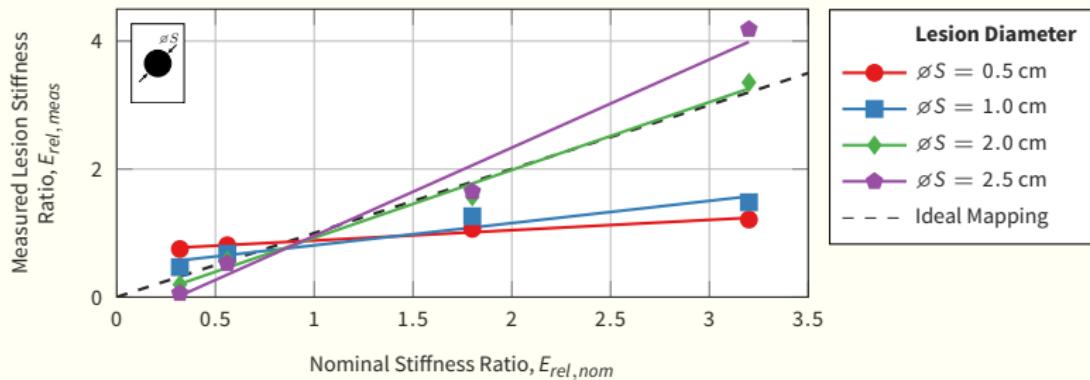


Measuring Shear Wave Speed

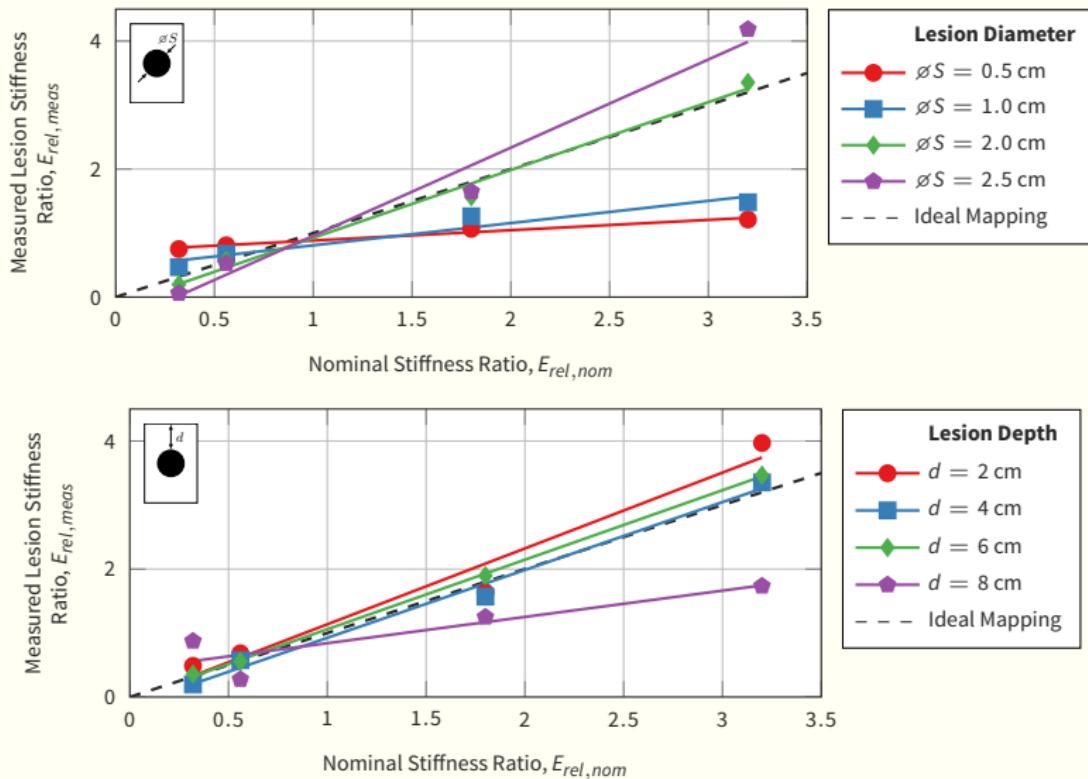
1. Induce ARFI at desired depth
 - ❖ Shear waves radiate outward, like “ripples in a pond”
2. Monitor deformation along a line extending from the focal point using B-mode ultrasound
 - ❖ Calculate speed of shear wave along this line



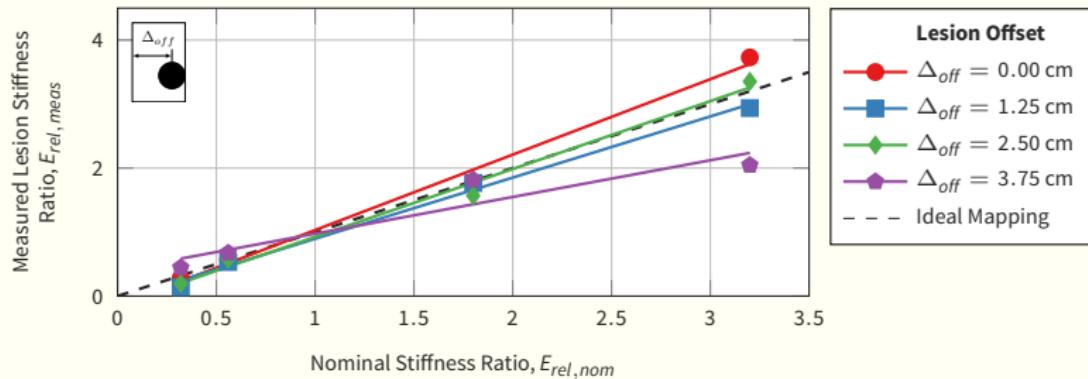
Sample Shear Results



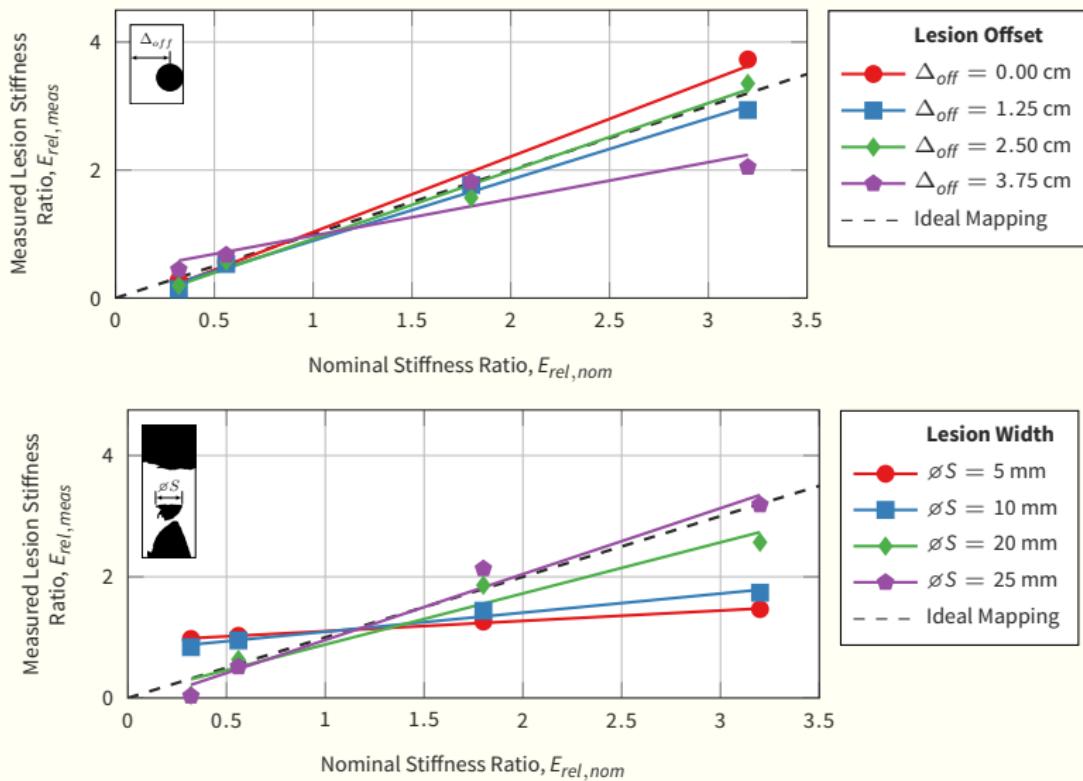
Sample Shear Results



Sample Shear Results



Sample Shear Results

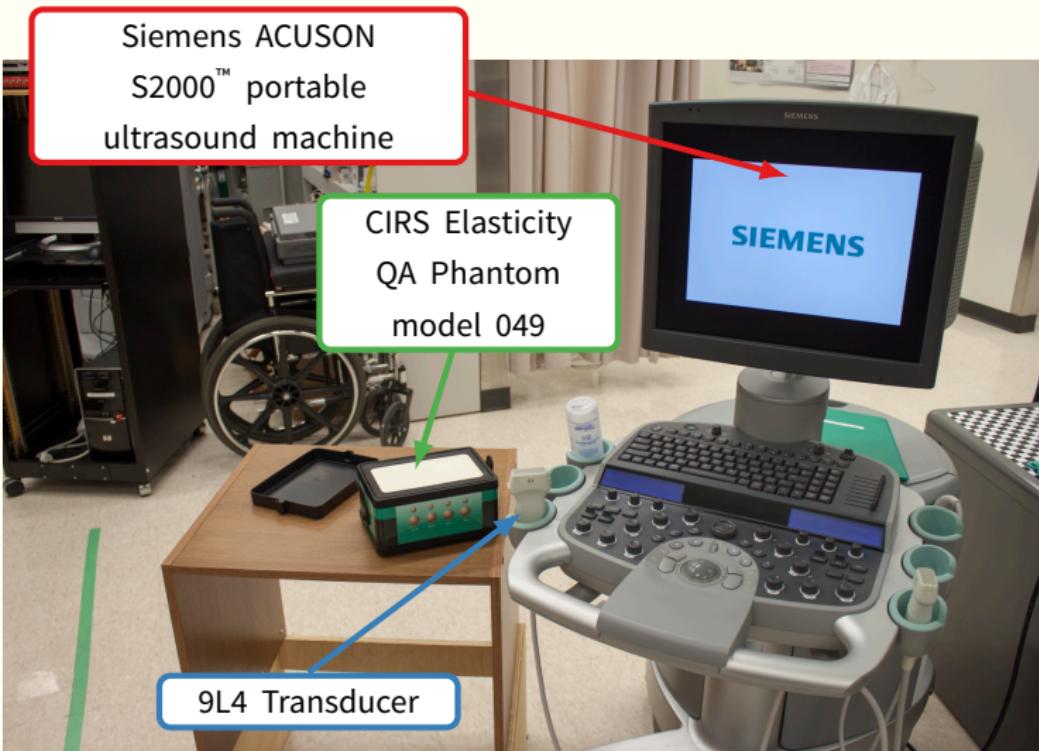


Shear Wave Speed Outcomes

- ❖ 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

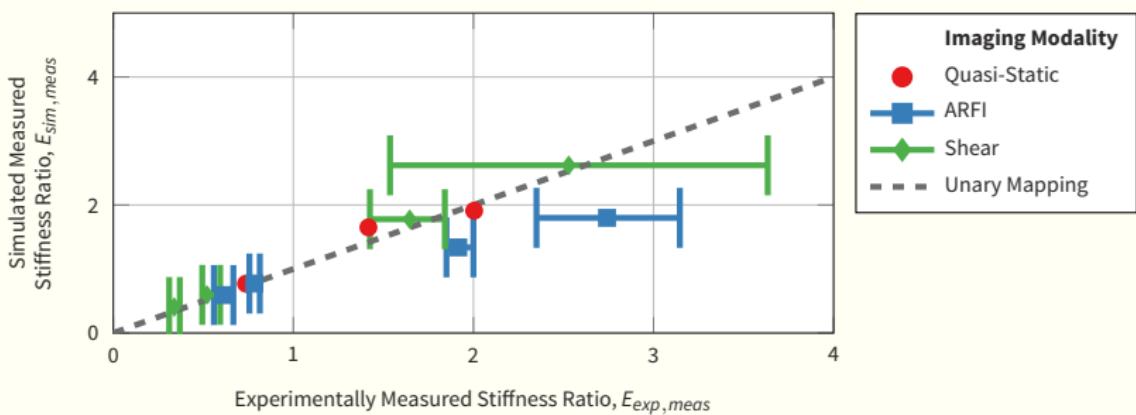
Experimental Validation & Method Comparisons

Experimental Setup

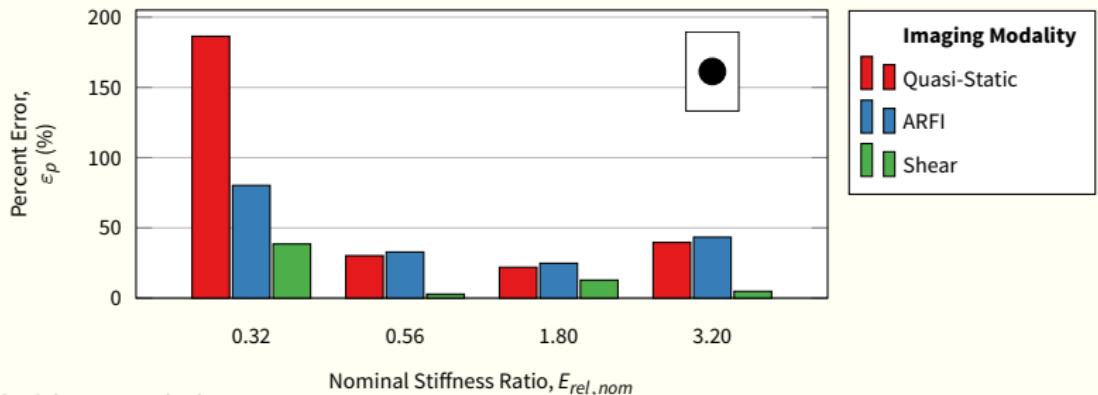
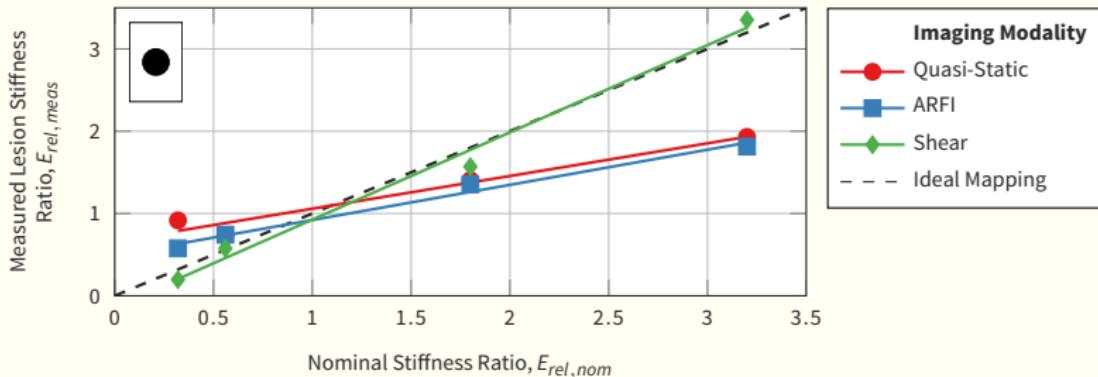


Experimental Validations

- 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

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

Recommendations

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

Thank You

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



Additional Slides

- ✚ Additional Figures
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- ✚ Derivation of ARFI
- ✚ K-Space Equations
- ✚ 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

References

- [Aoi et al., 2009] Aoi, N., Yoshimura, K., Kadono, T., Nakagami, G., Iizuka, S., Higashino, T., Araki, J., Koshima, I., and Sanada, H. (2009). **Ultrasound assessment of deep tissue injury in pressure ulcers: possible prediction of pressure ulcer progression.** *Plastic and reconstructive surgery*, 124(2):540–550.
- [Brusseau et al., 2008] Brusseau, E., Kybic, J., Deprez, J.-F. F., and Basset, O. (2008). **2-D locally regularized tissue strain estimation from radio-frequency ultrasound images: theoretical developments and results on experimental data.** *IEEE transactions on medical imaging*, 27(2):145–160.
- [Deprez et al., 2011] Deprez, J.-F. F., Brusseau, E., Fromageau, J., Cloutier, G., and Basset, O. (2011). **On the potential of ultrasound elastography for pressure ulcer early detection.** *Medical physics*, 38(4):1943–1950.
- [Gefen, 2009] Gefen, A. (2009). **Deep tissue injury from a bioengineering point of view.** *Ostomy/wound management*, 55(4):26–36.
- [Makhsous et al., 2010] Makhsous, M., Lin, F., Pandya, A., Pandya, M. S., and Chadwick, C. C. (2010). **Elevation in the serum and urine concentration of injury-related molecules after the formation of deep tissue injury in a rat spinal cord injury pressure ulcer model.** *PM & R : the journal of injury, function, and rehabilitation*, 2(11):1063–1065.
- [Russo et al., 2008] Russo, C., Steiner, C., and Spector, W. (2008). **Hospitalizations related to pressure ulcers among adults 18 years and older, 2006: Statistical brief no. 64.** *Agency for Health Care Policy and Research (US)*.

Derivation of Acoustic Force

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

$$\vec{F} = \nabla p_2 - \mu_{tissue} \nabla^2 \vec{v}_2$$

$$\vec{F} = \rho (\vec{v}_1 \nabla \cdot \vec{v}_1 + \vec{v}_1 \nabla \cdot \vec{v}_1)$$

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

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

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

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

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

K-Space Equations

$$\nabla^2 P - \frac{1}{c_0^2} \frac{\partial^2 P}{\partial t^2} = 0$$

Momentum conservation, mass conservation, and pressure-density relation in a homogeneous lossless medium:

$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0} \nabla P$$

$$\frac{\partial \rho}{\partial t} = -\rho_0 \nabla \cdot \vec{v}$$

$$P = c_0^2 \rho$$

Momentum conservation, mass conservation, and pressure-density relation in a non-linear heterogeneous lossy medium:

$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0} \nabla P$$

$$\frac{\partial \rho}{\partial t} = -(2\rho + \rho_0) \nabla \cdot \vec{v} - \vec{v} \cdot \nabla \rho_0$$

$$P = c_0^2 \left(\rho + \vec{u} \cdot \nabla \rho_0 + \frac{B}{2A} \frac{\rho^2}{\rho_0} - \mathbf{L} \rho \right)$$

$$\mathbf{L} = \tau (-\nabla^2)^{\frac{\gamma}{2}-1} + \eta (-\nabla^2)^{\frac{\gamma+1}{2}-1}$$

$$\tau = -2\alpha_0 c_0^{\gamma-1} \frac{\partial}{\partial t}, \quad \eta = 2\alpha_0 c_0^\gamma \tan\left(\frac{\pi\gamma}{2}\right)$$

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	ϕS	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_p	10, 20, 30 and 40	cm^{-2}
Clustered lesion radius	r_{bl}	0.5, 1.0 and 1.5	mm
Visible human lesion width	ϕL	0.5, 1.0, 2.0 and 2.5	cm
Visible human lesion depth	d	6.25, 6.75 and 7.25	cm

Quasi-Static Default Parameters

Property	Value	Units
Domain Width	4	cm
Domain Depth	12.5	cm
B-Mode Sampling Frequency	50	MHz
B-Mode Probing Frequency	4	MHz
Wave Speed	1540	m s^{-1}
Basal Stiffness	25	kPa
Tissue Density	1060	kg m^{-3}
Applied Strain	5	%

ARFI Parameters

K-Space Psuedospectral Model Parameters

Property	Symbol	Value	Units
Nonlinearity parameter	B/A	8	-
Power law prefactor	α_0	0.7	$Np \text{ (rad/s)}^{-y} \text{ m}^{-1}$
Power law exponent	y	0.95	-
Density	ρ_0	1060	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	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	ϕS	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_p	10, 20, 30 and 40	cm^{-2}
Clustered lesion radius	r_{bl}	0.5, 1.0 and 1.5	mm
Visible human lesion width	ϕL	0.5, 1.0, 2.0 and 2.5	cm

ARFI / Shear Default Parameters

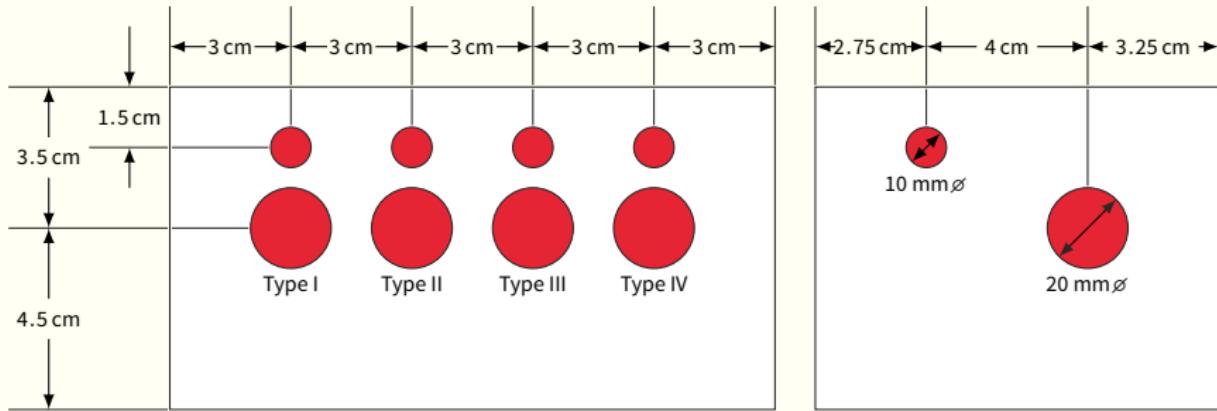
Property	Value	Units
Domain Width	4	cm
Domain Depth	10	cm
Acoustic Pressure	3.35	MPa
Probing Frequency	6	MHz
Pulse Cycles	300	-
Sound Speed	1540	m s^{-1}
Attenuation Coefficient	0.57	dB/MHzcm
Tissue Density	1060	kg m^{-3}
Power law prefactor	0.7	$\text{Np} (\text{rad/s})^{-y} \text{ m}^{-1}$
Power law exponent	0.95	-
%	8	-
FEA Time-Step	25	ns

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	ϕS	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	ϕL	0.5, 1.0, 2.0 and 2.5	cm

CIRS Phantom Properties

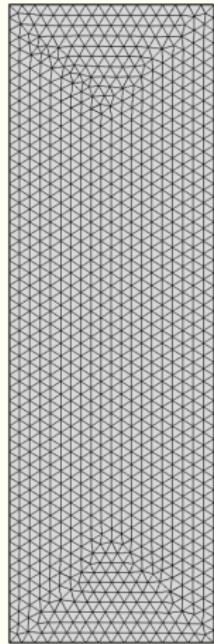


CIRS Phantom Material Properties and Geometry

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	m s^{-1}
Acoustic attenuation	α	0.5	$\text{dB cm}^{-1} \text{MHz}^{-1}$

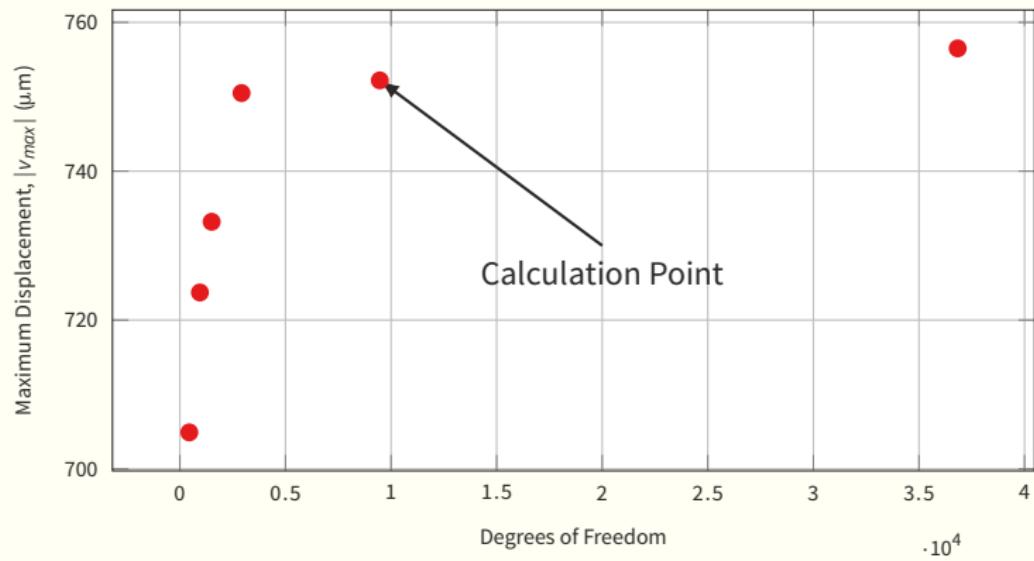
Quasi-Static FEA Details

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



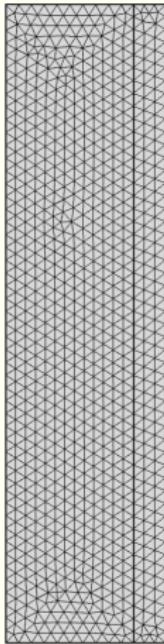
The Quasi-Static Mesh

Quasi-Static Mesh Dependency



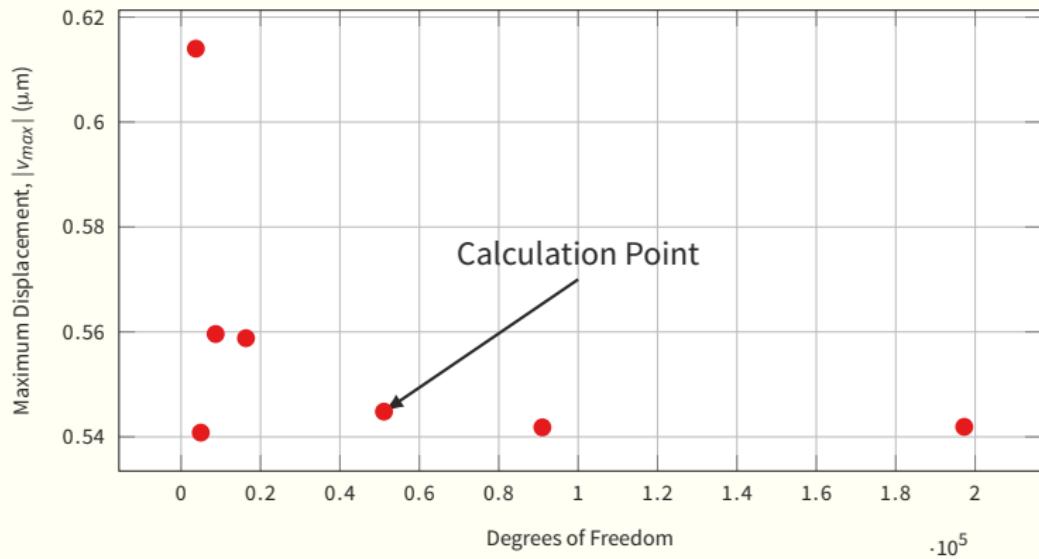
ARFI / Shear FEA Details

- 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

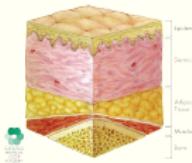
ARFI / Shear Mesh Dependency



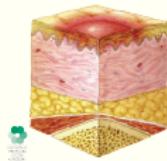
Additional Figures

- ☒ Additional Slides
- ☒ NPUAP Staging System
- ☒ Point Spread Function
- ☒ Quasi-Static Boundary Conditions
- ☒ Quasi-Static Error Comparison
- ☒ ARFI Boundary Conditions
- ☒ ARFI Error Comparison
- ☒ Shear Error Comparison

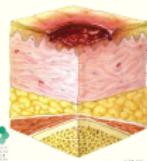
NPUAP Staging System



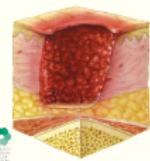
(a) Normal tissue



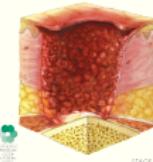
(b) Stage I



(c) Stage II



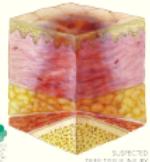
(d) Stage III



(e) Stage IV

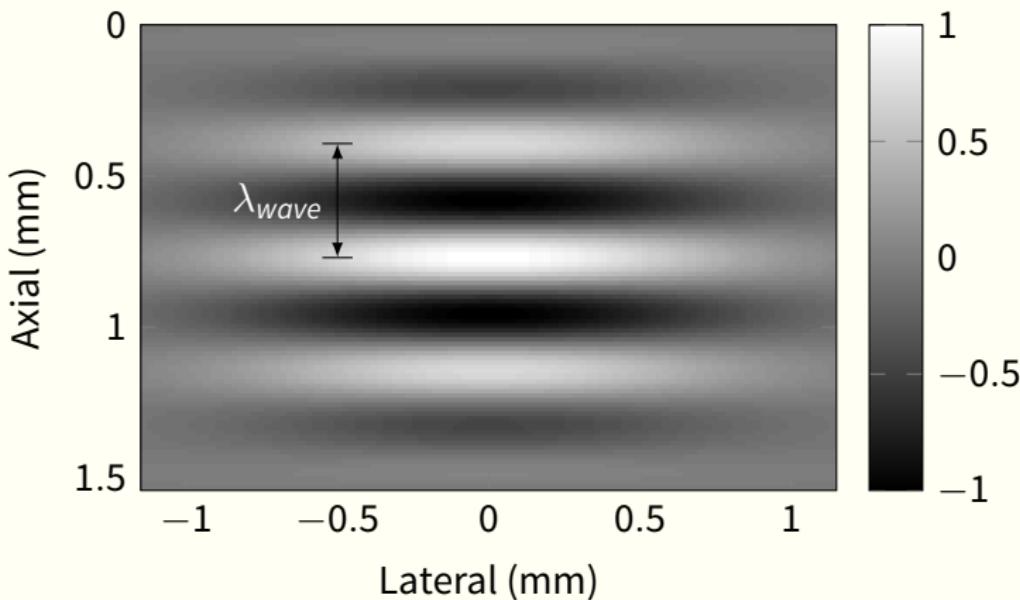


(f) Unstageable



(g) Suspected DTI

Point Spread Function



Point spread function used for simulating b-mode ultrasound scans. The function is defined axially by a cosine function at the probing frequency and modulated by a Gaussian function both axially and laterally.

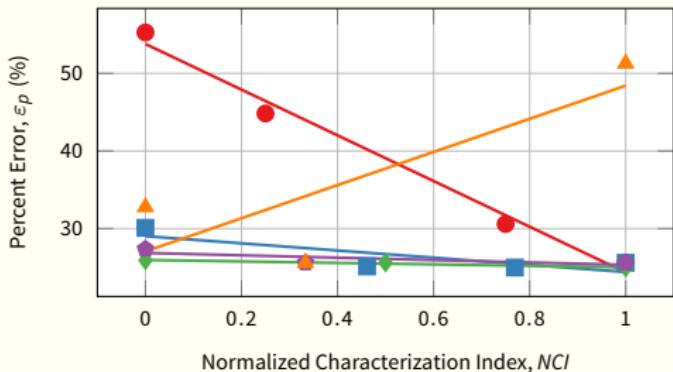
QS USE Boundary Conditions

$$\vec{u} = (0, -u_0)$$



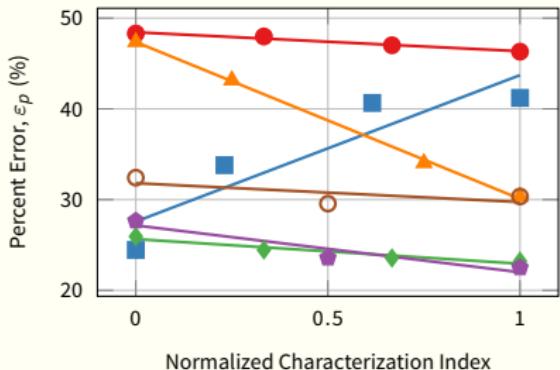
Boundary conditions used in the finite-element calculations of soft tissue deformation.

Quasi-Static Error



Investigated Parameters

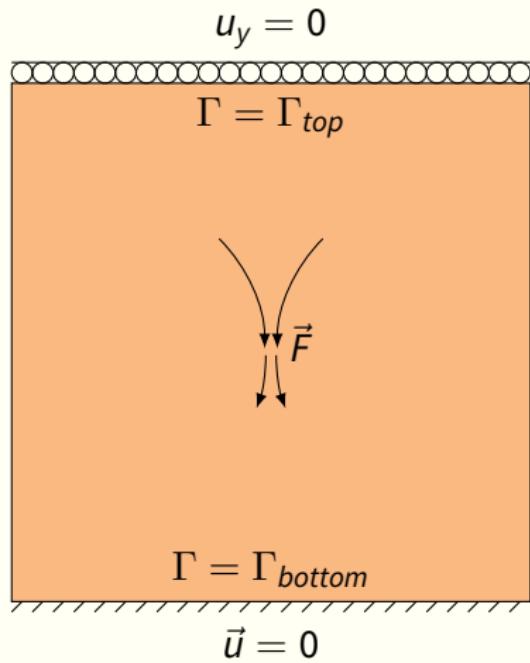
- Lesion Size, $\varepsilon_p = -29.44NCI + 53.79$
- Lesion Depth, $\varepsilon_p = -4.62NCI + 29.03$
- Lesion Altitude, $\varepsilon_p = -0.95NCI + 25.96$
- Probing Frequency, $\varepsilon_p = -1.54NCI + 26.87$
- Applied Strain, $\varepsilon_p = 21.36NCI + 27.06$



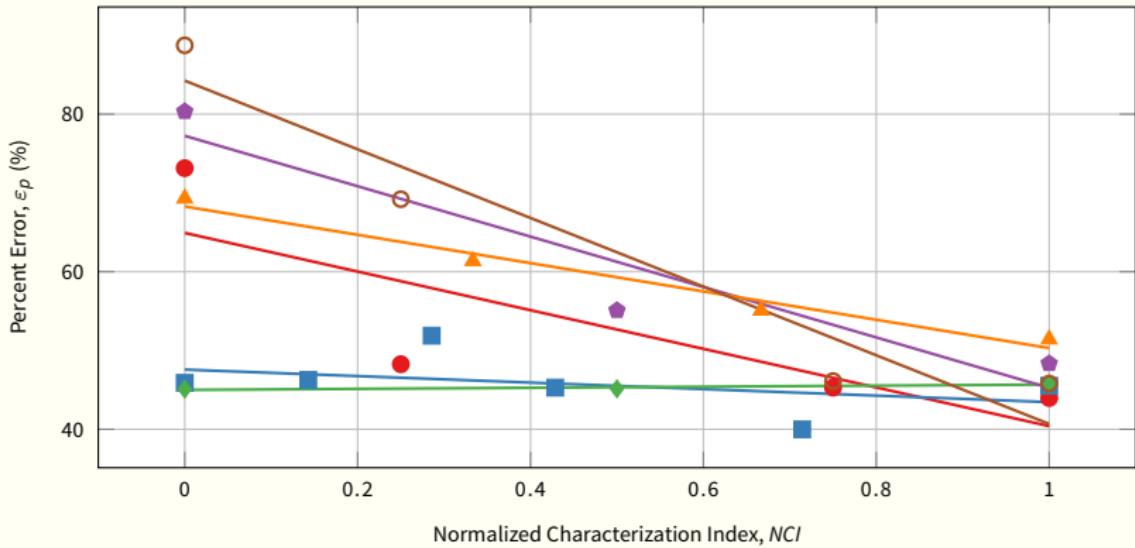
Investigated Parameters

- Boundary Blur Radius, $\varepsilon_p = -2.09NCI + 48.44$
- Co-Located Lesion Separation, $\varepsilon_p = 16.13NCI + 27.58$
- Clustered Lesion Density, $\varepsilon_p = -2.71NCI + 25.65$
- Clustered Lesion Size, $\varepsilon_p = -5.16NCI + 27.15$
- Human Lesion Size, $\varepsilon_p = -17.28NCI + 47.37$
- Human Lesion Depth, $\varepsilon_p = -2.08NCI + 31.81$

ARFI /Shear Boundary Conditions



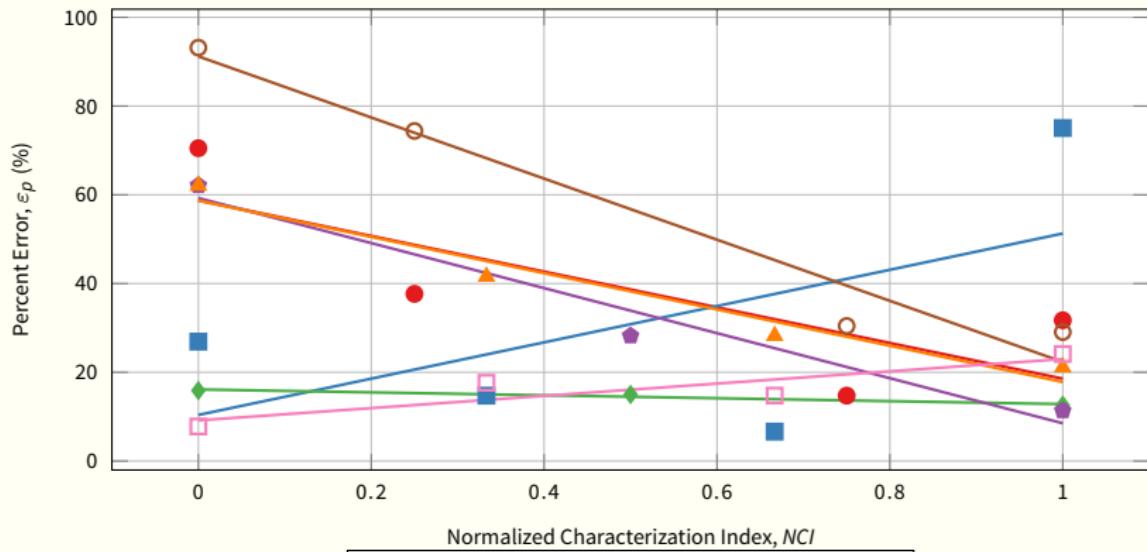
ARFI Error



Investigated Parameters

- Lesion Size, $\varepsilon_p = -24.52NCI + 64.92$
- Lesion Depth, $\varepsilon_p = -4.13NCI + 47.58$
- Blur Radius, $\varepsilon_p = 0.68NCI + 44.99$
- Cluster Radius, $\varepsilon_p = -31.99NCI + 77.25$
- Cluster Density, $\varepsilon_p = -17.97NCI + 68.28$
- Visible Human Width, $\varepsilon_p = -43.57NCI + 84.25$

Shear Error



Investigated Parameters

- Lesion Size, $\varepsilon_p = -40.2NCI + 58.75$
- Lesion Depth, $\varepsilon_p = 40.89NCI + 10.39$
- Blur Radius, $\varepsilon_p = -3.3NCI + 16.13$
- Cluster Radius, $\varepsilon_p = -50.76NCI + 59.27$
- Cluster Density, $\varepsilon_p = -40.88NCI + 58.7$
- Visible Human Width, $\varepsilon_p = -68.86NCI + 91.19$
- Focal Offset, $\varepsilon_p = 13.83NCI + 9.16$