

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

by

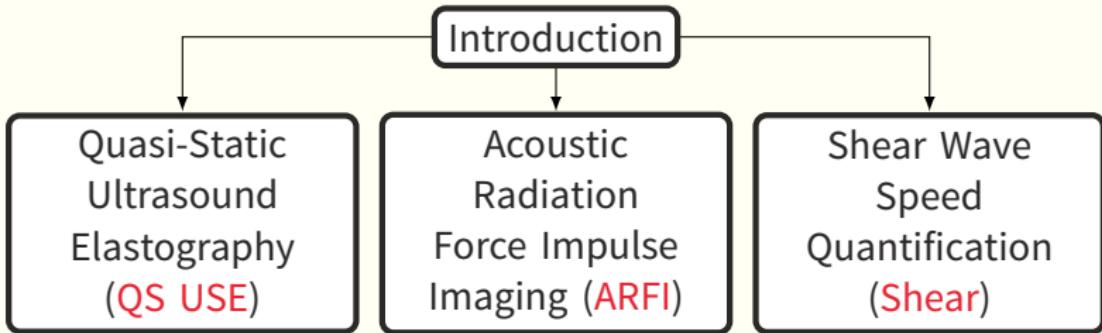
Kenton David Hamaluik

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

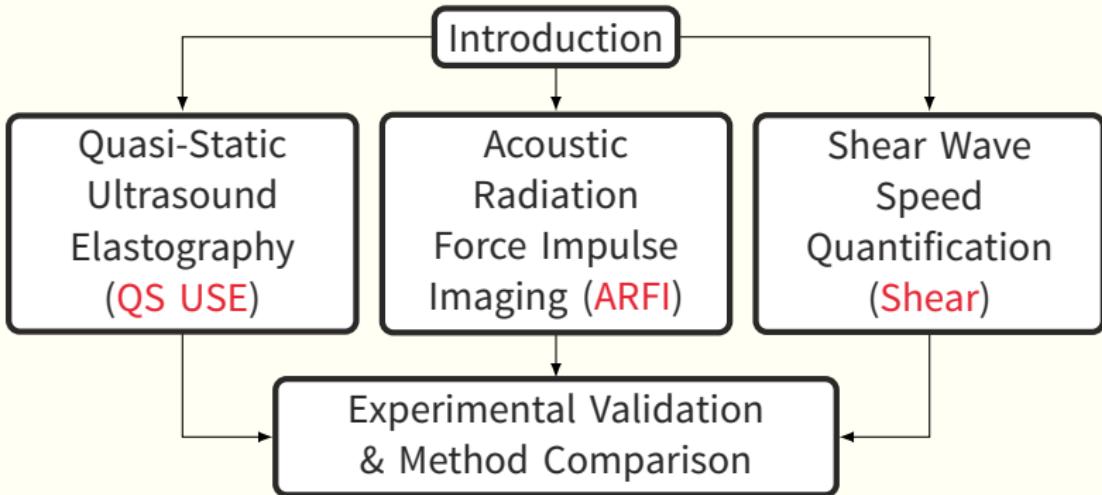
# Contents

Introduction

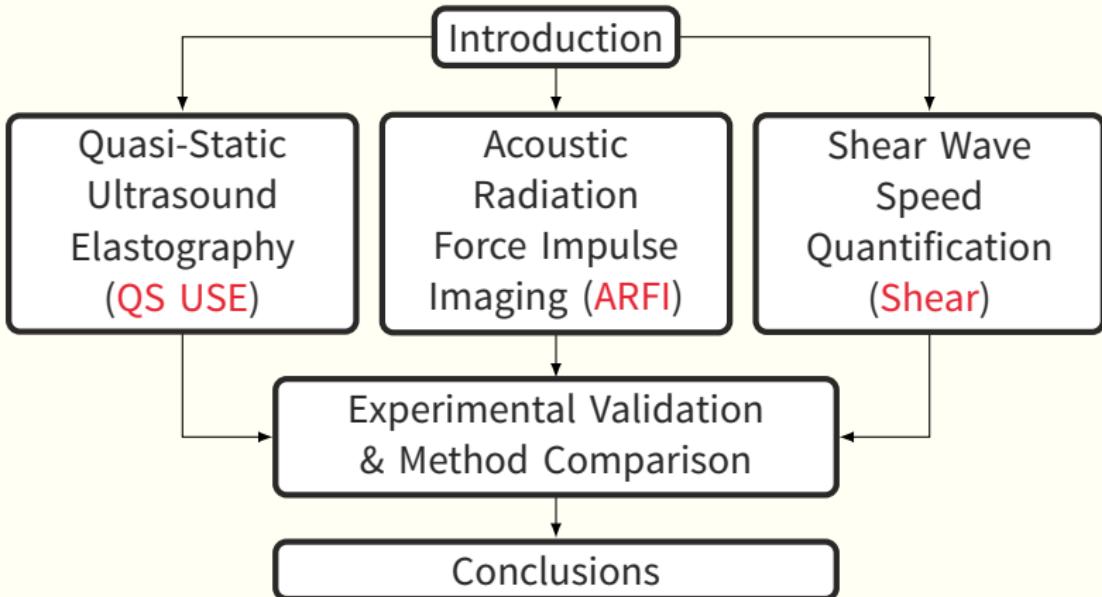
# Contents



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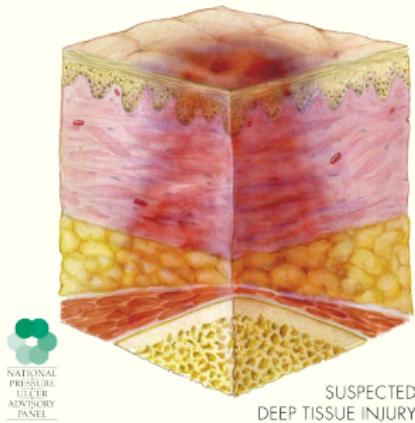
# Contents



# Introduction

# Deep Tissue Injuries (DTI)

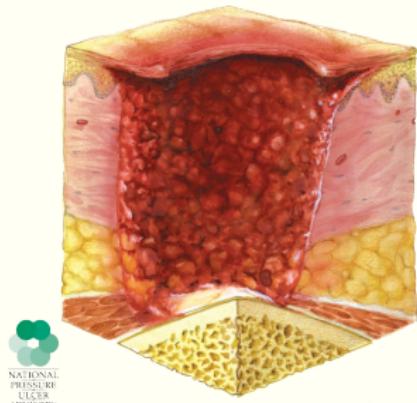
- ✚ Secondary injuries (limited mobility)
- ✚ Caused by pressure & deformation
- ✚ Stage III – IV pressure ulcers
- ✚ No clinical detection
- ✚ Severe health burdens  
[Russo et al., 2008]
  - 500,000 – 2,000,000 annually (USA)
  - Increased length of stay, mortality



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# Deep Tissue Injuries (DTI)

- ✚ Secondary injuries (limited mobility)
- ✚ Caused by pressure & deformation
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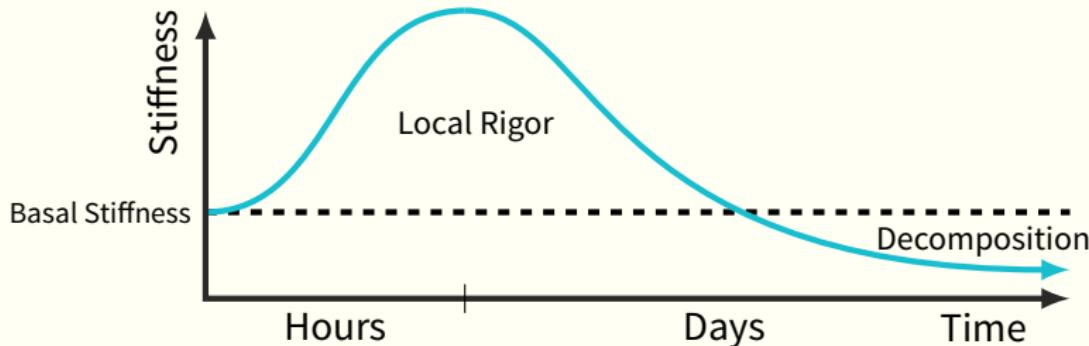
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# Current DTI Detection

- 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

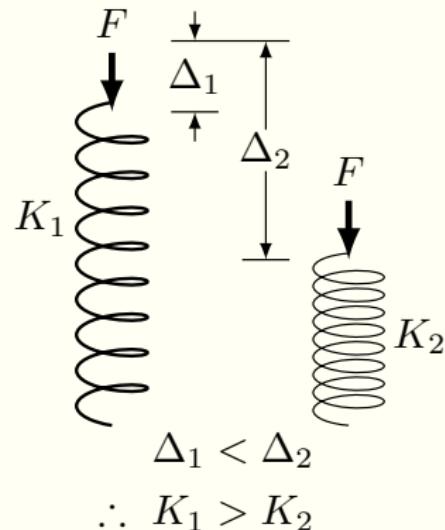
	DTI	B-Mode US	QS USE	ARFI	Shear	FE Models	Gel Phantoms	Animals	Humans	Characterized	Clinical
PU Risk scales	X	—	—	—	—	X	X	X	✓	✓	✓
MRI	✓	—	—	—	—	✓	✓	✓	✓	X	X
Aoi, 2009	✓	✓	X	X	X	X	X	X	✓	X	?
Makhsous, 2010	✓	—	—	—	—	—	—	✓	?	X	✓
Deprez, 2011	✓	X	✓	X	X	✓	✓	✓	?	X	✓
→ This work	✓	X	✓	✓	✓	✓	✓	?	?	✓	✓

# 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.

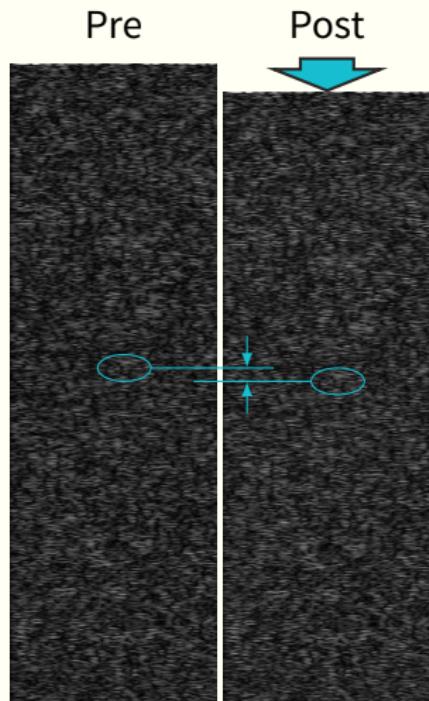
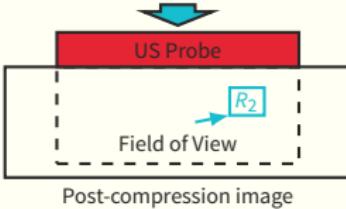
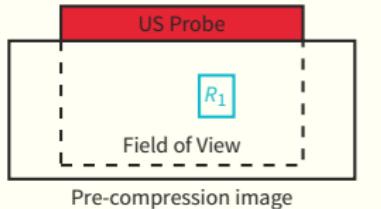
# Theory of Operation

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

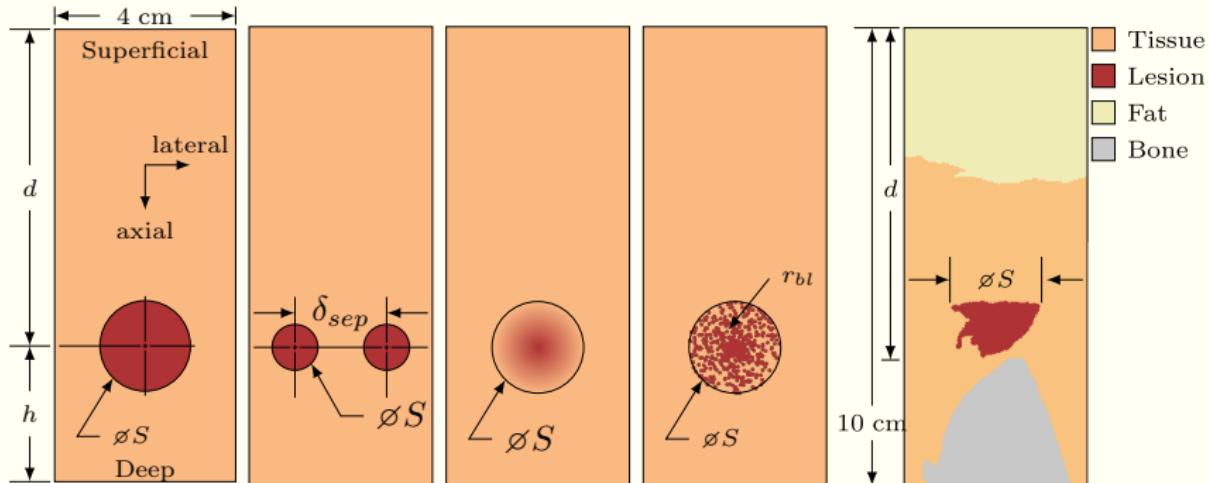


# Theory of Operation

- ✚ 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

$\phi S$ : lesion size

$f$ : interrogation frequency

$\varepsilon_{app}$ : applied strain

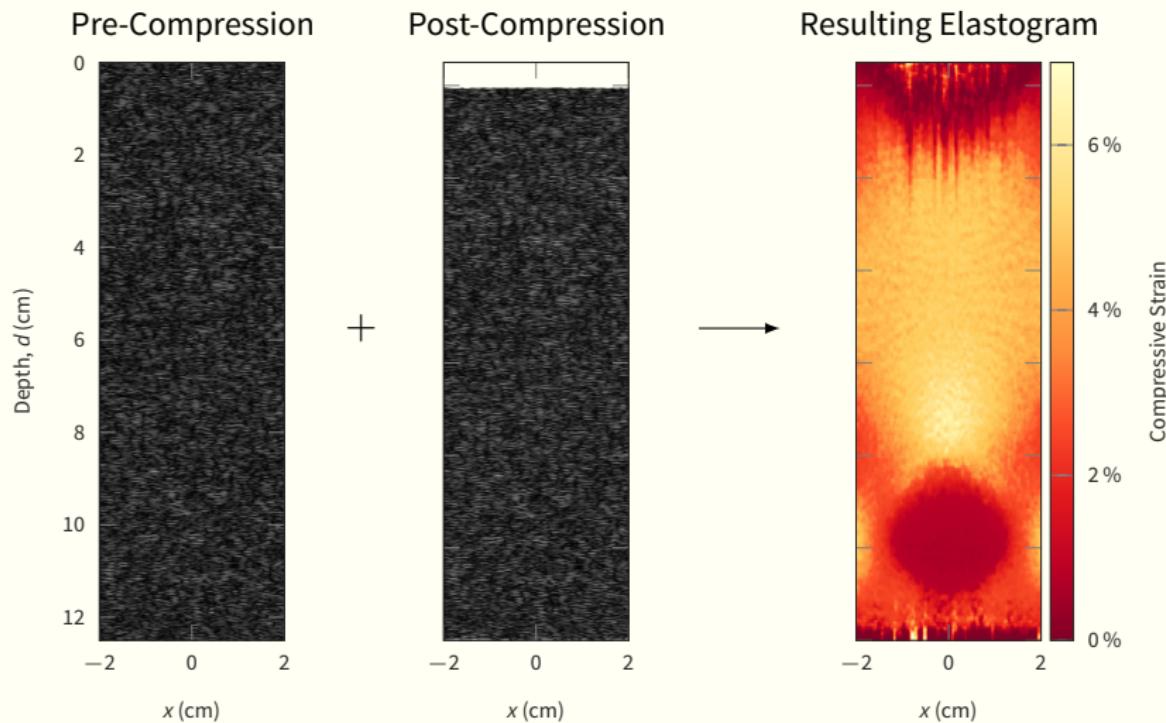
$\delta_{sep}$ : separation distance

$b_r$ : blur radius

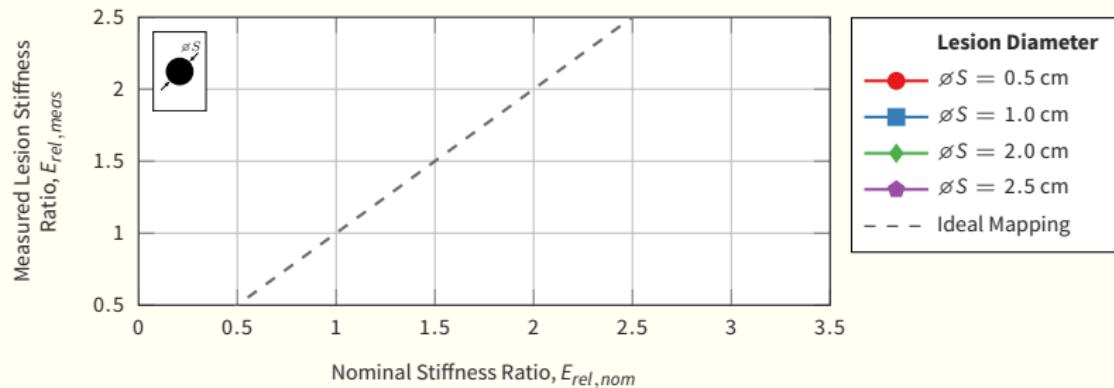
$b_\rho$ : cluster density

$r_{bl}$ : cluster radii

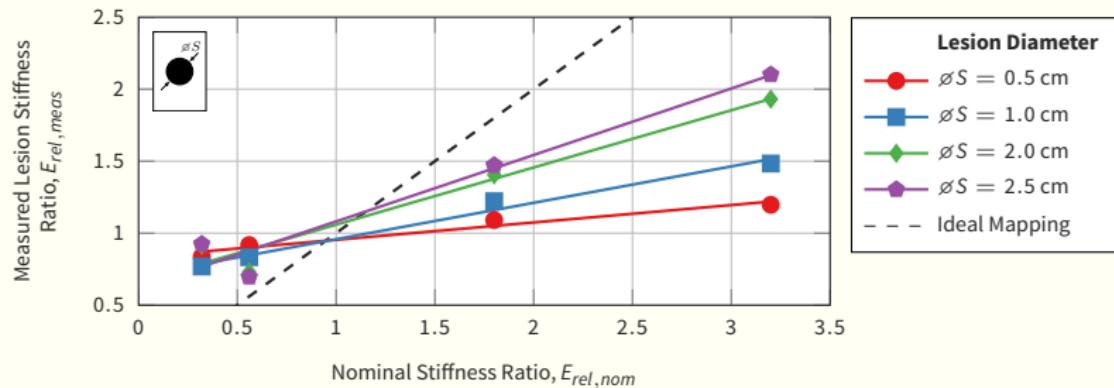
# Sample Simulated Elastogram



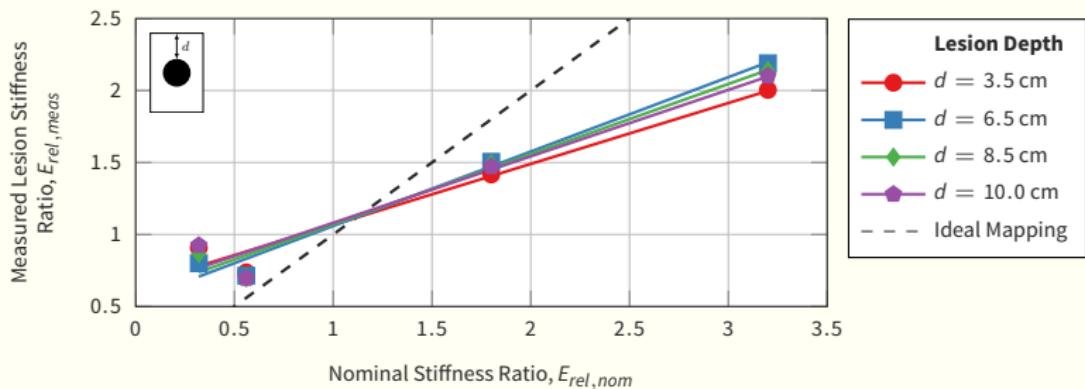
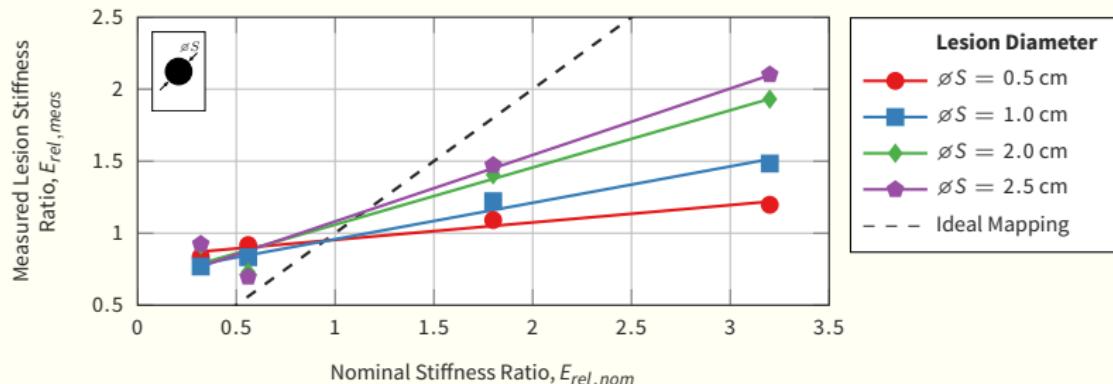
# Sample Quasi-Static Results



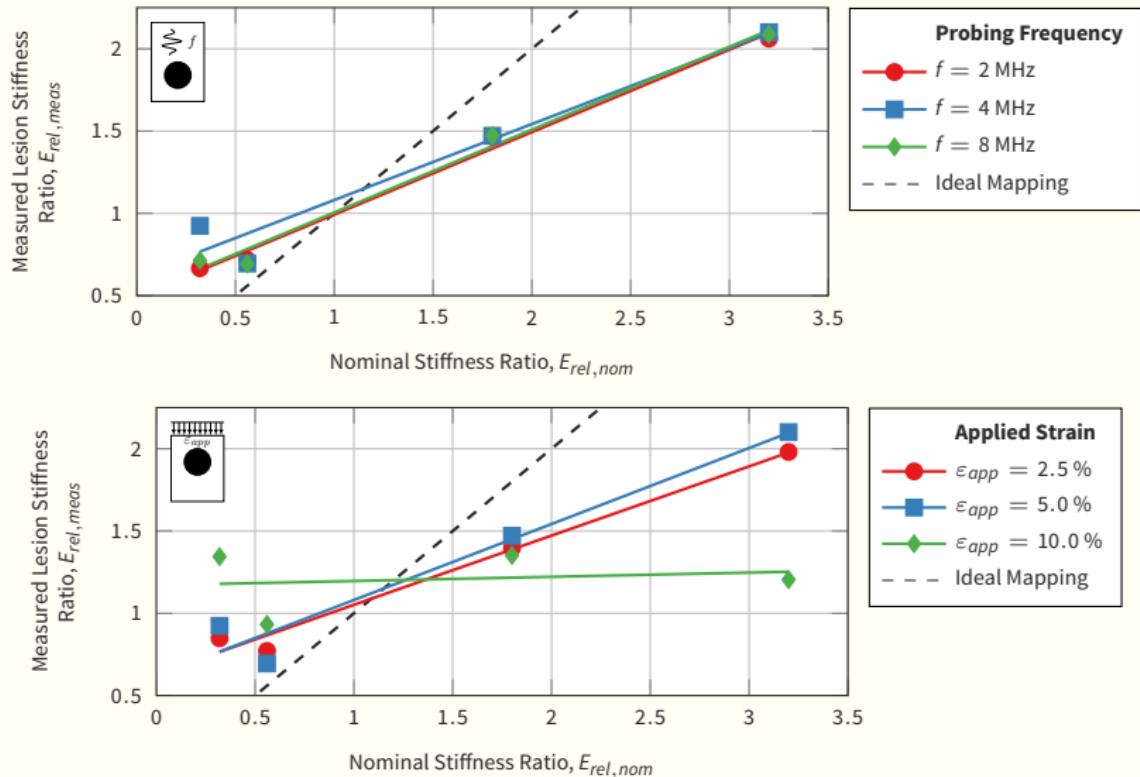
# Sample Quasi-Static Results



# 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
- ✚ Not ideally sensitive
- ✚ Can detect DTI
- ✚ Manual palpation not reliable
  - ✖ ARFI imaging as an alternative

# Acoustic Radiation Force Impulse Imaging

# Introduction

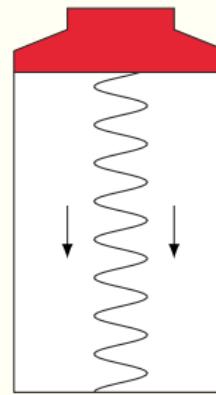
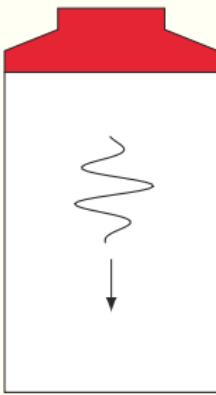
- QS USE has low detection sensitivity, unreliable
- Acoustic Radiation Force Impulse (**ARFI**) imaging similar to QS USE
  - Transducer-generated force instead of manual
- ↑ repeatability, ↑ inter-operator reliability
- Absorbed energy generates force:

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

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

# How ARFI Imaging Works

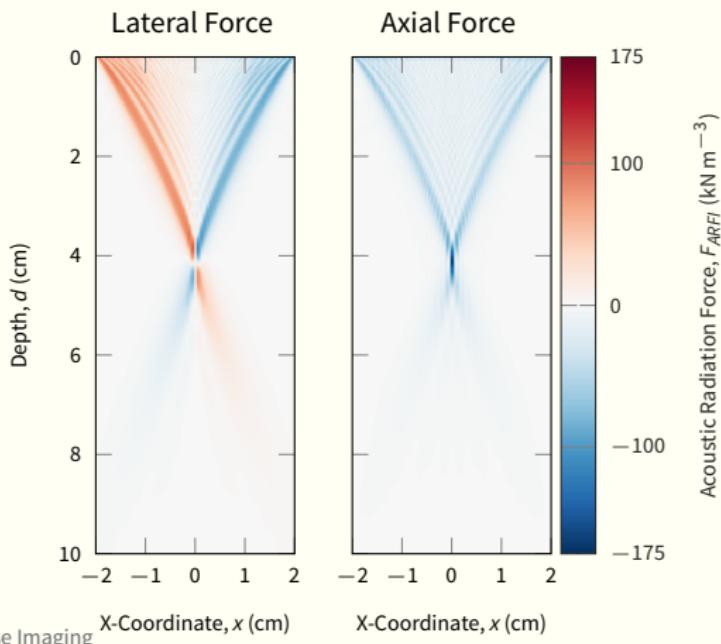
- Normal ultrasound is only a couple periods long ( $\approx 2$  ms)
- ARFI imaging uses continuous beams ( $\approx 100$  ms)



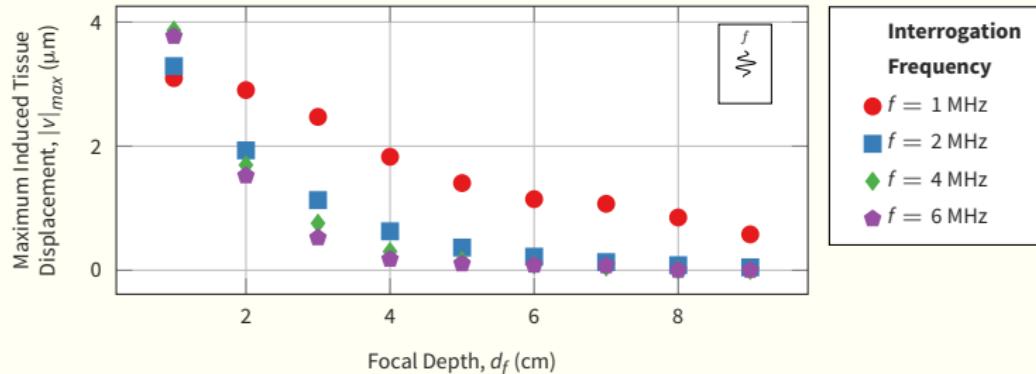
- Absorbed acoustic energy has safety implications

# Simulating ARFI Loads

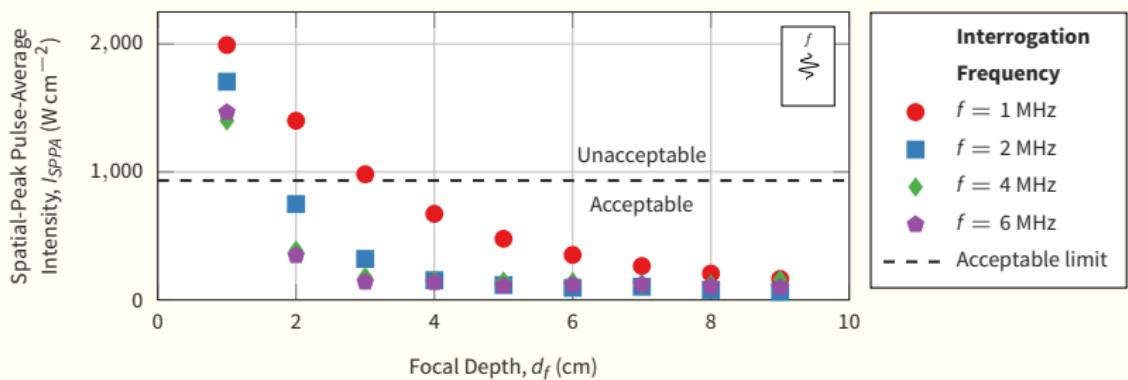
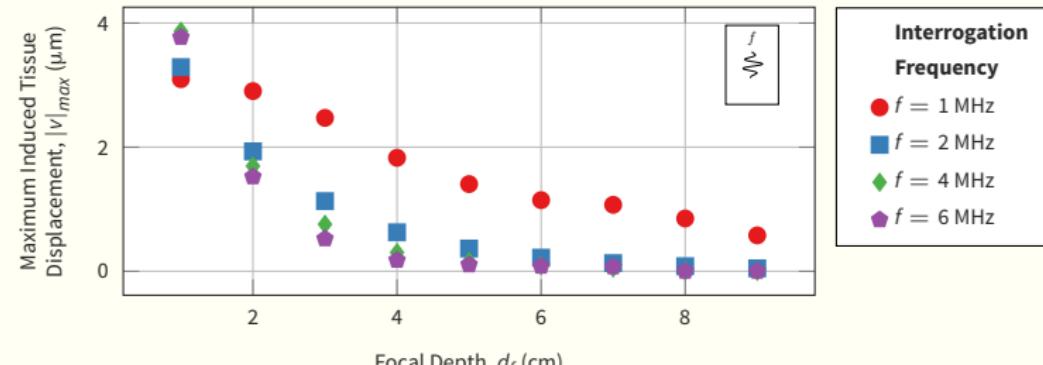
- Use k-space pseudo-spectral method to solve the wave equation
  - k-Wave MATLAB<sup>®</sup> toolbox



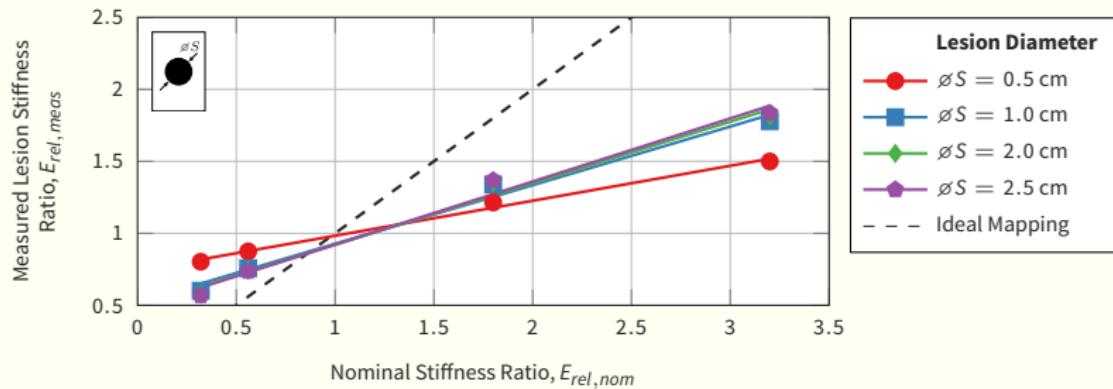
# Sample ARFI Results



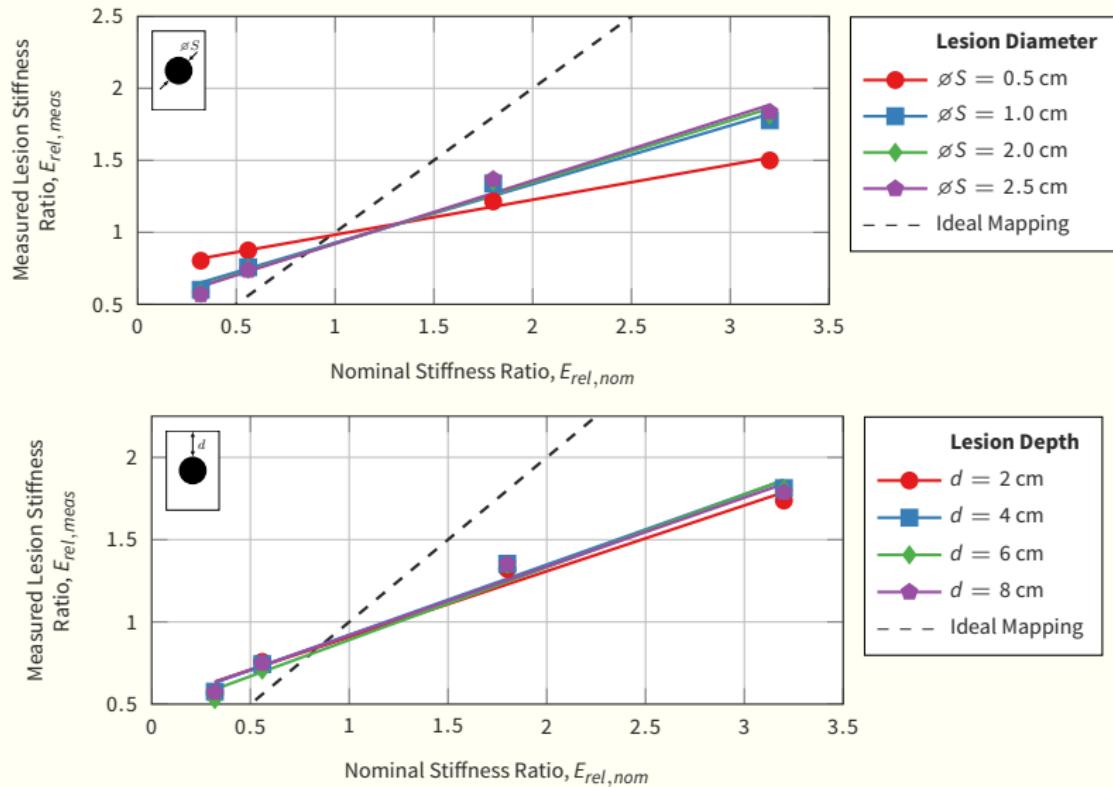
# Sample ARFI Results



# 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
  - ❖ Similar characterization results as QS USE
- Complicated geometry can affect results
- ARFI more reliable than QS USE
- ARFI has limited penetration depth
  - ❖ Significant safety considerations

# **Shear Wave Speed Quantification**

# Introduction

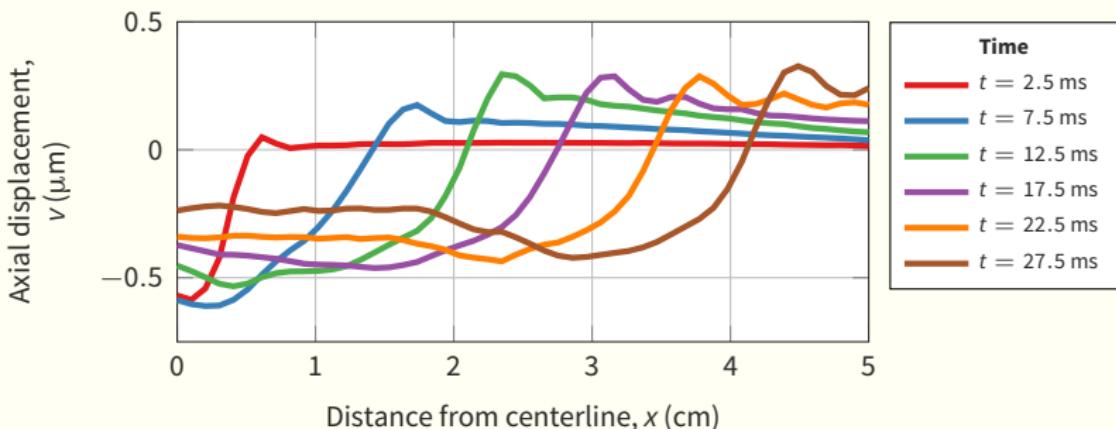
- QS USE and ARFI provide **qualitative** measures
- Shear wave speed quantification is **quantitative**
  - ▶ Absolute values
  - ▶ Track over time
- Uses ARFI pulses to generate shear waves
  - ▶ Measure shear wave speed → calculate stiffness:

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

$\mu$ : Shear modulus  
 $c_T$ : Shear wave speed  
 $\rho$ : Tissue density

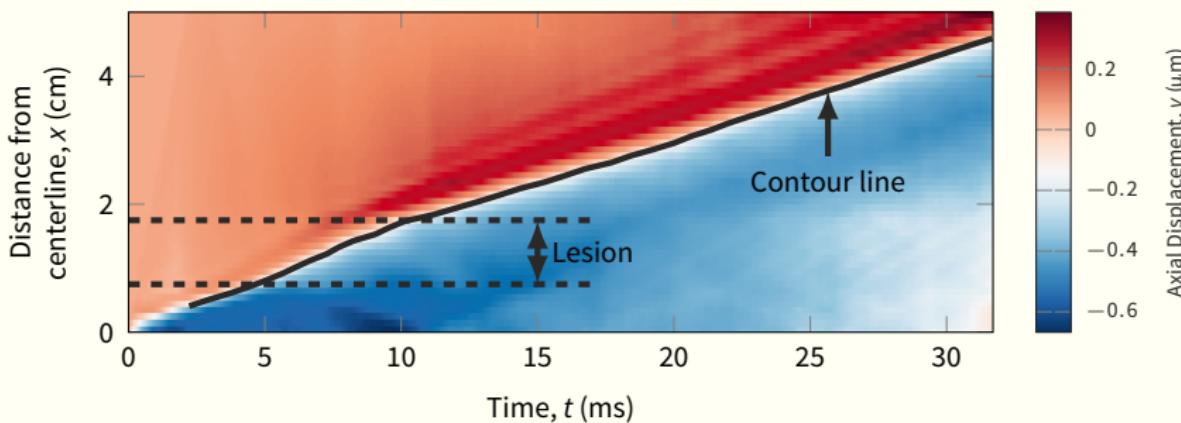
# Measuring Shear Wave Speed

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



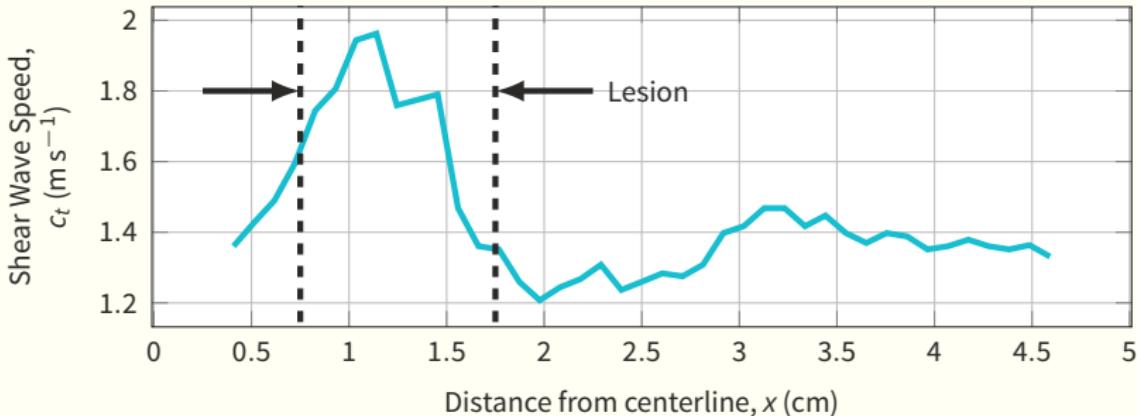
# Measuring Shear Wave Speed

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

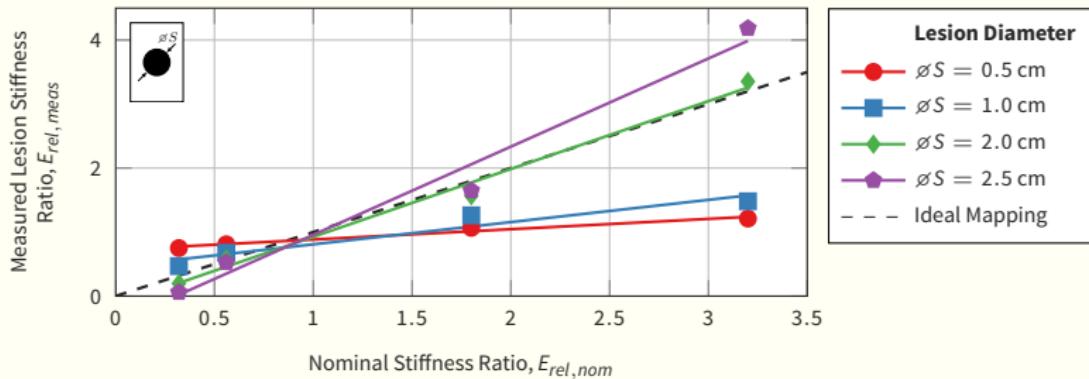


# Measuring Shear Wave Speed

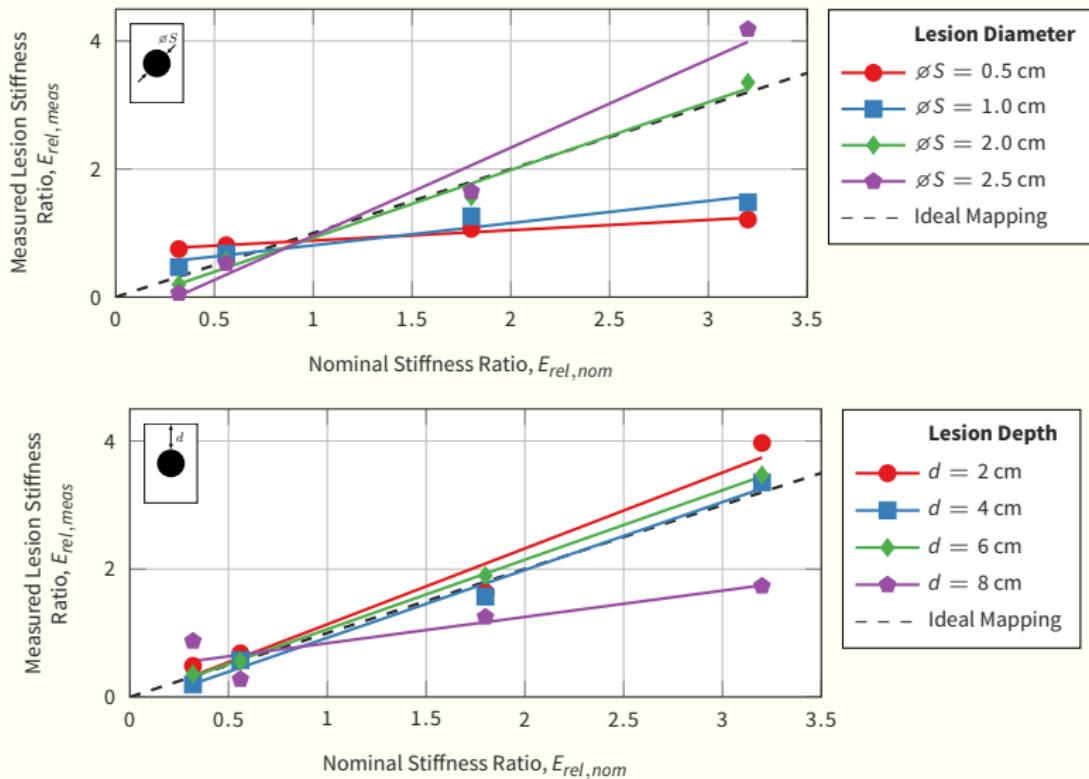
1. Induce ARFI at desired depth
  - Shear waves radiate outward, like “ripples in a pond”
2. Monitor deformation along a line extending from the focal point using B-mode ultrasound
  - Calculate speed of shear wave along this line



# Sample Shear Results



# Sample Shear Results

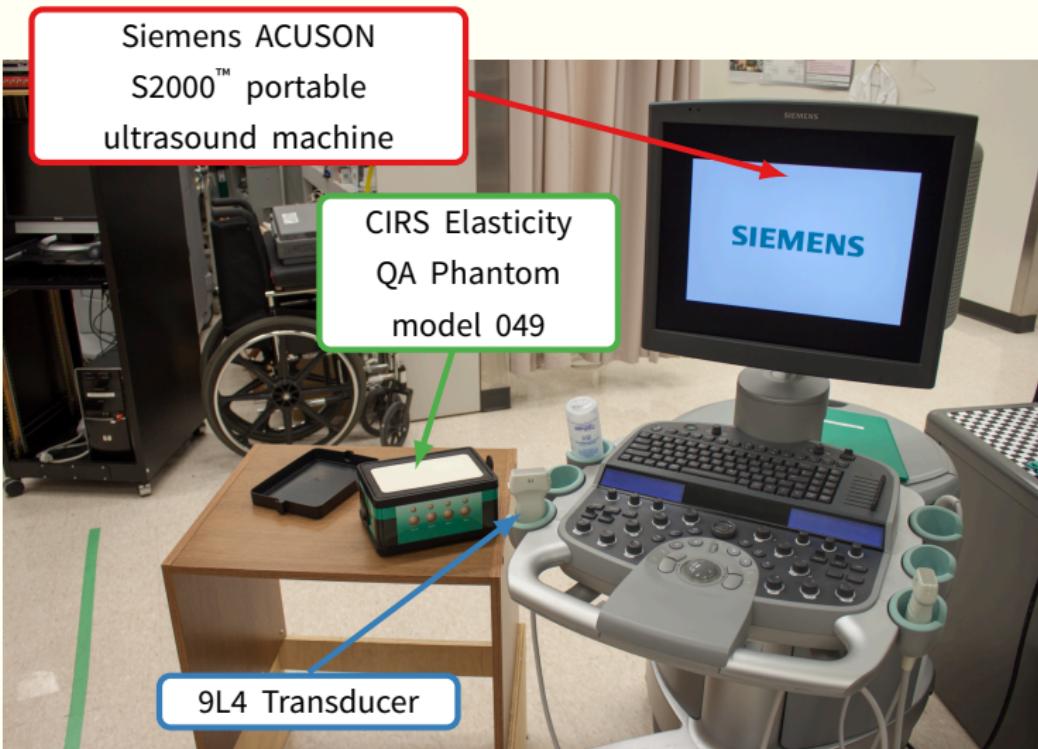


# Shear Wave Speed Outcomes

- ❖ 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

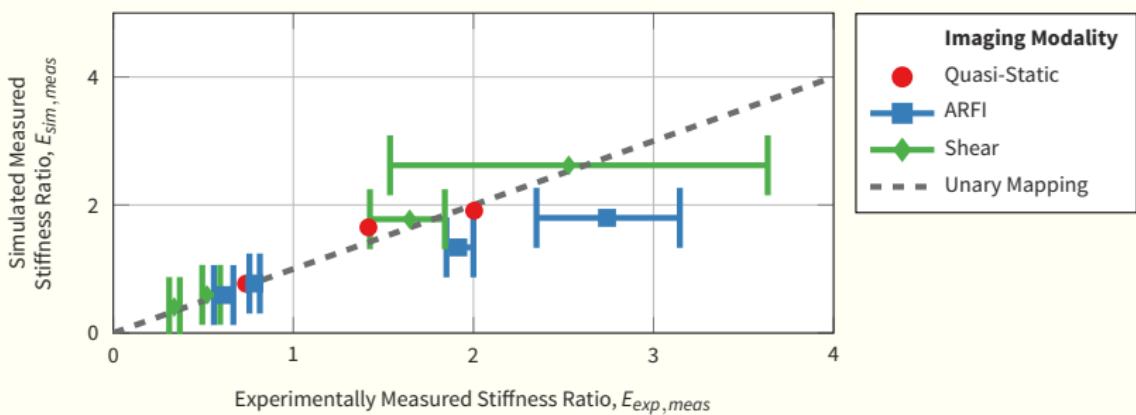
# **Experimental Validation & Method Comparisons**

# Experimental Setup

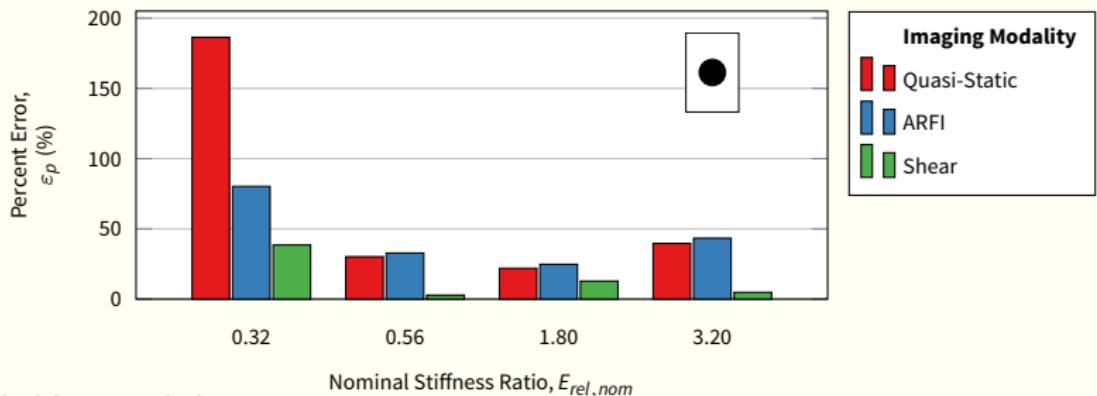
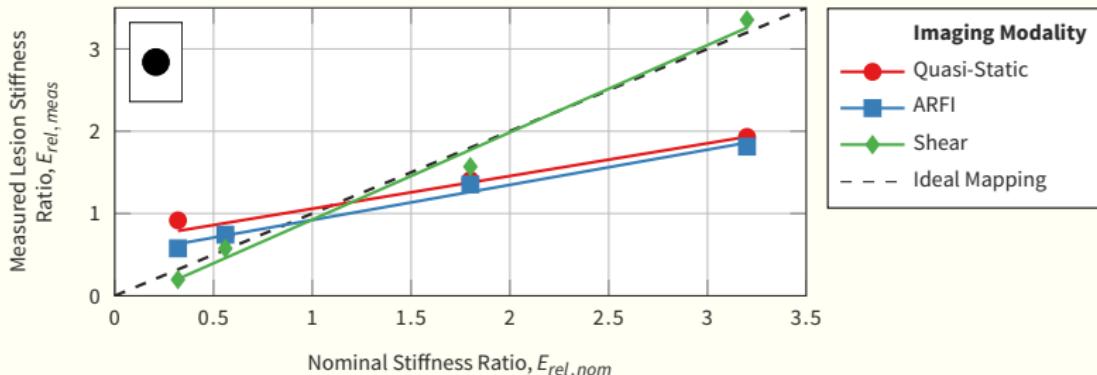


# Experimental Validations

- 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
- ✚ References
- ✚ 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.
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- [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
- $\rho$ : Tissue density
- $\alpha$ : 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	$\phi S$	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	$\varepsilon_{app}$	2.5, 5.0 and 10.0	%
Co-located separation distance	$\delta_{sep}$	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	$\phi L$	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	$\text{m s}^{-1}$
Basal Stiffness	25	kPa
Tissue Density	1060	$\text{kg m}^{-3}$
Applied Strain	5	%

# ARFI Parameters

K-Space Psuedospectral Model Parameters

Property	Symbol	Value	Units
Nonlinearity parameter	$B/A$	8	-
Power law prefactor	$\alpha_0$	0.7	$Np \text{ (rad/s)}^{-y} \text{ m}^{-1}$
Power law exponent	$y$	0.95	-
Density	$\rho_0$	1060	$\text{kg m}^{-3}$

# ARFI Parameters

Simulated Material Parameters

Property	Symbol	Value	Units
Bulk Modulus	$K$	515.7	kPa
Shear Modulus	$\mu_{tissue}$	1.0	kPa
Density	$\rho$	1060	$\text{kg m}^{-3}$

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	$\phi S$	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	$b_p$	10, 20, 30 and 40	$\text{cm}^{-2}$
Clustered lesion radius	$r_{bl}$	0.5, 1.0 and 1.5	mm
Visible human lesion width	$\phi L$	0.5, 1.0, 2.0 and 2.5	cm

# ARFI / Shear Default Parameters

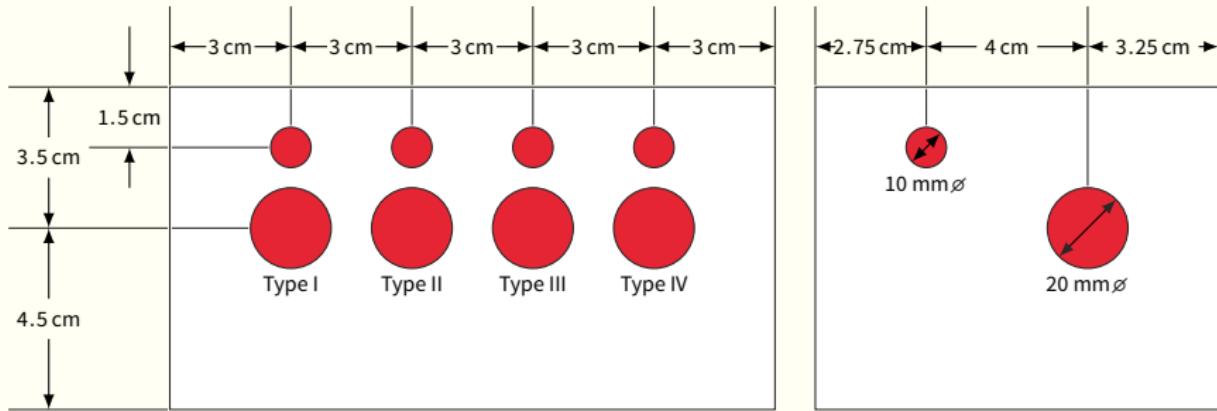
Property	Value	Units
Domain Width	4	cm
Domain Depth	10	cm
Acoustic Pressure	3.35	MPa
Probing Frequency	6	MHz
Pulse Cycles	300	-
Sound Speed	1540	$\text{m s}^{-1}$
Attenuation Coefficient	0.57	dB/MHzcm
Tissue Density	1060	$\text{kg m}^{-3}$
Power law prefactor	0.7	$\text{Np} (\text{rad/s})^{-y} \text{ m}^{-1}$
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	$\phi S$	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	$b_\rho$	10, 20, 30 and 40	$\text{cm}^{-2}$
Clustered lesion radius	$r_{bl}$	0.5, 1.0 and 1.5	mm
Visible human lesion width	$\phi L$	0.5, 1.0, 2.0 and 2.5	cm

# CIRS Phantom Properties



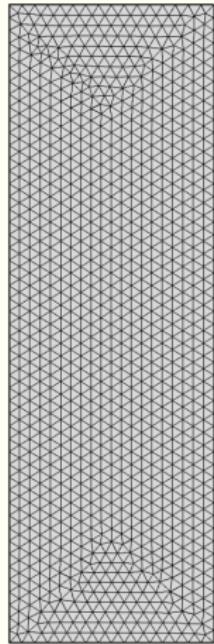
CIRS Phantom Material Properties and Geometry

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

# Quasi-Static FEA Details

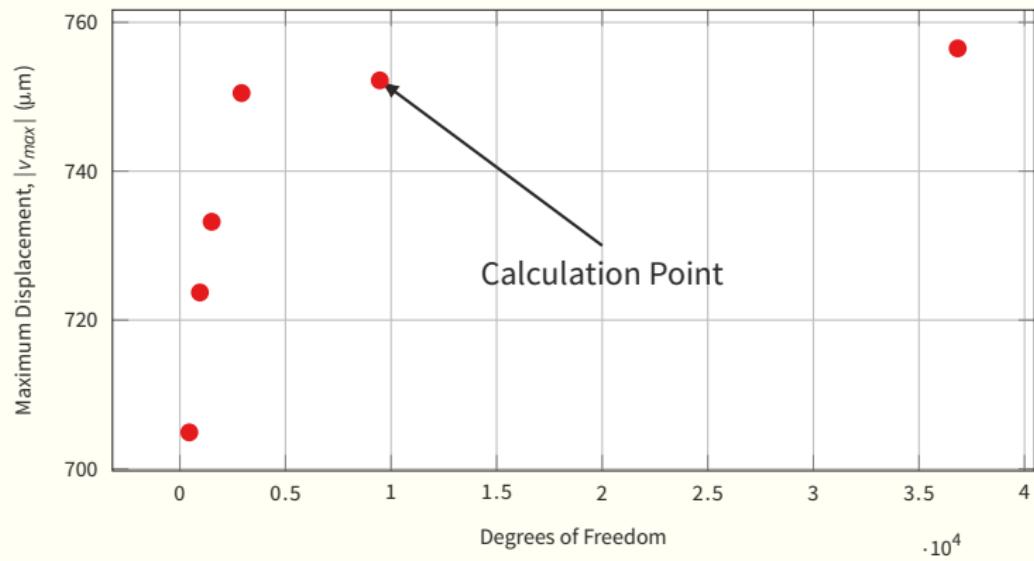
- Quadratic Lagrangian triangular elements
- 9,468 degrees of freedom
- Solved using COMSOL Multiphysics

$$-\nabla \cdot \sigma = \vec{F}$$



The Quasi-Static Mesh

# Quasi-Static Mesh Dependency

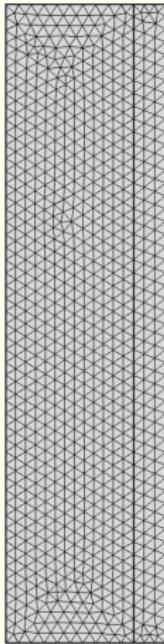


# ARFI / Shear FEA Details

- 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

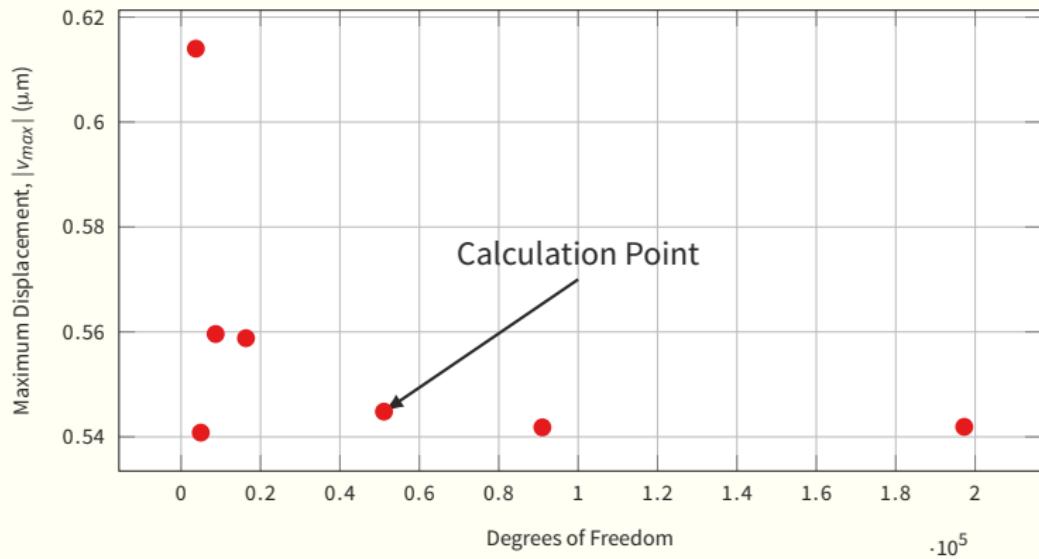
$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} - \nabla \cdot \sigma = \vec{F}$$

$$\sigma - \sigma_0 = C : \varepsilon + \sum_m 2G_m \tau_m \dot{\gamma}_m$$



The ARFI / Shear Mesh

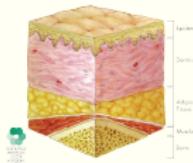
# ARFI / Shear Mesh Dependency



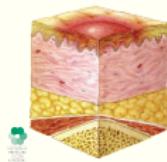
# Additional Figures

- ☒ 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

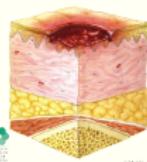
# NPUAP Staging System



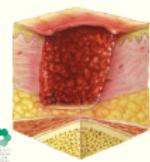
(a) Normal tissue



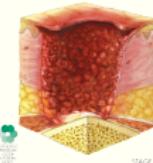
(b) Stage I



(c) Stage II



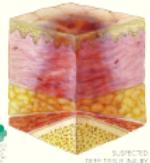
(d) Stage III



(e) Stage IV

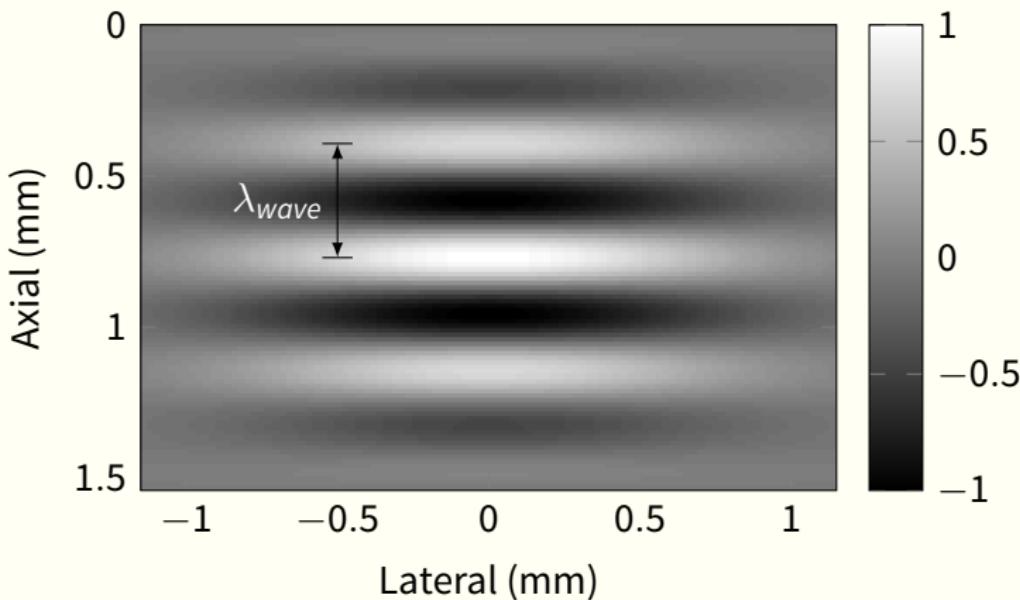


(f) Unstageable



(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.

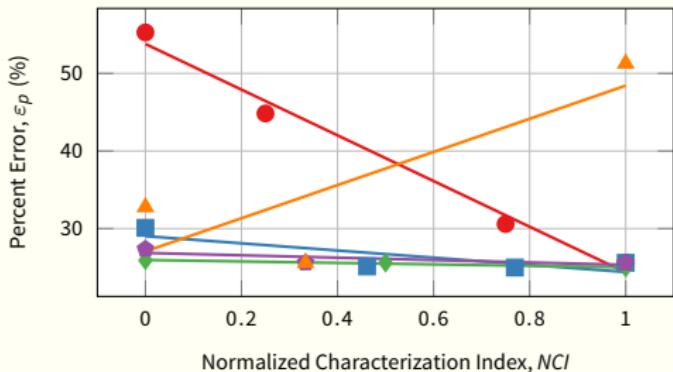
# QS USE Boundary Conditions

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



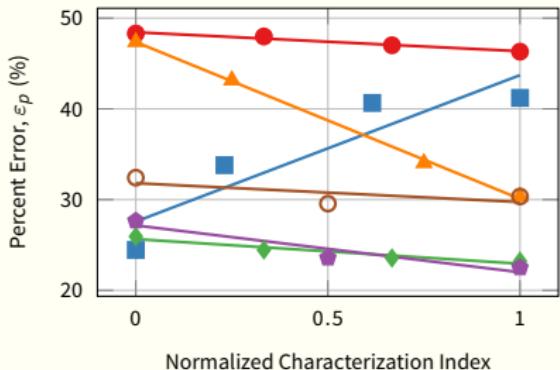
Boundary conditions used in the finite-element calculations of soft tissue deformation.

# Quasi-Static Error



## Investigated Parameters

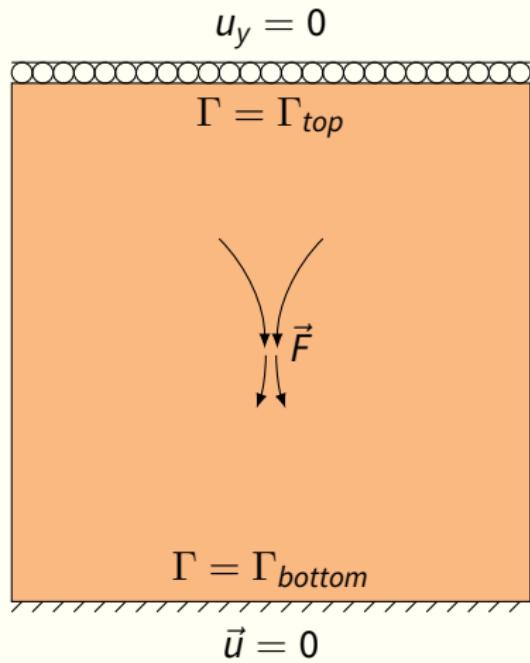
- Lesion Size,  $\varepsilon_p = -29.44NCI + 53.79$
- Lesion Depth,  $\varepsilon_p = -4.62NCI + 29.03$
- Lesion Altitude,  $\varepsilon_p = -0.95NCI + 25.96$
- Probing Frequency,  $\varepsilon_p = -1.54NCI + 26.87$
- Applied Strain,  $\varepsilon_p = 21.36NCI + 27.06$



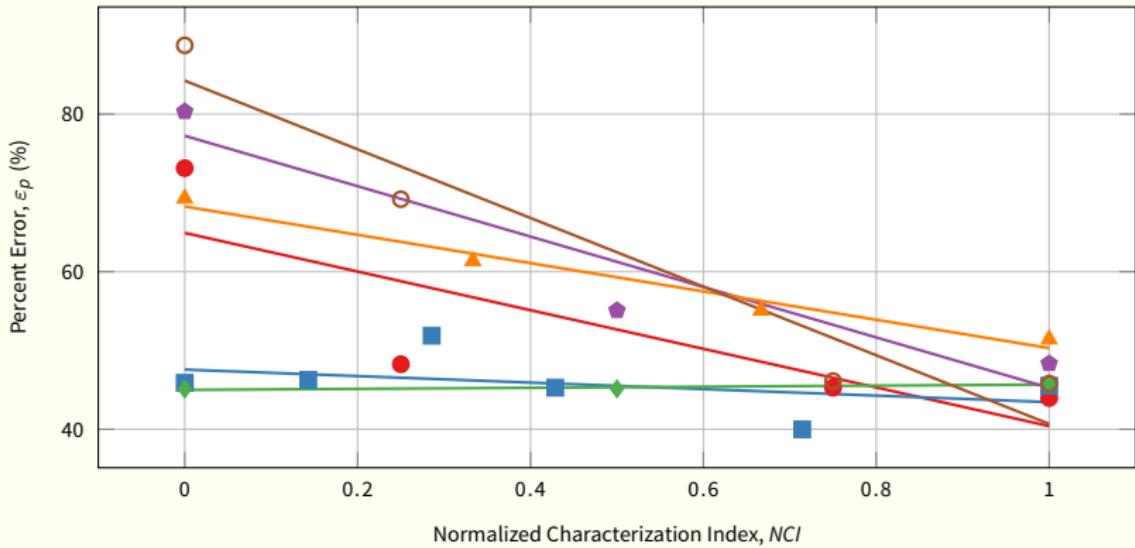
## Investigated Parameters

- 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



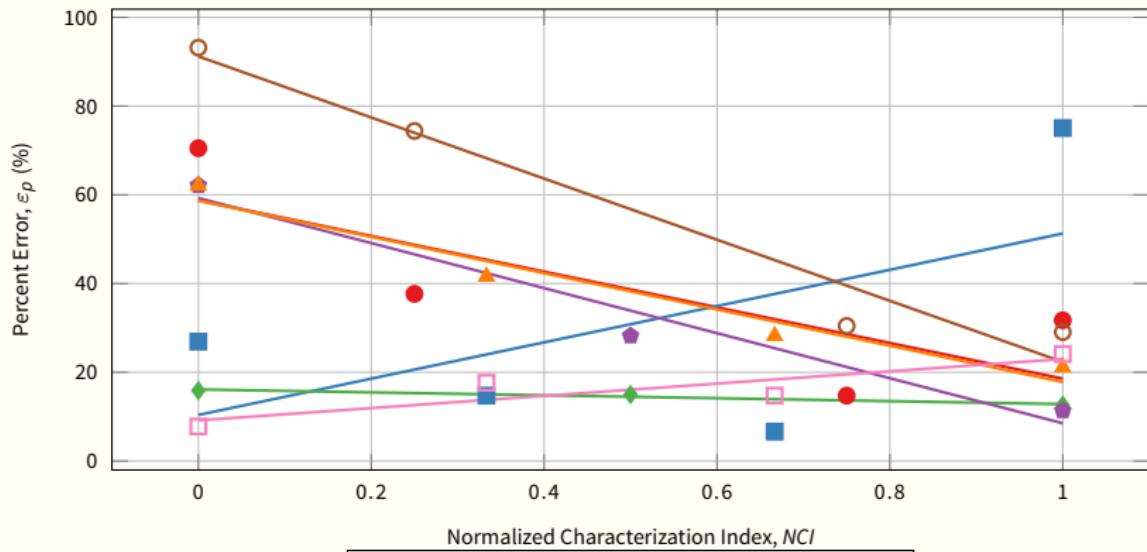
# ARFI Error



## 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,  $\varepsilon_p = 13.83NCI + 9.16$