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

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science

by

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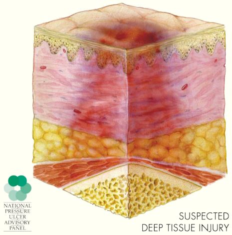
Contents

Introduction

Deep Tissue Injuries

- Deep tissue injuries (DTI)
  - Secondary injuries for those with limited mobility
  - Form deep in tissue
  - Eventually break out into stage III – IV pressure ulcers
- Tissue damage due to pressure and deformation
- Almost impossible to detect clinically
- Severe health and monetary burdens

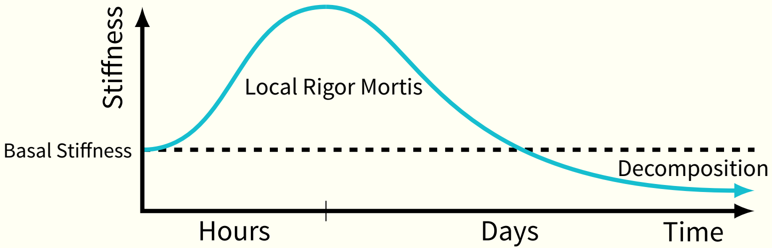


Current DTI Detection

- Clinical settings: risk assessment scales
  - Norton, Braden, and Risk Assessment Pressure Sore scales
  - No actual detection, only risk assessment
- Research settings: T_2^*-weighted MRI
  - Not feasible clinically
- New research:
  - B-mode imaging (Aoi et al. [1])
  - Blood / urine markers (Mahksous et al. [2])
  - Ultrasound elastography (Deprez et al. [3])

Ultrasound Elastography

- Mechanical stiffness changes with injury formation and progression



Adapted from Gefen [4], used with permission

- Ultrasound elastography is a technology which measures tissue stiffness

Literature Review

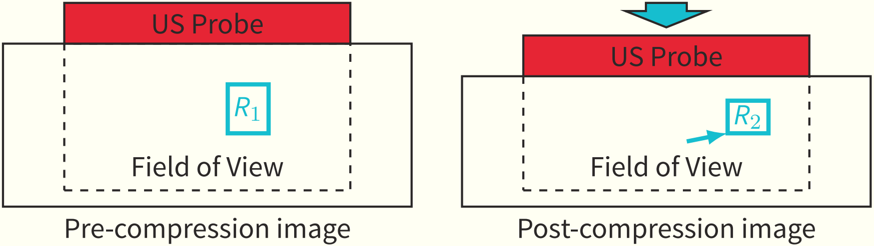
	DTI	B-Mode US	QS USE	ARFI	Shear	FE Models	Gel Phantoms	Animals	Humans	Characterized	Clinical
PU Risk scales	✗	—	—	—	—	✗	✗	✗	✓	✓	✓
T_2^* MRI	✓	—	—	—	—	✓	✓	✓	✓	✗	✗
Aoi et al. [1]	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗
Deprez et al. [3]	✓	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓
Mahksous et al. [2]	✓	—	—	—	—	—	—	✓	✗	✗	✓
This work	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓

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

Quasi-Static Ultrasound Elastography

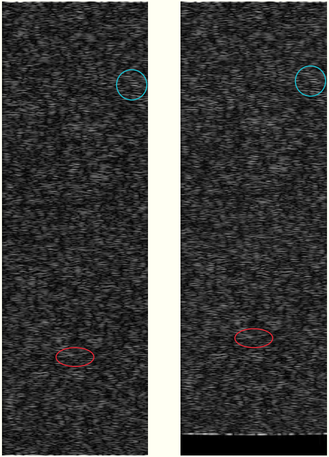
Introduction

- Earliest form of ultrasound elastography
- Apply manual pressure to tissue
  - Measure localized deformation of tissue
- Magnitude of deformation related to stiffness
  - $\downarrow$ deformation $\approx \uparrow$ stiffness $\approx \uparrow$ damage magnitude



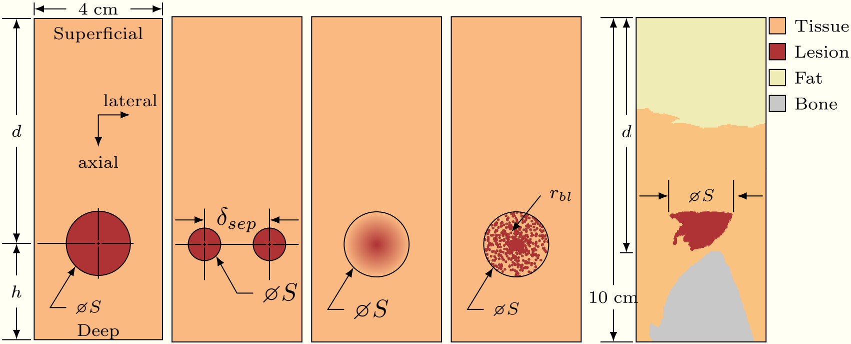
Tracking Localized Deformation

- “Noise” isn’t actually noise
  - Scattering centres anchored in tissue
- Track motion of scattering centres between pre/post compression
  - Under assumptions of motion (Brusseau et al. [5])

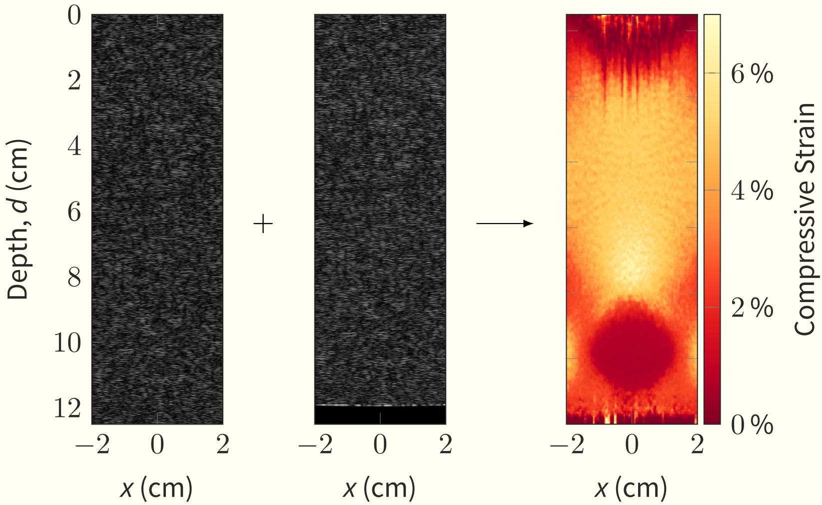


Pre- and Post- Compression B-Mode Images of DTI

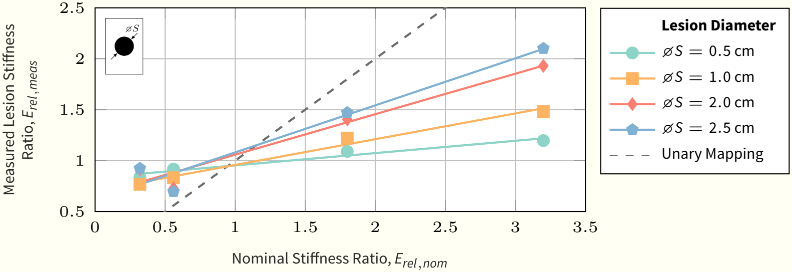
Investigated Models

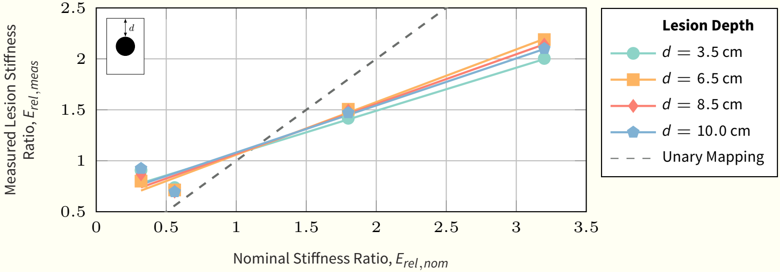


Sample Resultant Elastogram



Sample Quasi-Static Results





Quasi-Static USE Outcomes

- QS USE is capable of DTI detection
- Detection sensitivity less than desirable
- Manual palpation is not ideal
  - Suggest ARFI imaging for machine-induced tissue deformation instead
- Small lesions almost undetectable
- Use $\leq 5\,\%$ applied strain
- Depth, interrogation frequency don't affect detection ability

Acoustic Radiation Force Impulse Imaging

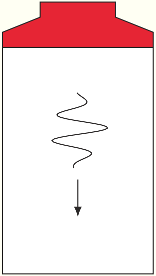
Introduction

- QS USE has low detection sensitivity, manual palpation is difficult and unreliable
- ARFI imaging works on the same principles as QS USE
  - But uses transducer-generated force to displace tissue
- $\uparrow$ repeatability, $\uparrow$ inter-operator reliability
- By imparting acoustic energy to the tissue, body force is generated:

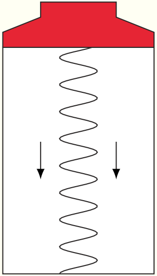
$$\left|\vec{F}\right| = \frac{2\alpha I}{c}$$

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

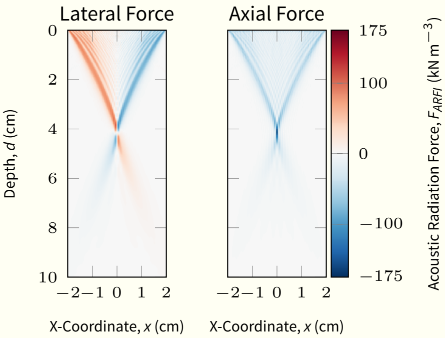
Simulating ARFI Loads

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

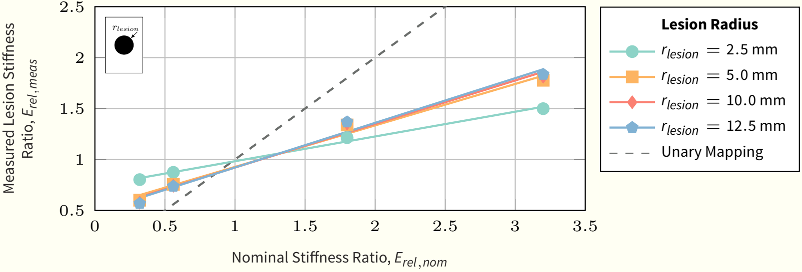
$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0}\nabla p$$

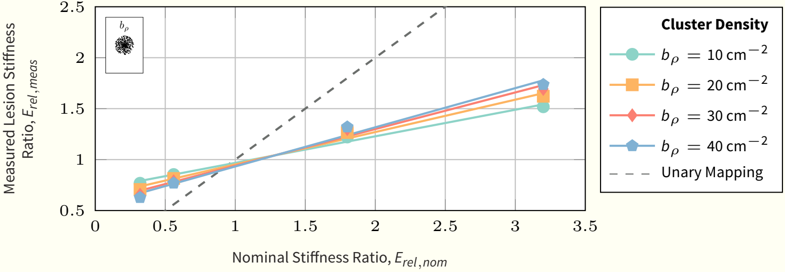
$$\frac{\partial p}{\partial t} = -\left(2\rho + \rho_0\right)\nabla \cdot \vec{v} - \vec{v} \cdot \nabla \rho_0$$

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



Sample ARFI Results





ARFI Imaging Outcomes

- ARFI more reliable than QS USE
  - Computer-controlled deformation force
- Safety implications
  - High intensity acoustic waves can damage tissue
  - Difficult to get deep penetration without damage
- No effect on detection sensitivity of lesion size for radii $\geq$ 2.5 mm
- Lesion depth only a factor in generating radiation force
  - Soft tissue absorption makes deep penetration difficult
- Better at interrogating complicated geometry than QS USE

Shear Wave Speed Quantification

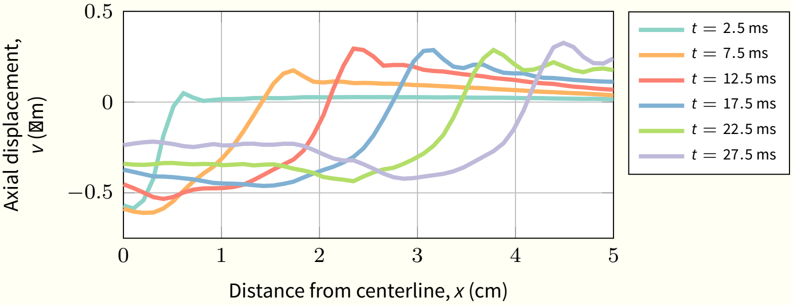
Introduction

- QS USE and ARFI only provide qualitative measures of stiffness
- Measuring shear wave speed allows quantifiable calculation of stiffness
  - Can be used to accurately track over time and give absolute references
- Uses ARFI pulses to generate shear waves in tissue
  - Measure shear wave speed $\rightarrow$ calculate stiffness:

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

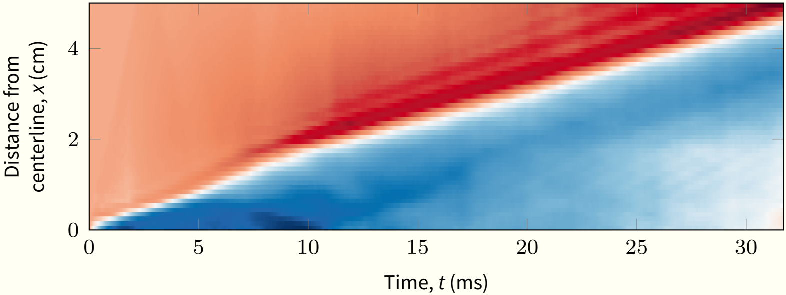
Measuring Shear Wave Speed

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



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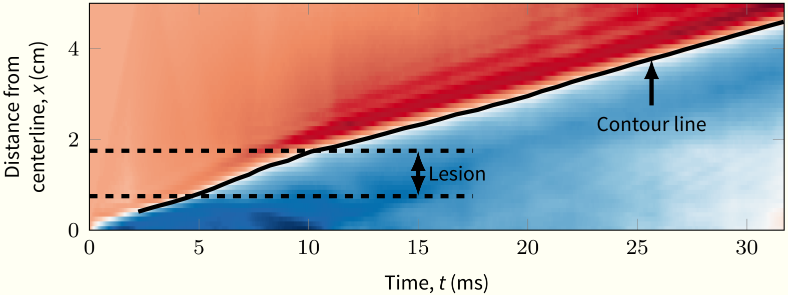
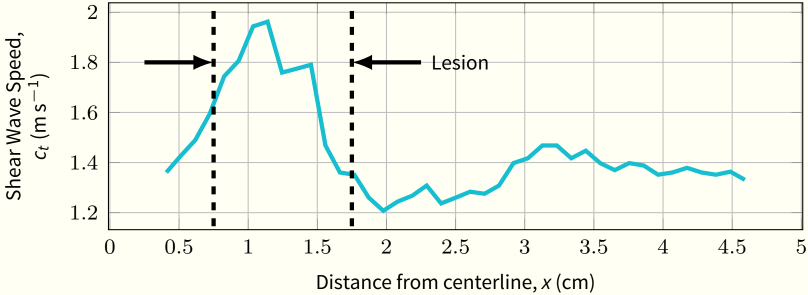
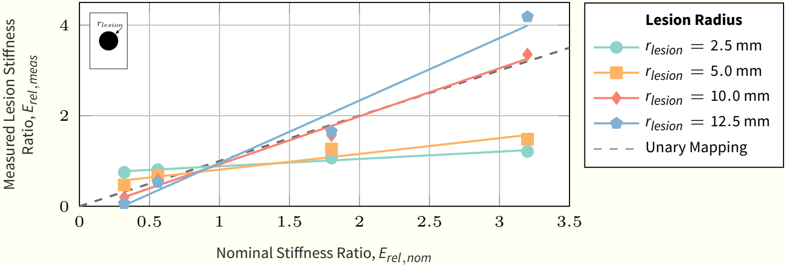


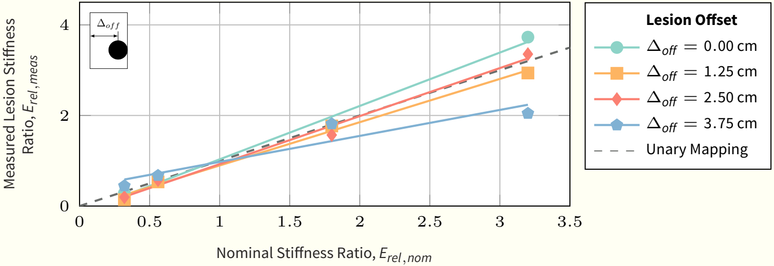
Measuring Shear Wave Speed

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





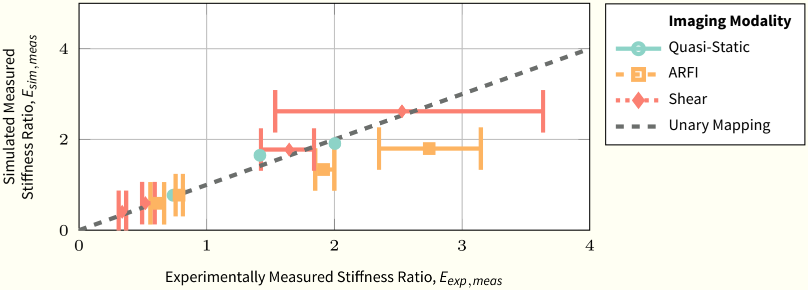
Shear Wave Speed Outcomes

- More accurate than ARFI and QS USE
- Quantifiable
  - Can monitor injury over time
- Localized interrogation instead of full domain imaging
- Necessary to locate ARFI focal point 1.25 cm – 2.50 cm away from the region of interest
- Lesions with radii $\lesssim$ 5 mm difficult to detect
- Depths $\lesssim$ 8 cm
- Not strongly dependent on complicated geometry

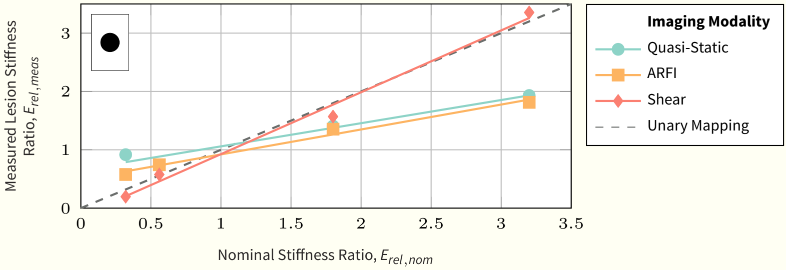
Conclusions

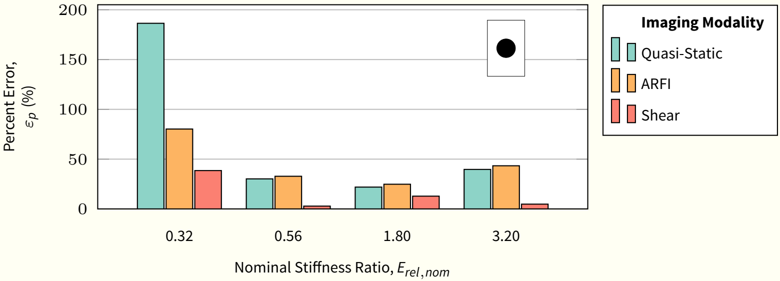
Experimental Validations

- 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





Recommendations

- Shear wave speed quantification yields best results
  - Quantifiable
  - Most accurate
- ARFI and shear wave speed quantification are depth-limited (tissue safety)
  - Quasi-static elastography for deep ($\gtrsim 5$ cm) regions
- Small lesions ($r \lesssim 5$ mm) are difficult to detect
- Complicated geometries can affect results
- Future work should involve animal and human studies
  - This is the first stage in employing ultrasound elastography as a clinical deep tissue injury detection mechanism

Thank-You

Thank-you to my supervisors, Dr. Walied Moussa and Dr. Martin Ferguson-Pell for their guidance, my labmates for support, and the Project SMART team for funding and support.

Project
SMART
Sensory Motor Adaptive Rehabilitation Technology

Additional Slides

- References
- Experimental Setup
- Derivation of ARFI
- Quasi-Static Parameters
- ARFI Parameters
- Shear Parameters
- Phantom Properties

References

[1] N. Aoi, K. Yoshimura, T. Kadono, G. Nakagami, S. Iizuka, T. Higashino, J. Araki, I. Koshima, and H. Sanada, "Ultrasound assessment of deep tissue injury in pressure ulcers: possible prediction of pressure ulcer progression." *Plastic and reconstructive surgery*, vol. 124, no. 2, pp. 540–550, Aug. 2009. [Online]. Available: http://dx.doi.org/10.1097/prs.0b013e3181addb33

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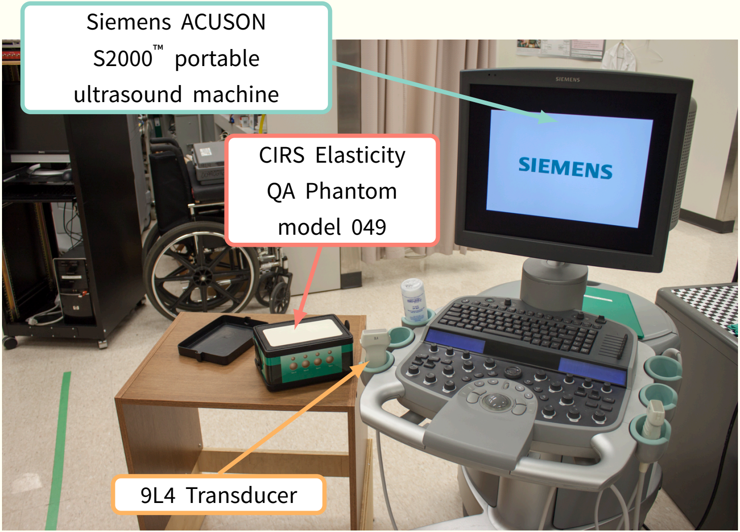
[5] E. Brusseau, J. Kybic, J.-F. F. Deprez, and O. Basset, "2-D locally regularized tissue strain estimation from radio-frequency ultrasound images: theoretical developments and results on experimental data." *IEEE transactions on medical imaging*, vol. 27, no. 2, pp. 145–160, Feb. 2008. [Online]. Available: http://dx.doi.org/10.1109/tmi.2007.897408

Experimental Setup



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

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

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	$\mathrm{kg}\,\mathrm{m}^{-3}$

ARFI Parameters

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

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

ARFI 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

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

Property	Symbol	Value	Units
Nominal basal elastic modulus	E_{tissue}	25	kPa
Lesion elastic modulus	E_{lesion}	8, 14, 45 and 80	kPa
Speed of sound	c_0	1540	$\mathrm{m\,s^{-1}}$
Acoustic attenuation	α	0.5	$\mathrm{dB\,cm^{-1}\,MHz^{-1}}$
Lesion diameter	$\varnothing S$	10 and 20	mm
Lesion depth	d	15 and 35	mm