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Acoustic radiation force creep and shear wave dispersion method for elasticity imaging

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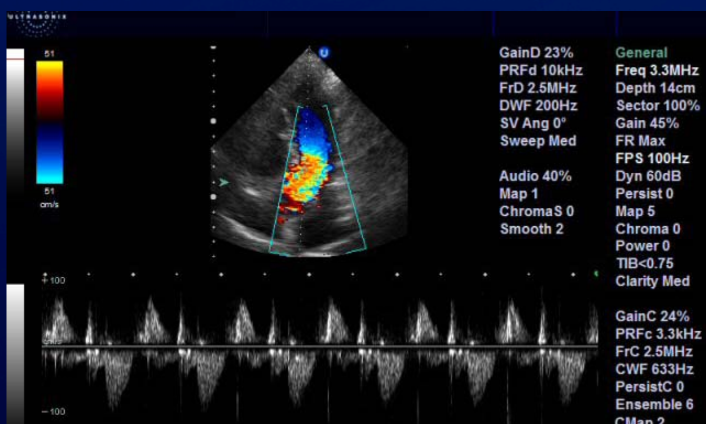
Mayo Clinic Ultrasound Laboratory Overview

- Research Areas
  - Shearwave Dispersion Ultrasound Vibrometry (SDUV)
  - Vibro-acoustography
  - Ultrasound imaging
- Mayo Clinic
  - Rich history of clinical collaboration
  - Diverse patient population for translation of research techniques.

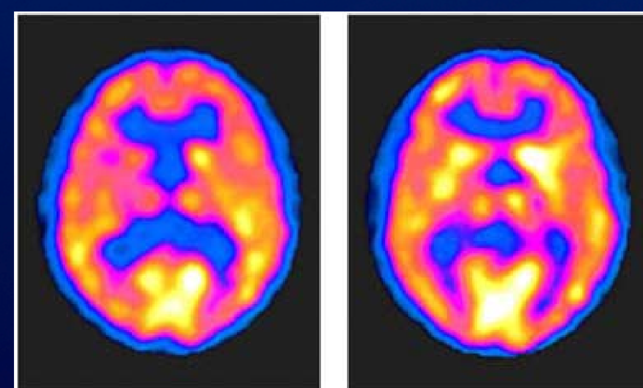
Medical Imaging Modalities

X-ray Computed Tomography
Contrast: Mass density

Magnetic Resonance Imaging
Contrast: Proton Density,
Relaxation Times

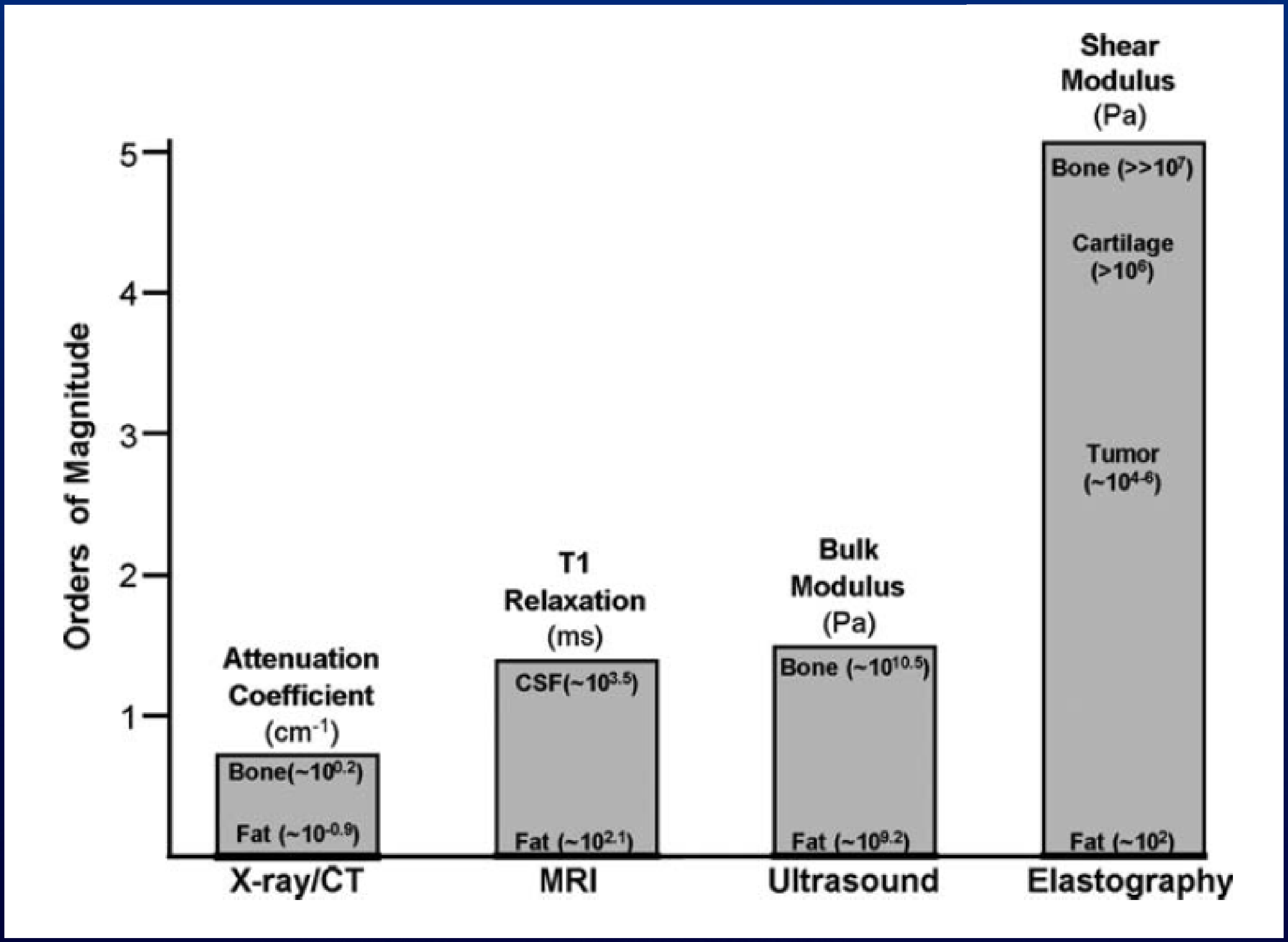


Ultrasound Imaging
Contrast: Bulk Modulus



PET/SPECT
Contrast: Radioactive Decay

Medical Imaging Modalities



Y. K. Mariappan, K. J. Glaser, and R. L. Ehman, "Magnetic Resonance Elastography: A Review," *Clinical Anatomy,* vol. 23, pp. 497-511, Jul 2010.

Palpation and its Role in Medicine

- Palpation is fundamental to the practice of medicine.
- The premise of palpation is that diseased tissue "feels" different than normal surrounding tissue, typically the diseased tissue is stiffer.
- Studies have shown a positive correlation between pathology and stiffer tissue in the breast, prostate, liver, and arteries.

Palpation and Elasticity Imaging

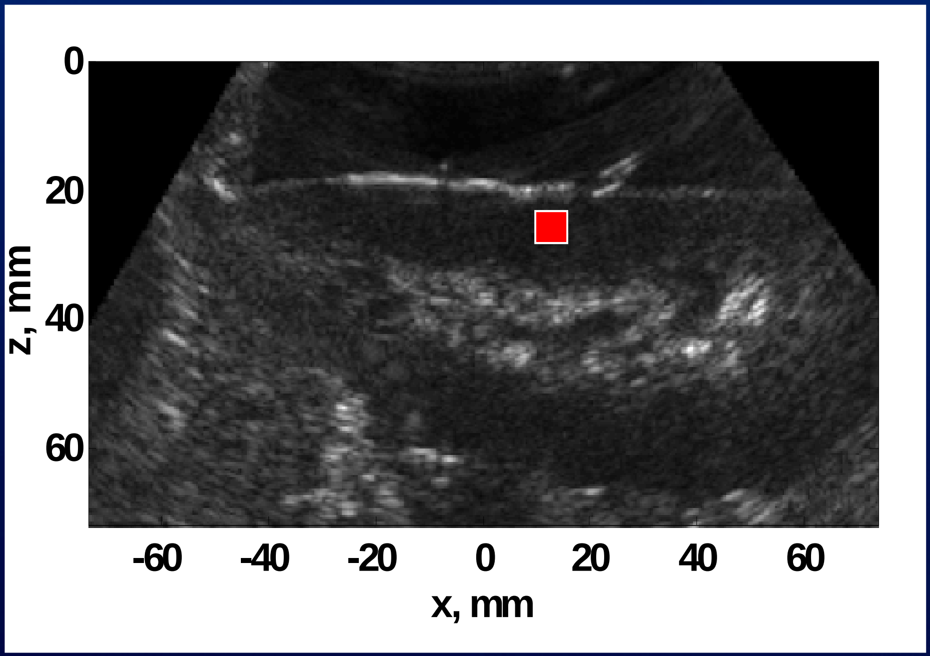
- There are some limitations of palpation:
  - Subjective
  - Dependent on proficiency of examiner
  - Non-reproducible
  - Not sensitive to small or deep lesions
- The goal of any elasticity imaging modality therefore is to produce images that are:
  - Quantitative
  - Reproducible
  - High resolution
  - Noninvasive

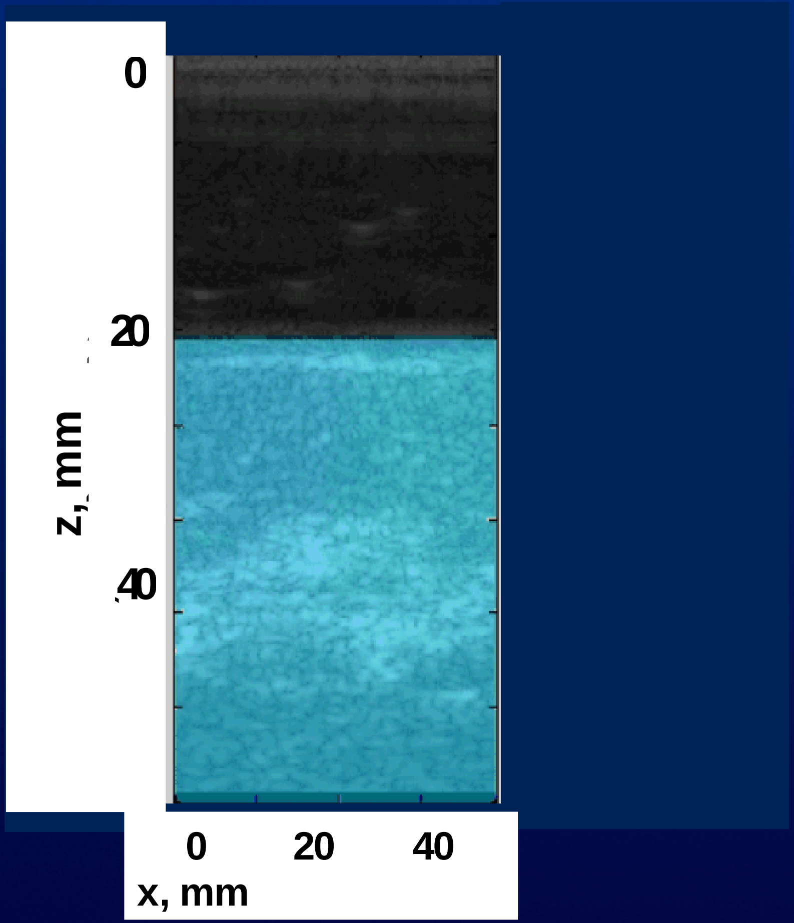
Shear wave elasticity imaging

- Introduce shear wave to tissue (external mechanical actuator, ultrasound radiation force)
- Measure shear wave speed with conventional imaging methods (MRI, Ultrasound)
- Shear wave speed depends only on mechanical properties of tissue
- Mechanical properties are estimated by assuming mechanical models (elastic models, viscoelastic models)

Shear wave elasticity imaging

• Measurements are local (usually 5 – 10 mm^2 regions of interest)

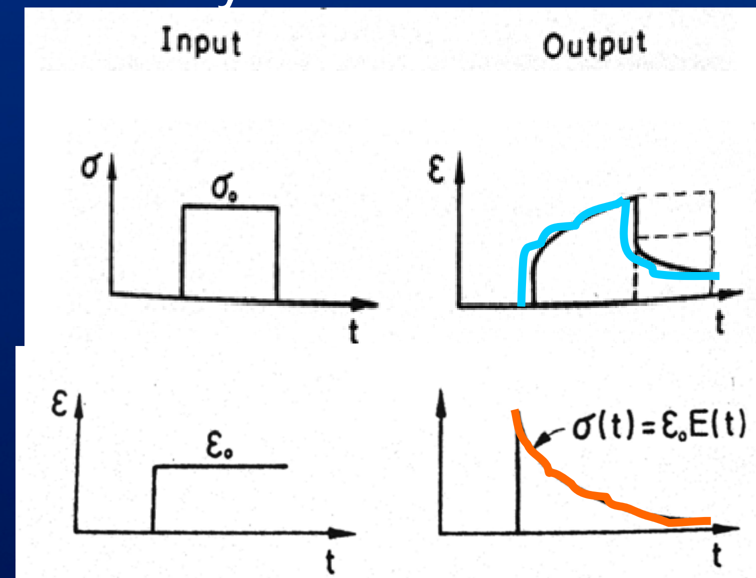




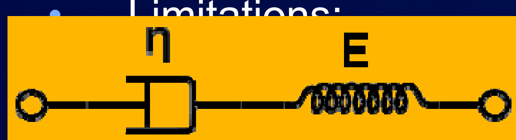
B-scan image of the kidney with Verasonics ultrasound system equipped with linear curved array transducer.

General background

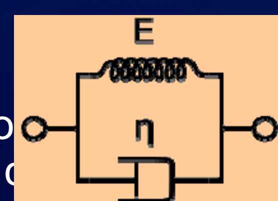
- Viscoelastic behavior is usually studied by:
  1. Static tests
     - Creep test
       - Strain under step - stress
     - Stress relaxation test
       - Stress under step – strain



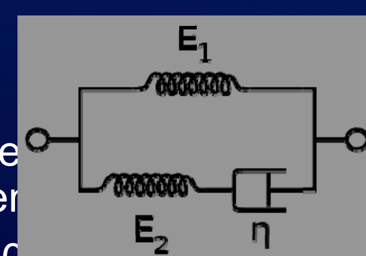
- To quantify the viscoelastic properties, a model is usually fit to the data
  - Limitations:
    - ese mo ally for ste
    - tically c experimen
    - Usually, the first reliable time-point is around 10 seconds
    - There are some materials where their viscoelastic behavior occurs early in time (< 10 seconds)



Maxwell



Voigt

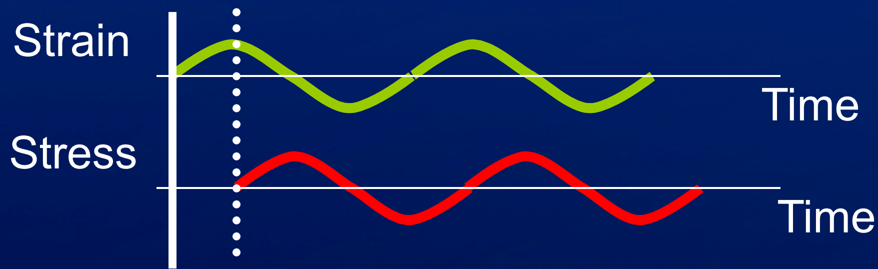


Linear Solid

General background

- Viscoelastic behavior is usually studied by:

2. Dynamic tests
   - Oscillatory stress/strain applied
   - For a sinusoidal strain in time, the stress response in also sinusoidal with a phase shift (δ)



$$\varepsilon(t) = \sin(\omega t) \approx \exp(i\omega t)$$

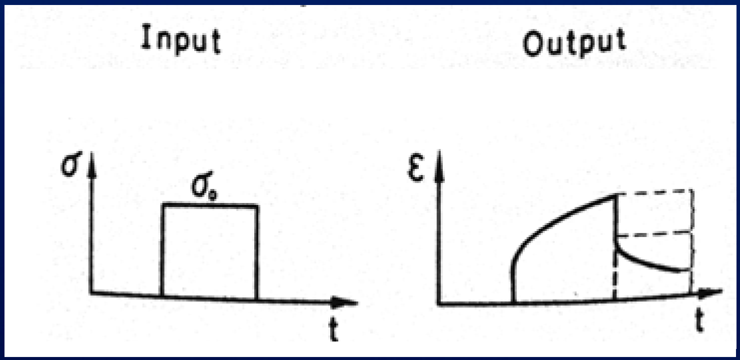
$$\sigma(t) = \sin(\omega t + \delta) \approx \exp(i(\omega t + \delta))$$

$$G^* = \frac{\sigma}{\varepsilon} = \exp(i\delta)$$

   - The dynamic modulus, G*, is a function of frequency and it is a complex variable → $G^*(\omega) = G_s(\omega) + iG_l(\omega)$
     - $G_s(\omega)$ is the elastic or storage modulus
     - $G_l(\omega)$” is the viscous or loss modulus
     - The ratio of $G_l(\omega)$ to $G_s(\omega)$ is the loss tangent or $\tan(\delta)$
   - Capable of studying viscoelastic response between 10^{-8} to 10^{3} seconds
     - Limitations:
       - Measure one frequency at a time
       - Specialized instruments and techniques

Time vs. frequency measurements

- Creep test → static test to measure viscoelastic behavior
  - Time domain
  - Study viscoelastic behavior from 10 seconds to 'days'
  - Requires a viscoelastic model (Kelvin-Voigt,Maxwell, etc..)



- Creep test will be ideal if
  - The output is converted to frequency domain (complex modulus)
  - No model is required
  - The material creep response is measured early in time

Complex modulus related to time-creep compliance

- Definition: creep compliance, J, is the ratio of strain and stress in a creep test.
- The complex modulus, $G^*(\omega)$, is related to the complex creep compliance, $J(\omega)$, by a convolution[1]

$$\varepsilon(t) = \int_0^t J(t-\xi)\frac{\partial \sigma(\xi)}{\partial \xi} d\xi$$

Fourier Transform (FT)

$$\therefore G^*(\omega) = \frac{1}{(i\omega) FT\left[J(t)\right]}$$

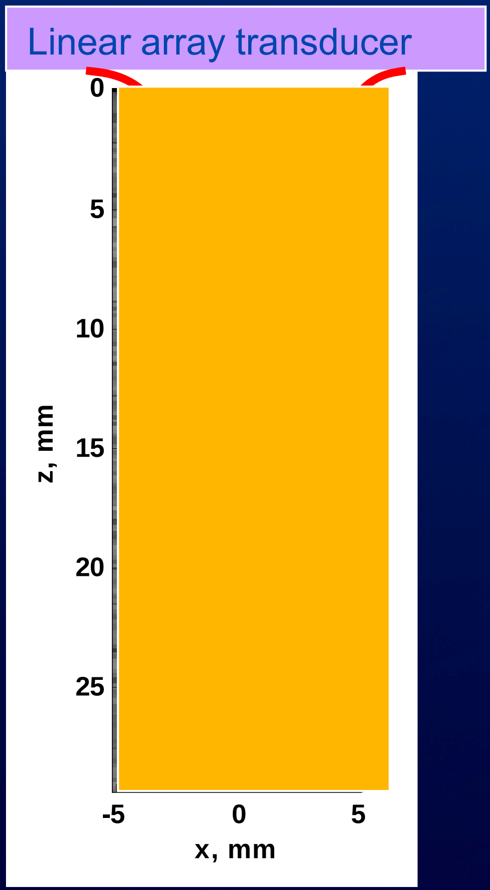
- The problem is that FT(J(t)) is not a convergent integral because J(t) grows with increasing time
  - Solution[2]:
    - J(t) grows with increasing time but its second derivate vanishes at large time
    - Complex modulus is related to the Fourier transform of the creep compliance second derivative

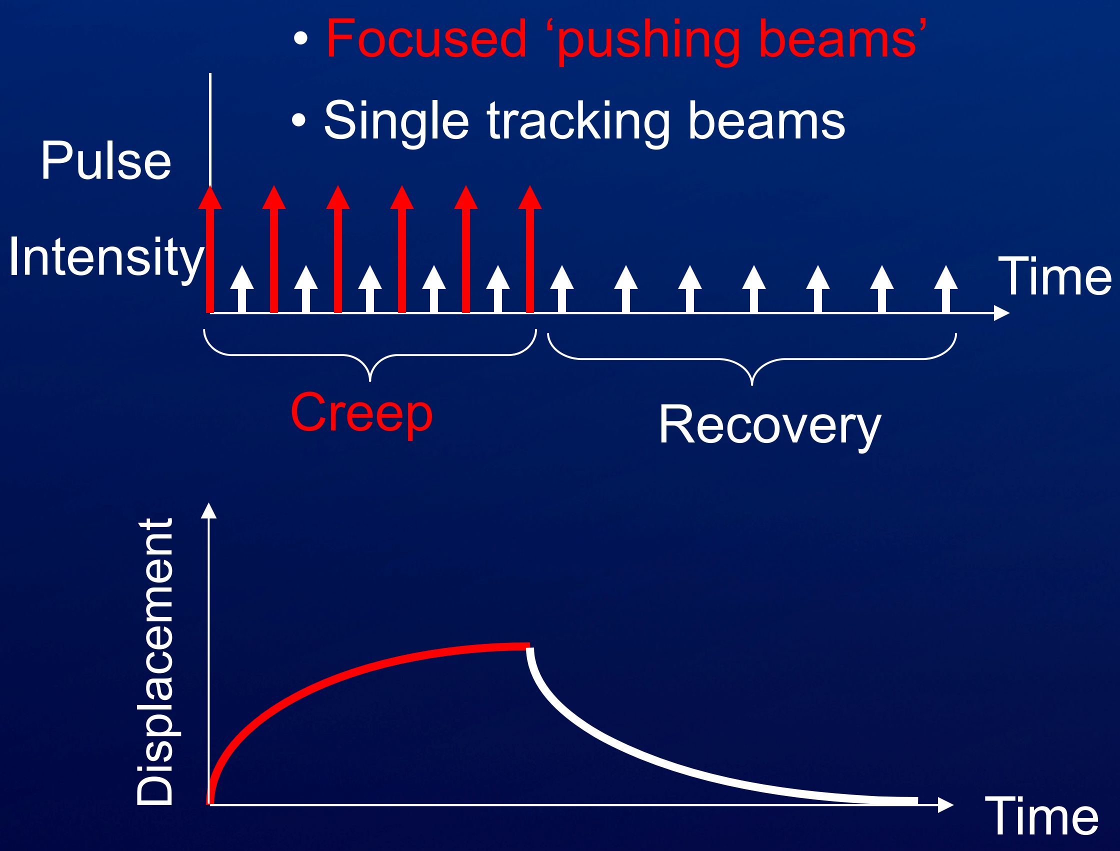
[1]Findley, 1976

[2]Evans et al. Physical Review, 2009.

Acoustic radiation force creep

- Besides shear wave excitation, acoustic radiation force has been used to study tissue steady-state response, assuming that the force is a temporal step function





F.W. Mauldin et al, 2008.

Acoustic radiation force creep

- Purpose is to use acoustic radiation force to induce tissue creep response
- Use time-creep compliance conversion formula to get complex modulus → model-free method

Creep Compliance: $J = \frac{\varepsilon}{\sigma} = \beta \cdot u(t)$

$$\therefore G^*(\omega) = \frac{1}{(i\omega) FT[J(t)]} \qquad G(\omega) = \frac{1}{\beta} \frac{1}{(i\omega) FT[u(t)]}$$

- Output from conversion formula (estimated modulus, C) is scaled by a factor β of the complex modulus, G,

$$C^*(\omega) = \beta[G_s(\omega) + iG_l(\omega)] \qquad \tan(\delta) = \frac{\beta \cdot G_l(\omega)}{\beta \cdot G_s(\omega)}$$

Calibrate complex modulus with SDUV

- The wavenumber *k* and the shear modulus *G* are simply linked through the shear wave propagation equation

$$G = \rho \frac{\omega^2}{k^2}$$

ρ = density

ω = frequency

- In the case of linear viscoelastic medium, the shear modulus is complex, $G = G_s + iG_l$, and the wavenumber is complex, $k = k_r + ik_i$, then:

$$G_s(\omega) = \rho\omega^2 \frac{k_r^2 - k_i^2}{\left(k_r^2 + k_i^2\right)^2}$$

$$G_l(\omega) = -2\rho\omega^2 \frac{k_r k_i}{\left(k_r^2 + k_i^2\right)^2}$$

c_s=shear wave speed

$k_r = \omega / c_s$

α = shear wave attenuation

$k_i = \alpha$

Vappou, J., C. Maleke, et al. (2009). "Quantitative viscoelastic parameters measured by harmonic motion imaging."
Physics in Medicine and Biology **54**(11): 3579-3594.

RFCreep and shearwave relation

- From radiation force creep, we can get the loss tangent or the ratio between G_l and G_s
- From shear wave dispersion, we can get the real wave number, k_r ($k_r = \omega/c_s$).
- Then, if we know $\tan(\delta)$ and k_r, we can estimate k_i (shear wave attenuation α)

$$\frac{G_s(\omega)}{G_l(\omega)} = \frac{k_r^2 - k_i^2}{2k_r k_i} \qquad k_i = k_r\left(\frac{1}{\tan(\delta)} - \sqrt{1+\left(\frac{1}{\tan(\delta)}\right)^2}\right)$$

- <u>If both k_r and k_i are known, we can get the complex modulus G*</u>

Materials and Method

- Two homogeneous elasticity phantoms (custom-made by CIRS, Inc., Norfolk, VA) and one excised swine kidney were used in this study.
- A Verasonics V-1 ultrasound system (Verasonics, Redmond, WA) equipped with a L7-4 linear array transducer.
- Creep displacement is induced by acoustic radiation force to estimate tan(δ) and shear wave dispersion ultrasound vibrometry is used to calculate the model-free complex shear modulus

Materials and Method

Model-Free modulus

$$G_s(\omega) = \rho\omega^2 \frac{k_r^2 - k_i^2}{\left(k_r^2 + k_i^2\right)^2}$$

$$G_l(\omega) = -2\rho\omega^2 \frac{k_r k_i}{\left(k_r^2 + k_i^2\right)^2}$$

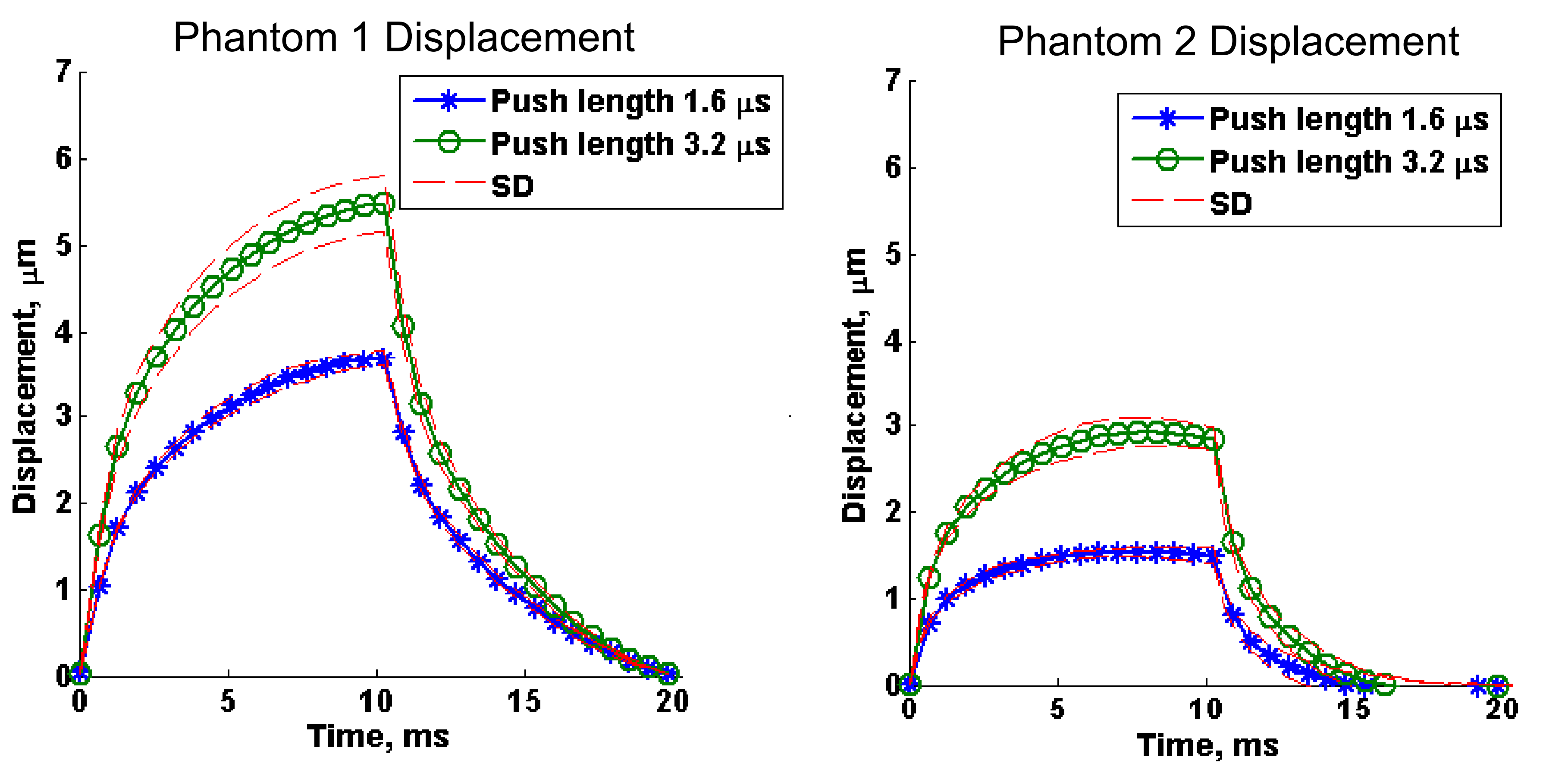
Radiation force creep

$$k_i = k_r \left(\frac{1}{\tan(\delta)} - \sqrt{1 + \left(\frac{1}{\tan(\delta)} \right)^2} \right)$$

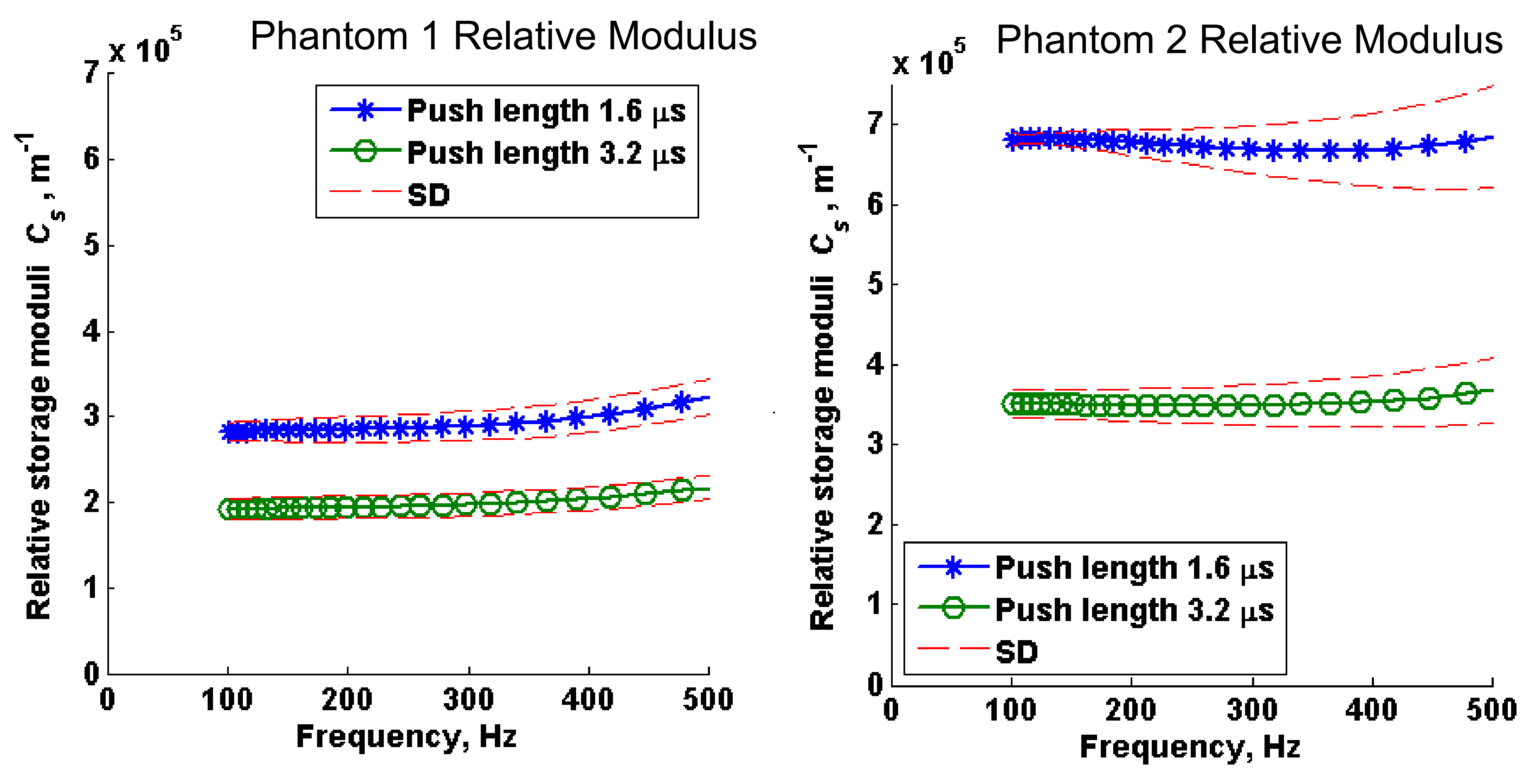
Shear wave

$k_r = \omega / c_s$

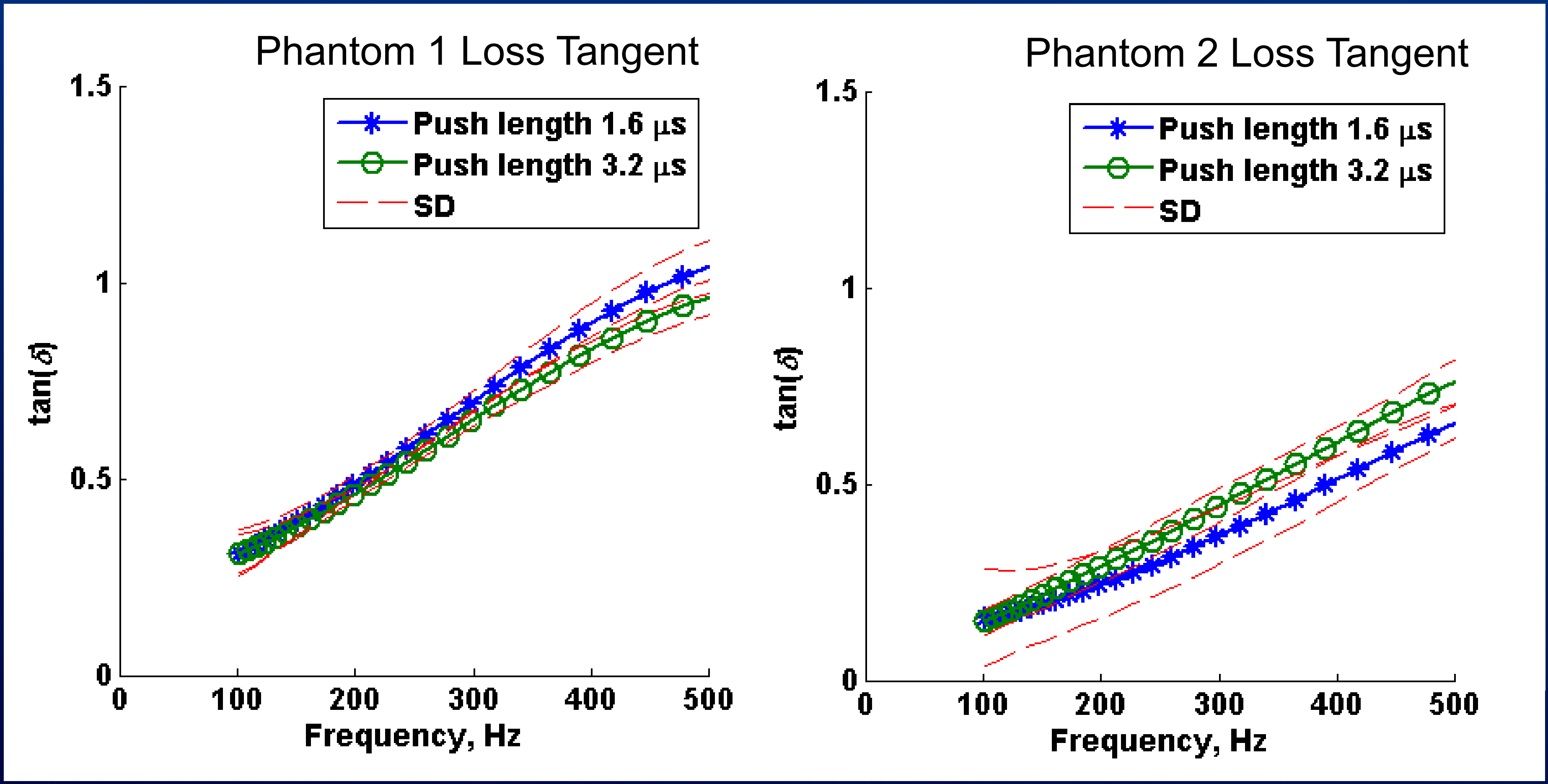
Results – Creep Displacement



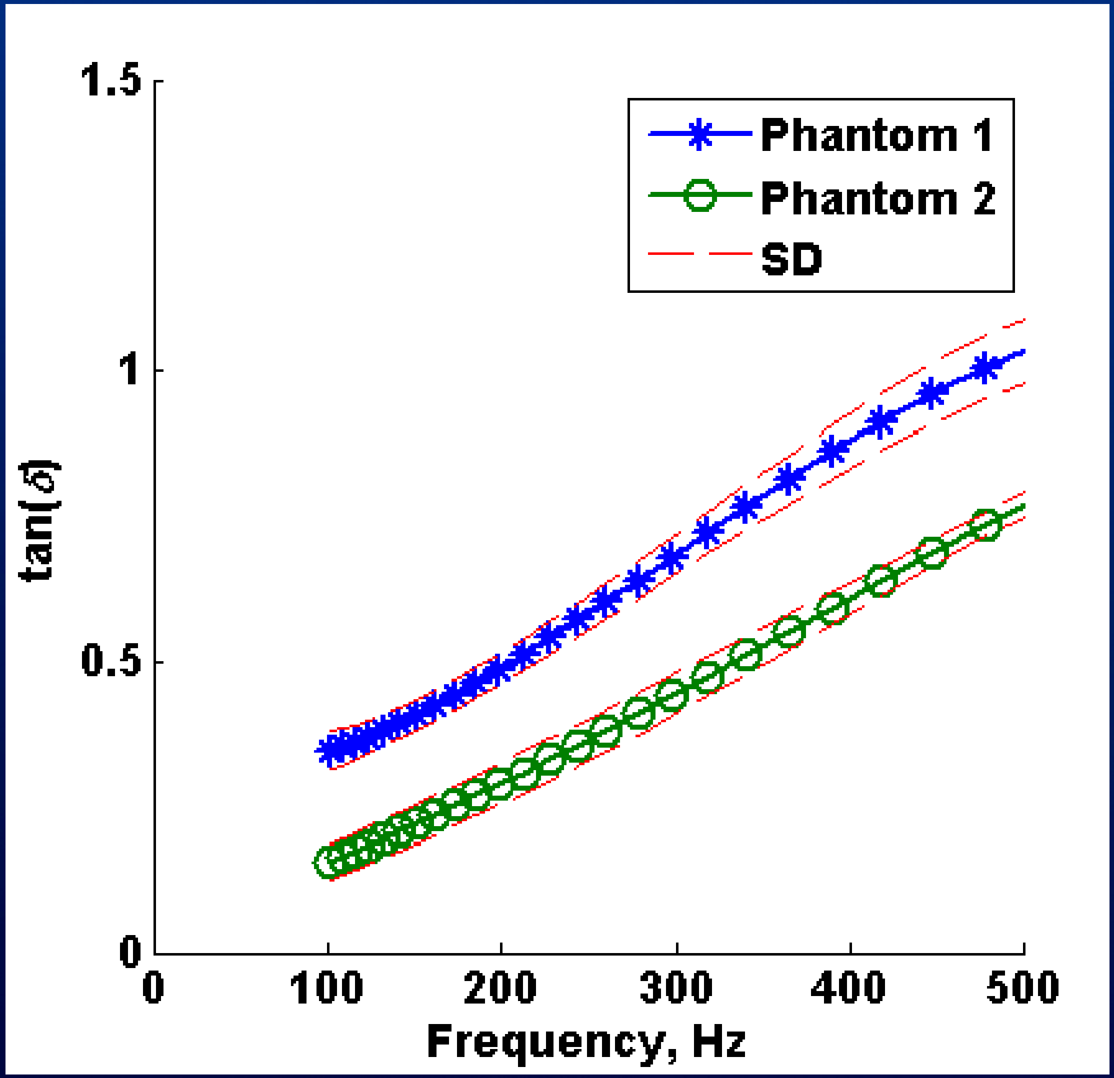
Results – Relative Modulus



Results – Loss Tangent



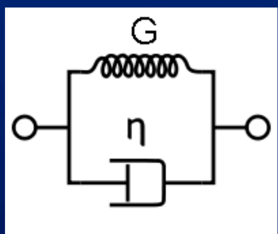
Results – Loss Tangent



Results

Phantom 1

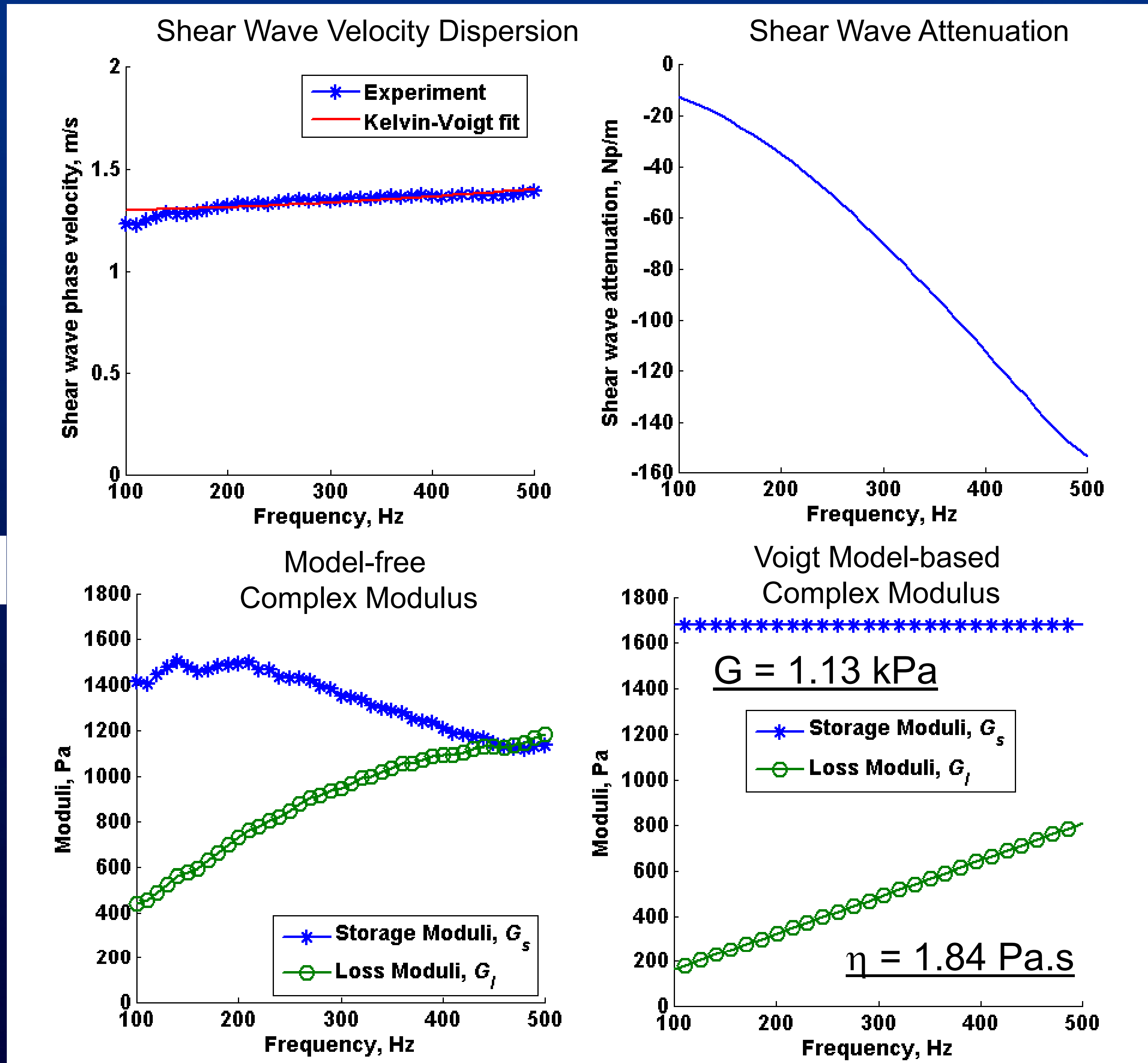
Kelvin-Voigt



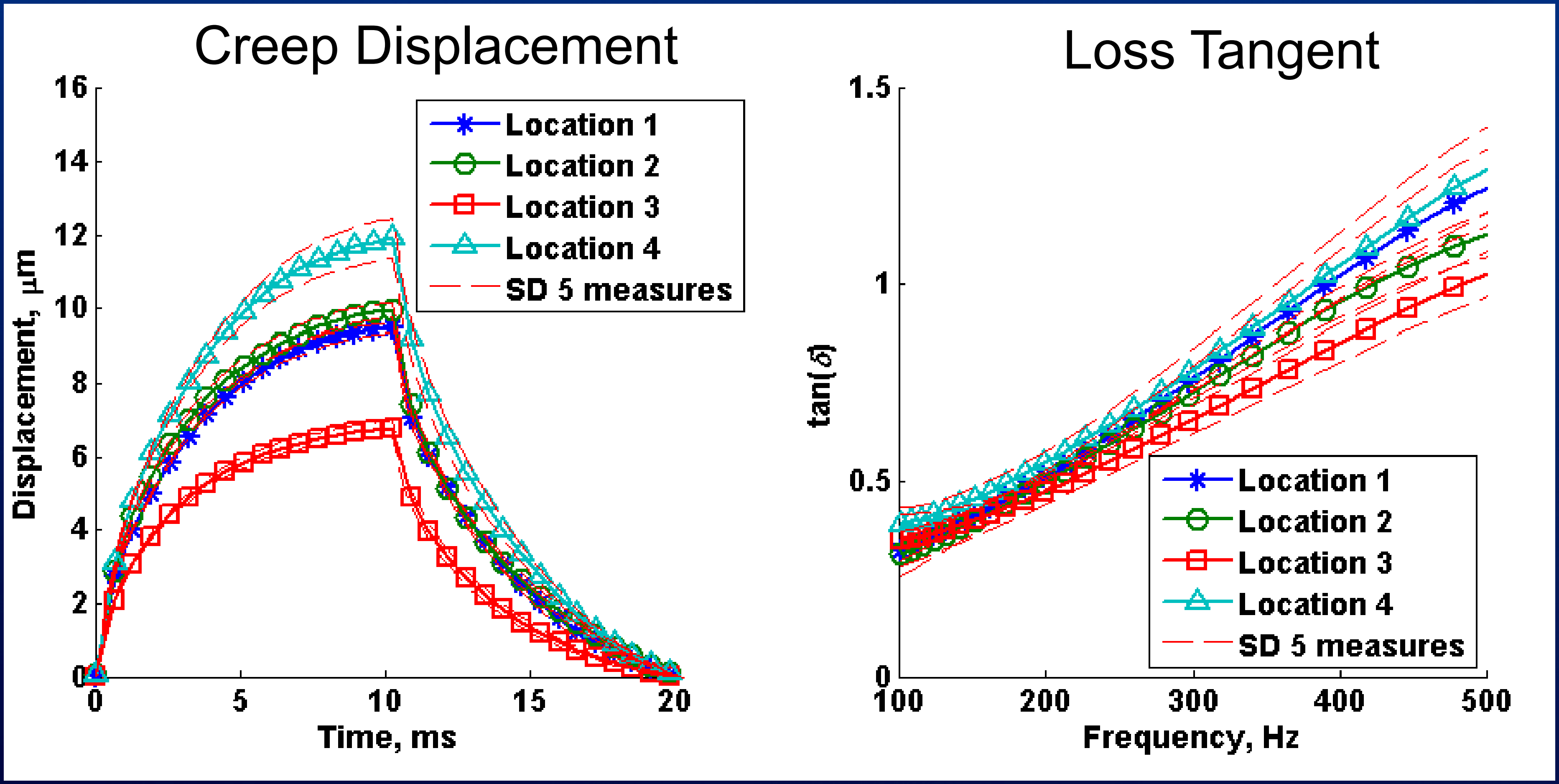
$$G^*(\omega) = G + i\omega\eta$$

G* = Complex shear modulus
G = Shear modulus

η = Viscosity

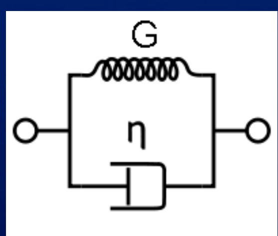


Results – Excised Kidney



Results Excised Kidney

Kelvin-Voigt



$$G^*(\omega) = G + i\omega\eta$$

G^* = Complex shear modulus
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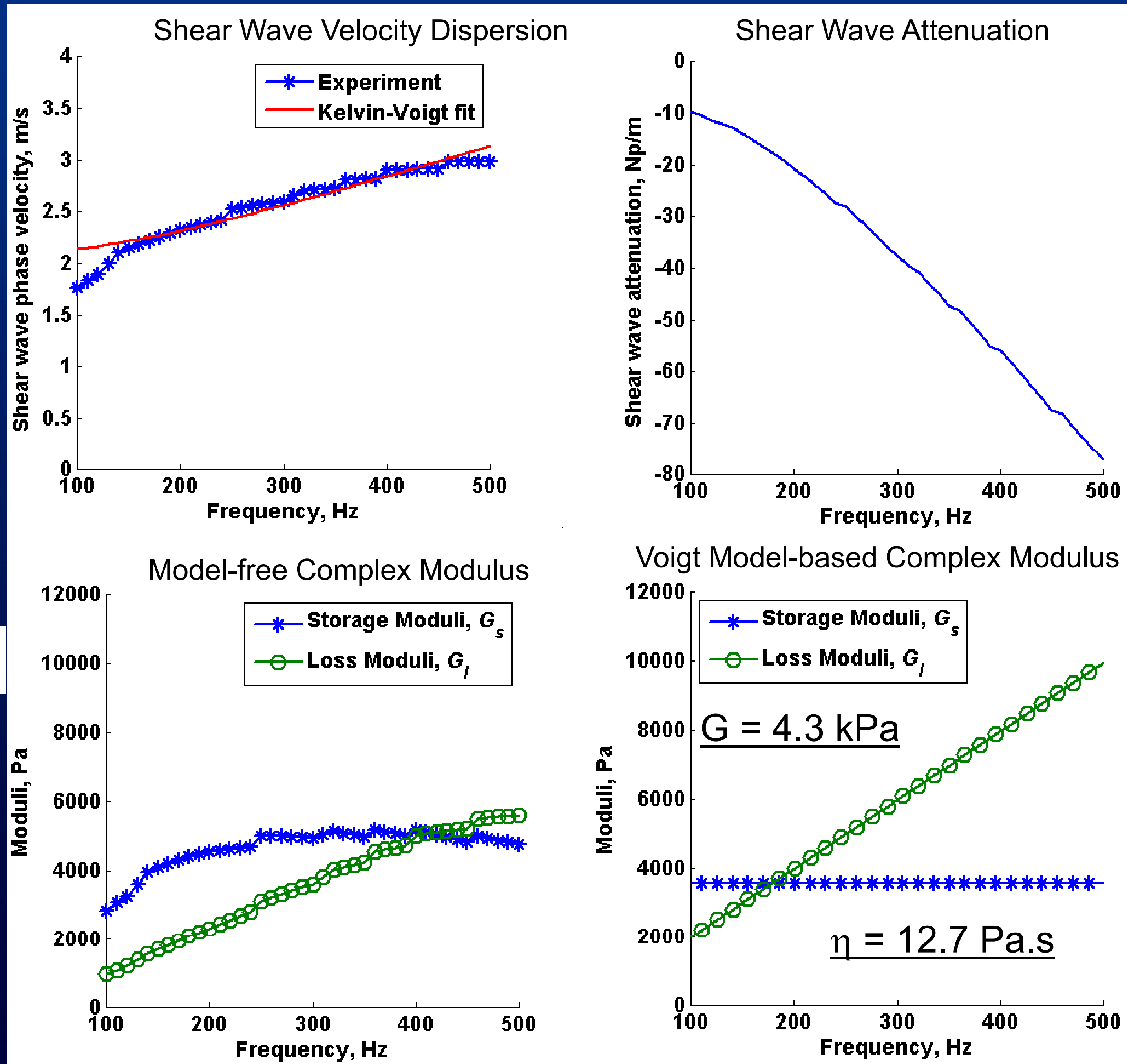

Conclusion

- Presented a model to measure viscoelastic properties by studying creep response induced by acoustic radiation force

- Advantages:
  - Model free!
  - Fast acquisition (10 ms), local measurements (3 x 1 mm^2)
  - Measurements over a wide frequency range with high resolution
    - Low frequencies could be explored if creep is maintained for longer periods
  - Robust approach to estimate complex modulus by using the analytic solution to the complex compliance vs. modulus constitutive equation
  - Push beams are compatible with Doppler pulse, therefore this method is compatible with most ultrasound scanners.

Acknowledgments

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Mayo Clinic Ultrasound Research Laboratory