Principles and Applications of Ultrasound Elastography

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Disclosures

- In-kind support from Siemens Healthineers
- Co-chair of Shear Wave Speed Biomarker Committee of the Radiological Society of North America (RSNA) Quantitative Imaging Biomarkers Alliance (QIBA)

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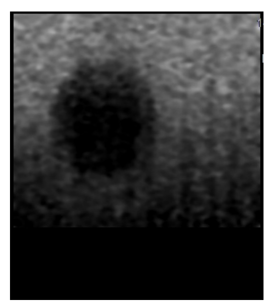
Learning Objectives

- Be able to identify the modes of ultrasound elastography currently in clinical use and describe how they work
- Understand relationship between elastic modulus and wave speed, and how ultrasound elastography differs from conventional ultrasound
- Be able to identify advantages, limitations, and potential sources of artifacts error associated with of each ultrasound elastography

- Changes in the palpable stiffness of tissue are associated with disease
  - Liver fibrosis
  - Breast, prostate carcinoma

  ...but not all tissues are accessible for palpation
- Conventional ultrasound imagery doesn't match tactile perception of tissue stiffness
- How is elastography different?

Grayscale Ultrasound



Ultrasound Elastogram

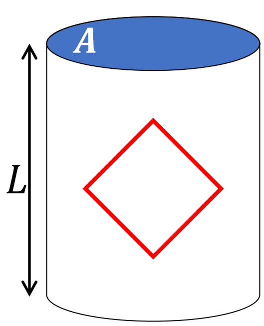
UNIVERSITY of ROCHESTER
AAPM 2022: TU-H-207-1: Ultrasound Elastography in the Clinic

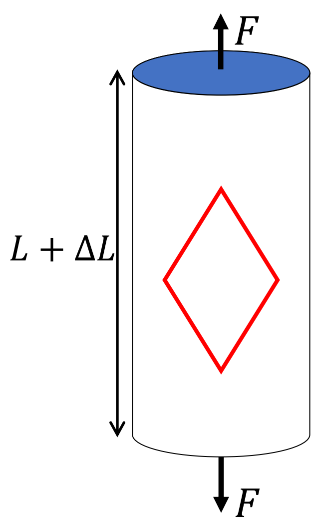
The isotropic linear elastic material model

- No preferred orientation
- No time dependence
- Deformations proportional to applied forces
- Tissue violates all these assumptions…

  but some (liver) are a better match than others (tendons)

- Completely characterized by just two parameters
- Most commonly seen in elastography literature:
  - **Young's Modulus ($\boldsymbol{E}$)** and Poisson's Ratio (ν)
  - Bulk (K) and **Shear ($\boldsymbol{G}$)** moduli
- All these values are related:
  - $G = \frac{E}{2(1+\nu)}$
  - $K = \frac{E}{3(1-2\nu)}$

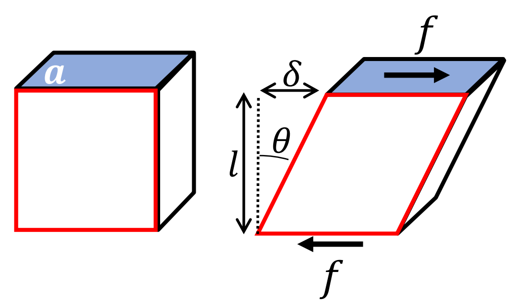




Stress: $\sigma = \frac{F}{A}$

Strain: $\epsilon = \frac{\Delta L}{L}$

Young's Modulus: $E = \frac{\sigma}{\epsilon}$



Shear stress: $\tau = \frac{f}{a}$

Shear strain: $\gamma = \tan\theta = \frac{\delta}{l}$

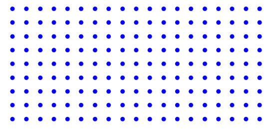
Shear Modulus: $G = \frac{\tau}{\gamma}$

For incompressible, isotropic materials $\boldsymbol{E = 3G}$

Wave speed reveals modulus

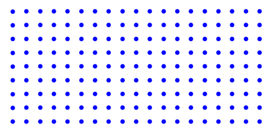
- Longitudinal waves
  - Propagation by compression, rarefaction of medium – volume change
  - **Wave speed** determined by ***bulk modulus***: $c_l = \sqrt{\frac{K}{\rho}}$
  - Fast: 1540 m/s

ultrasound imaging

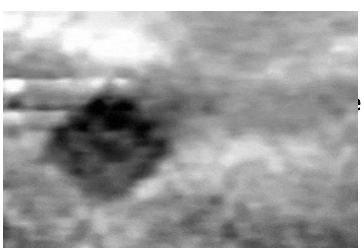


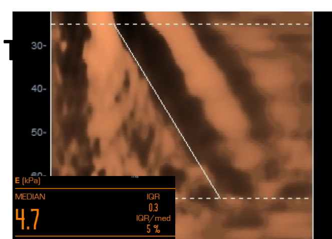
- Shear waves
  - Propagation by distortion of medium – no volume change
  - **Wave speed** determined by ***shear modulus***: $c_s = \sqrt{\frac{G}{\rho}}$
  - Slow: 0.5 – 20 m/s

elastography



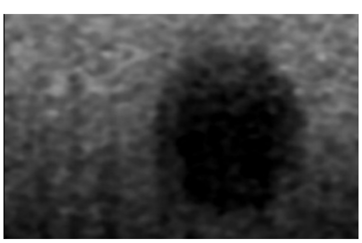
Major types of ultrasound elastography

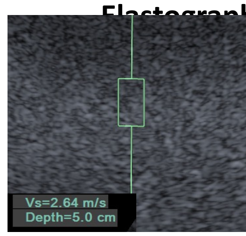


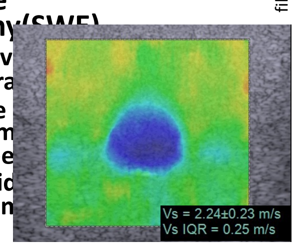


fibroscan image: gehealthcare.com

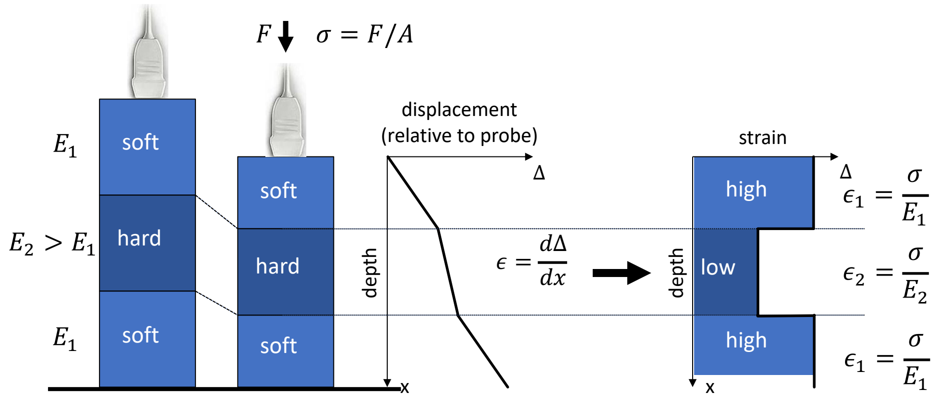
- **Shear Wave**







Strain Elastography Principle



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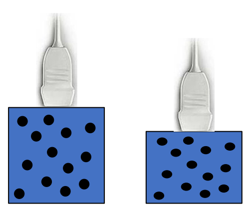
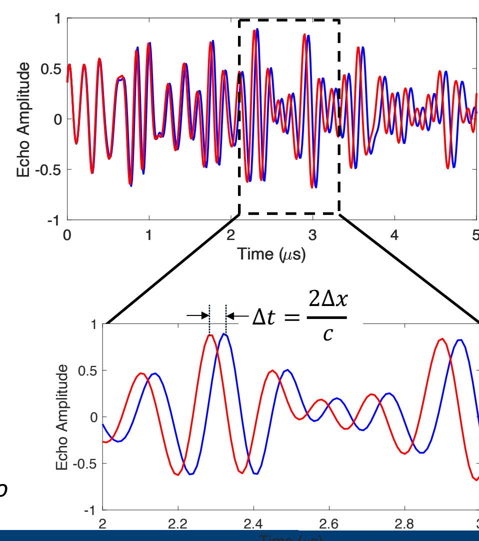
How is displacement measured?



- Scattering sites within tissue generate a random echo pattern – speckle
- Slight compression preserves the speckle pattern
- Movement of scatterers towards transducer causes echo to arrive earlier
- Normalized cross correlation and phase shift methods for calculating the time shift
- Displacements on order of **~1µm** measurable *in vivo*



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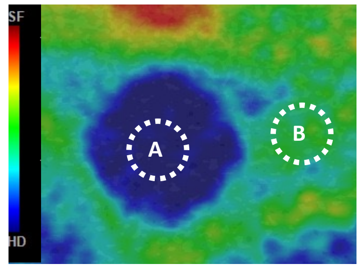
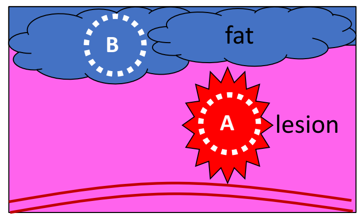
Strain Ratio

- Strain is not a material property – it varies with applied stress
- *Ratio* of strains in two materials under similar stress provides a measure of their relative stiffness

$$\text{strain ratio} = \frac{\epsilon_B}{\epsilon_A}$$

- In breast, fat is often used as the "reference" material





E/B Ratio

$$\frac{\text{Length in Elastogram}}{\text{Length in B-mode}}$$

- Malignant lesions appear larger in elastogram compared to B-mode
- Benign lesions appear smaller

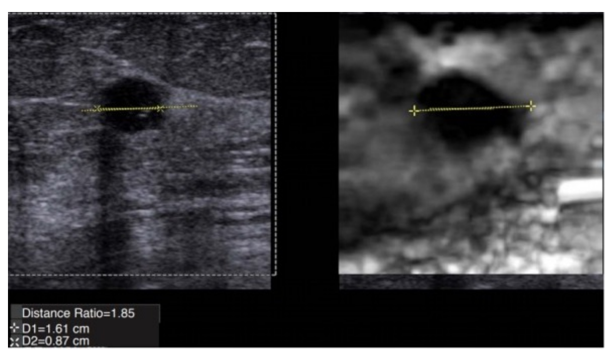
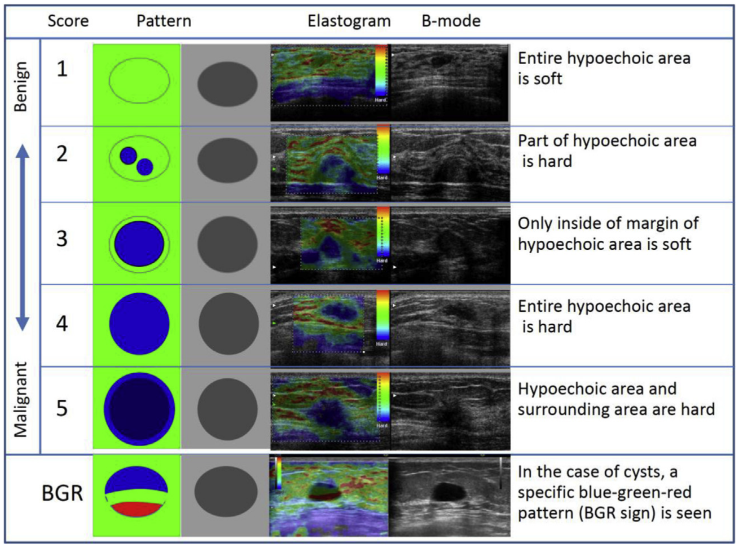


Image from Barr RG., "Future of breast elastography" in *Ultrasonography,* April 2019;38(2):93-105. PMCID: PMC6443587.

5-Point Color Scale (Itoh)



Shiina et al, Ultrasound in Med. & Biol., Vol. 41, No. 5, pp. 1126–1147, 2015: Figure 4

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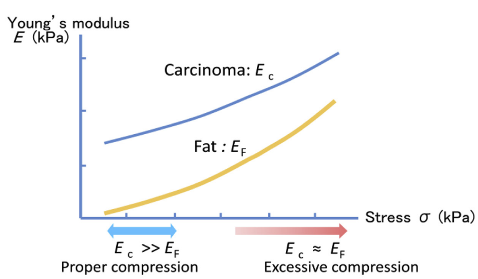
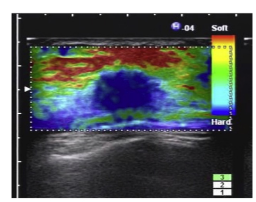
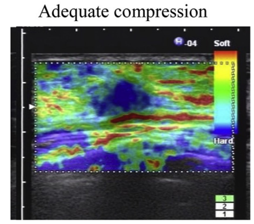
Complication: Modulus Nonlinearity



- Linear elastic model assumes moduli are independent of strain
- Tissue exhibits strain hardening – increase in modulus with strain
- Excessive compression can reduce contrast



Adequate compression



Excessive compression

Figures from Shiina et al, Ultrasound in Med. & Biol., Vol. 41, No. 5, pp. 1126–1147, 2015

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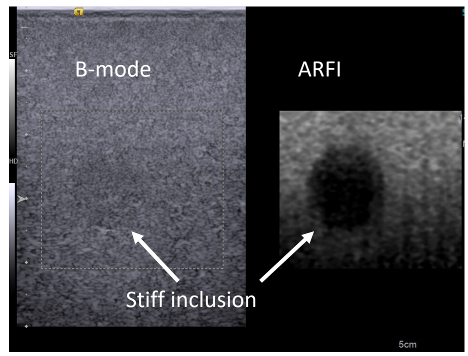
Acoustic Radiation Force Impulse (ARFI) Imaging

- Acoustic radiation force is a *body force* resulting from momentum transfer from acoustic wave to the propagating medium
- In a weakly scattering medium, the radiation force F is proportional to ultrasound intensity I:

$$F = \frac{2\alpha I}{c}$$

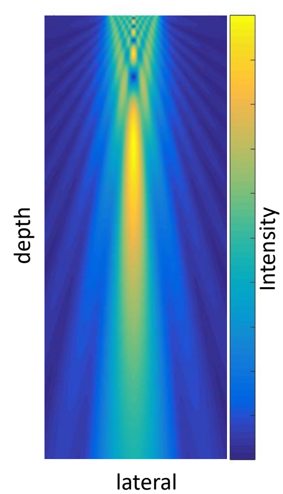
  - c (1540 m/s) is the speed of (ultras)sound
  - α is the ultrasound attenuation coefficient

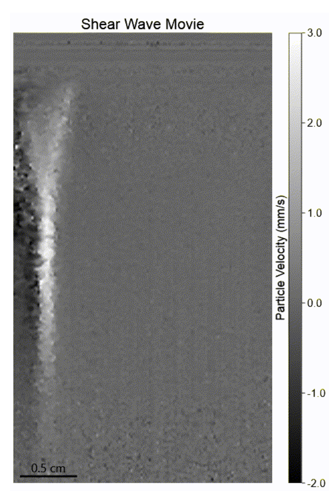
- ARFI imaging produces maps of tissue displacement following application of the acoustic radiation force impulse



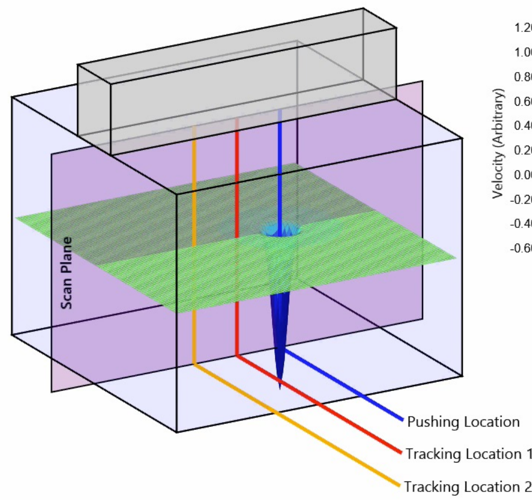
Making Shear Waves with Ultrasound

- Radiation force of focused *ultrasound* tonebursts (MHz frequency, 0.1-1ms duration) generate micrometer-amplitude *shear waves* (50-500Hz)
- Fast ultrasound imaging (1540 m/s) used to observe propagation of slow (1-10 m/s) shear waves
- Tissue motion tracked using Doppler-like methods





Shear Wave Elastography



Motion tracked and **compared at two or more a-lines:**

$$c_{\text{estimated}} = \frac{\textbf{track}\text{ beam spacing}}{\text{arrival time difference}} = \frac{\Delta T}{\tau}$$

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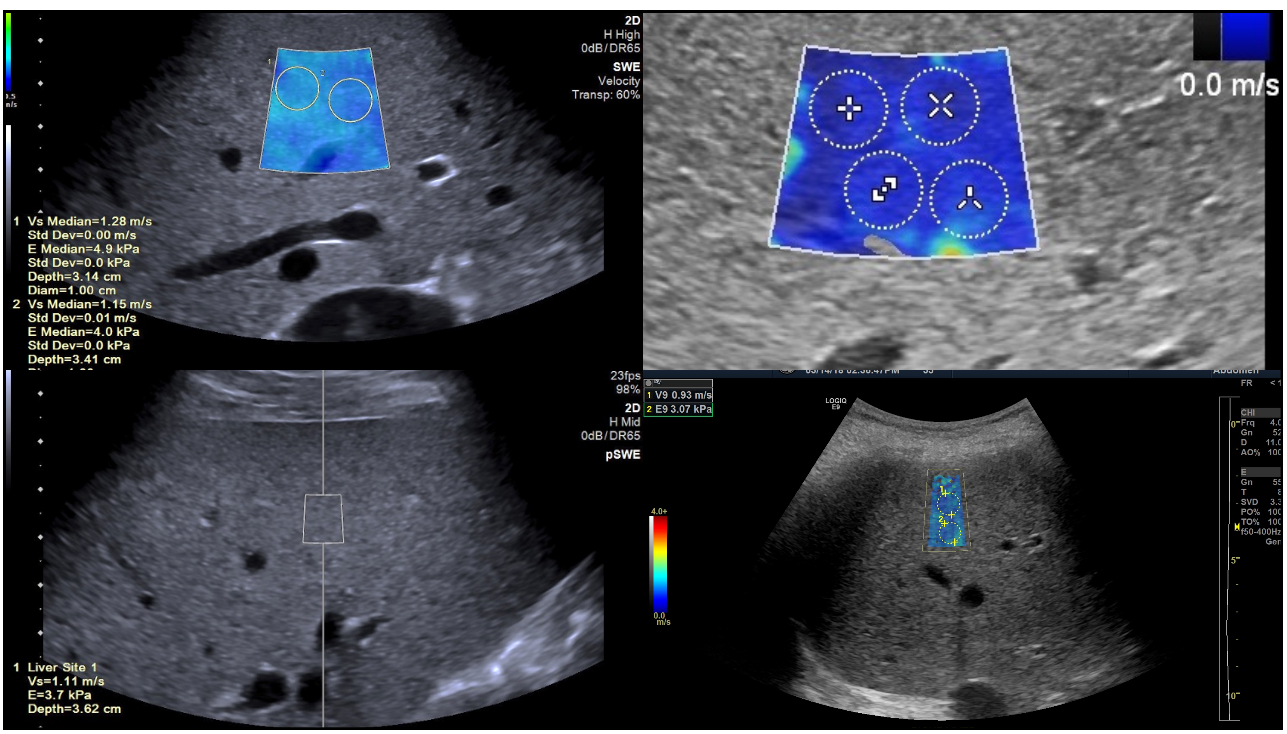

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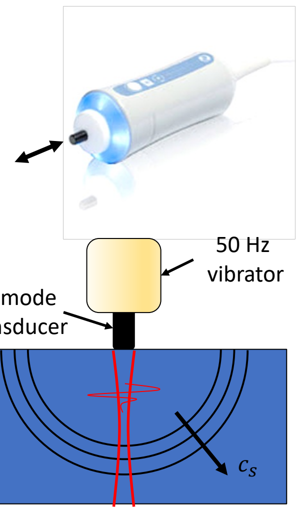
Transient Elastography

- Non-imaging, point estimate of Young's Modulus, especially for liver fibrosis
- Tissue "thumped" with single cycle 50 Hz oscillation, launching a spherical shear wave
- Fast (1540 m/s) ultrasound wave tracks motion of slow (1-20 m/s) spherical shear wave
- Wave speed converted to modulus assuming linear elastic model: $c_s = \sqrt{\frac{E}{3\rho}}$



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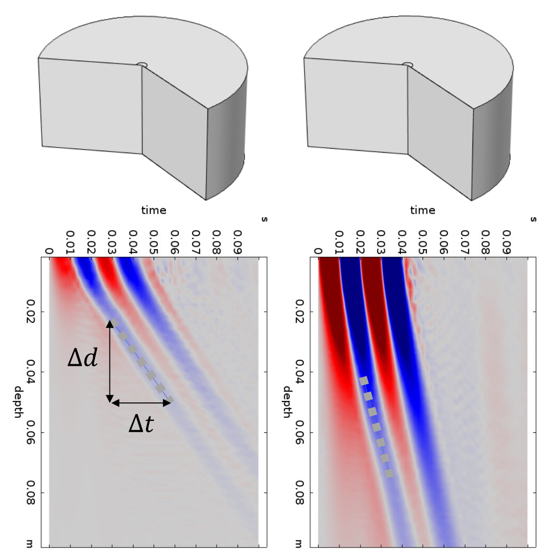
TE Quantification

E=3kPa
c_s=1 m/s

$c_s = \sqrt{\frac{E}{3\rho}}$

E=27kPa
c_s=3 m/s

- M-mode imaging tracks tissue motion following launch of shear wave
- Space-time graph depicts shear wave displacement (color) as a function of depth and time
- Slope of line is shear wave speed:
  $$\frac{\Delta\text{depth}}{\Delta\text{time}} = c_s$$
- Young's Modulus computed from c_s as $E = 3\rho c_s^2$



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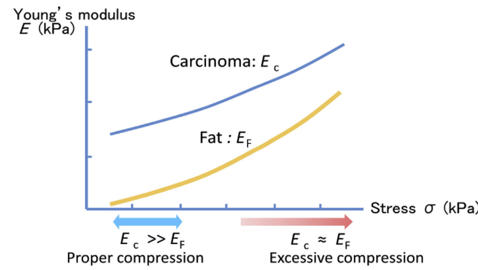
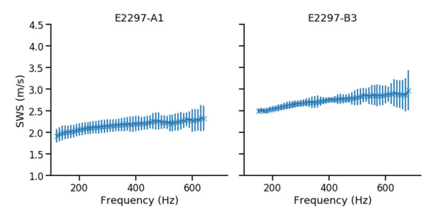
Complicating Factors in SWE

- Modulus non-linearity
  - Shear wave speed depends on applied strain
  - Pre-strains on tissue (breath hold, portal hypertension, excessive transducer pressure, inflammation) can elevate shear wave speed



(Shiina et al, Ultrasound in Med. & Biol., Vol. 41, No. 5, pp. 1126–1147, 2015)

- Viscoelasticity
  - Tissue stiffness depends on frequency at which it's vibrated
  - Estimates obtained at different shear wave frequencies may not agree



Summary

- Elastography (all forms) provides image contrast based on the tremendous biological variability in shear or Young's modulus – distinct from conventional ultrasound imaging
- Methods based on shear wave propagation (**transient and SWE**) provide quantitative measures of tissue properties
- **Strain Imaging** methods provide real-time, non-quantitative imaging
- **Acoustic radiation force** is a means of remote palpation used in **ARFI** and **SWE**