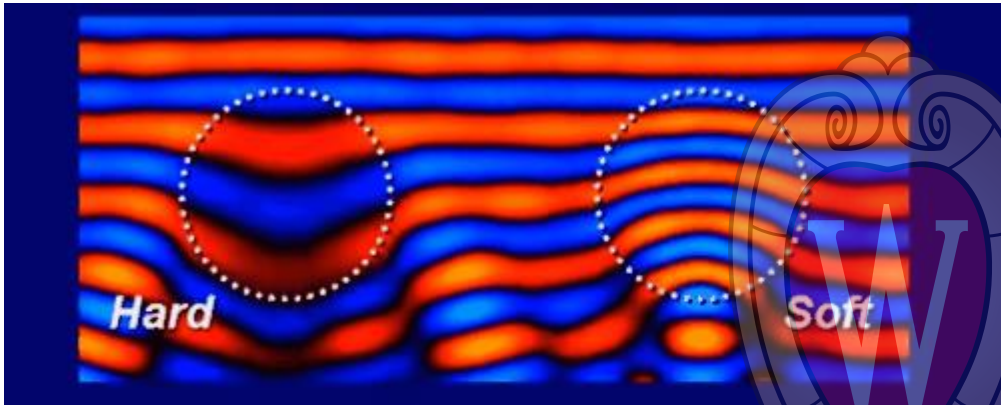
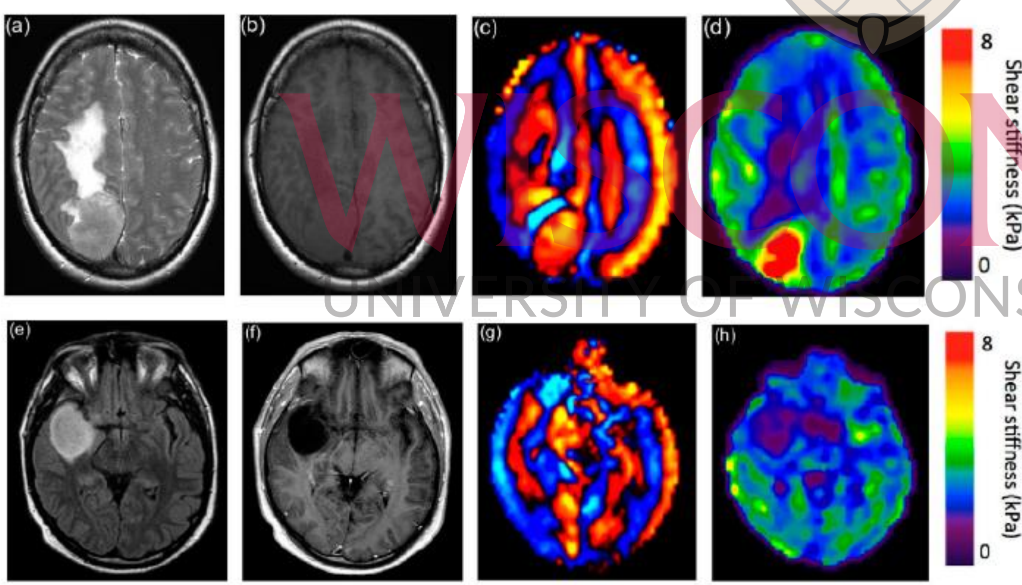
Brain MR Elastography:
Acquisition and Reconstruction Strategies



From: https://www.youtube.com/watch?v=CcmZi0J_u3Y



From: Hiscox. *Phys Med Bio* (2016)

MRI Group Talk

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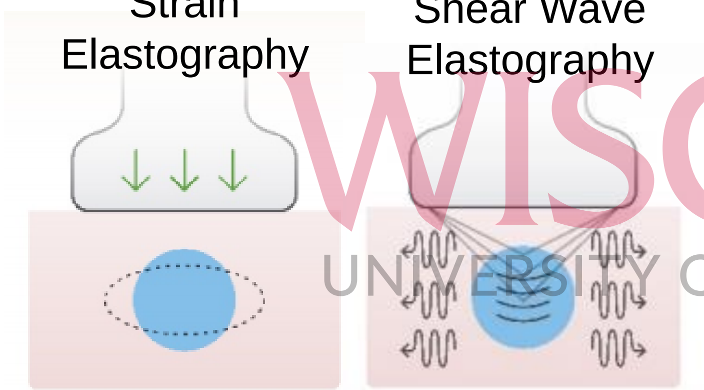
Elastography Introduction

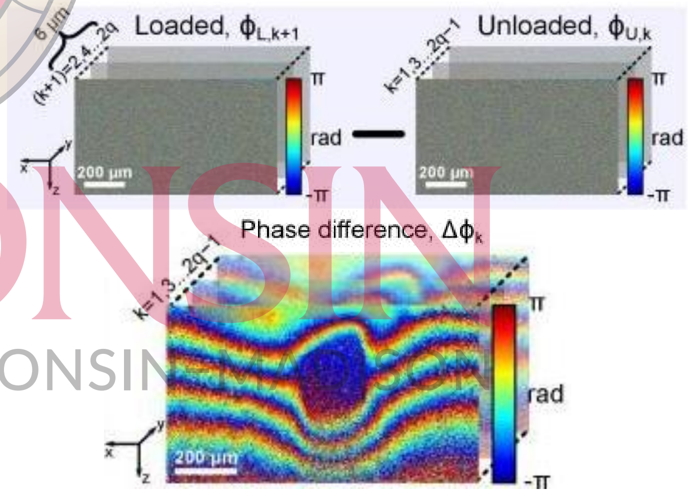
- Ingredients for elastography
  1. Mechanical excitation
  2. Measurement of tissue response
  3. Mechanical parameter estimation

Ultrasound



From: Sigrist, et al. *Theranostics*. (2017)

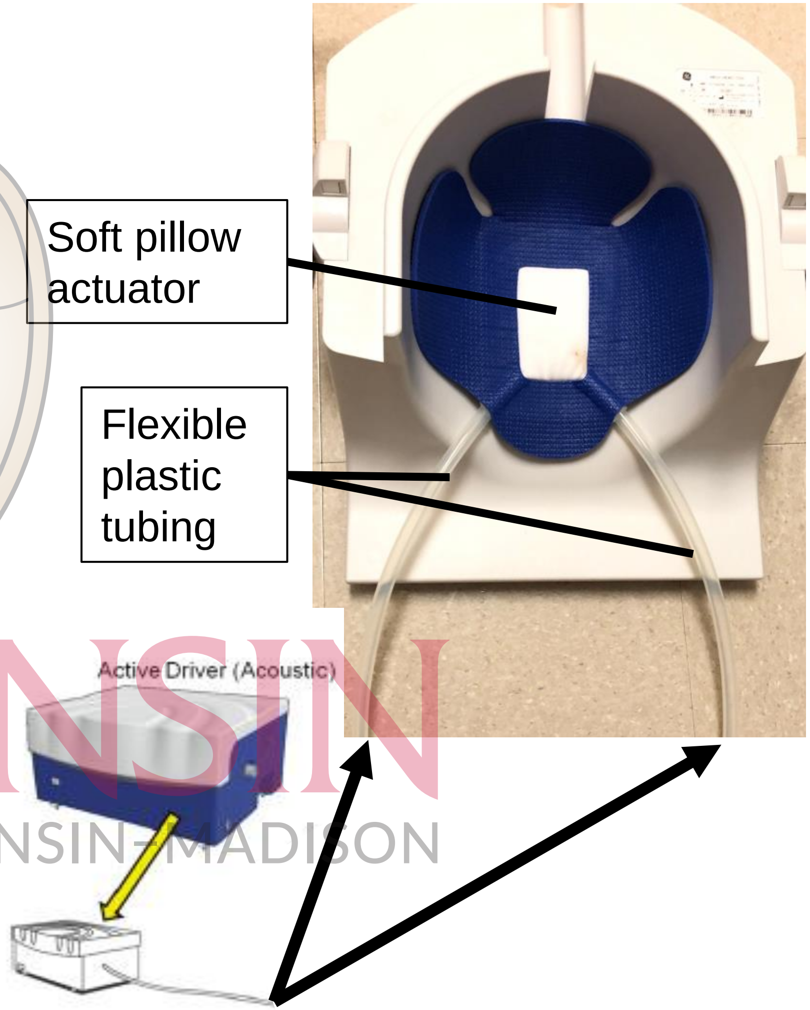
Optical Imaging



From: Kennedy, et al. *Biomed Opt Express*. (2014)

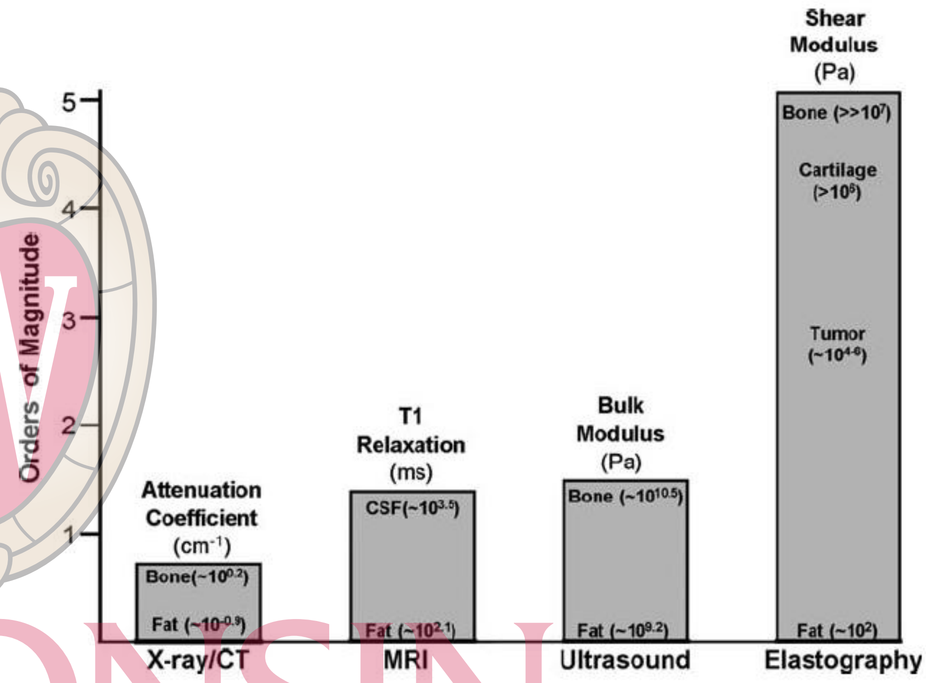
MR Elastography

- MRE allows quantitative analysis of viscoelastic properties of tissue
  - "Virtual palpation"
- Shear waves are introduced by driver (20-200Hz)
  - Active pneumatic driver placed outside of MR room
  - Passive driver placed under patient's head
- Wavelength dependent on shear modulus
  - Waves propagate rapidly in rigid tissue, slower in softer tissue

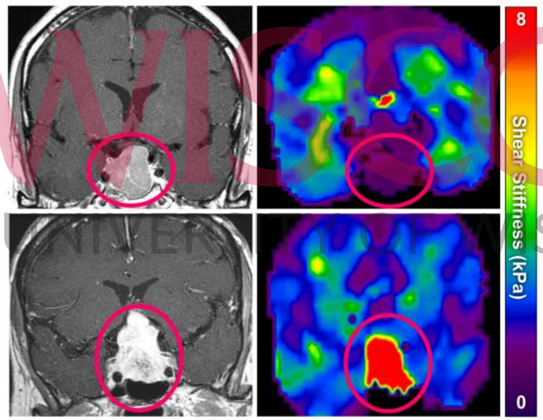


Shear Elastic Modulus

- **MRE measures shear modulus (G)**
  - $\tilde{G} = G' + iG''$
  - Other elastic moduli:
    - Young's Modulus (E), Bulk Modulus (K), etc.
  - High inherent dynamic range



From: Mariappan, et al. *Clin Anat* (2010)



MRE Encoding

- Modified phase-contrast sequence
- Sensitized motion to cyclic displacement from shear waves
  - Spins accumulate phase along motion encoding gradients
    - Bipolar or 1st order motion compensated gradient
  - Synchronized to driver frequency
- Multiple acquisitions with phase offsets
  - Shows shear wave at different points in cycle
- <u>Goal: Acquire displacement fields in 3D (encode x,y,z) at different phase offsets</u>

MRE Encoding

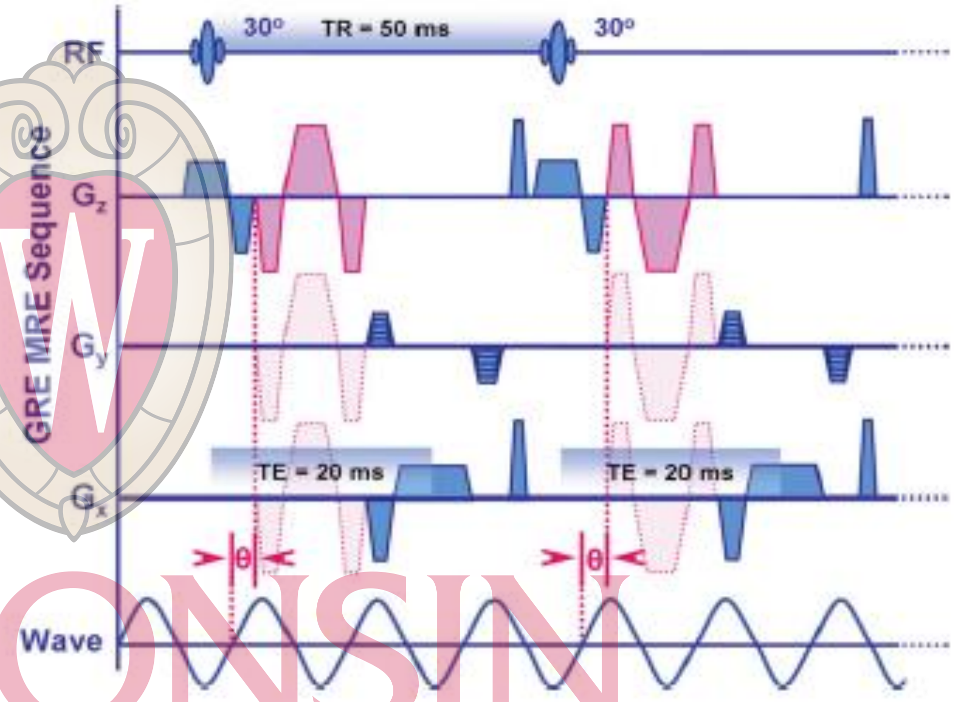
- Phase is described by the following equation
  - $\phi(\vec{r},\theta) = \frac{\gamma NT(\vec{G}\cdot\xi_0)}{2}\cos(\vec{k}\cdot\vec{r}+\theta)$
    - ϕ = displacement induced phase
    - $\vec{r}$ = spatial position
    - θ = phase offset
    - γ = gyromagnetic ratio
    - N = number of MEG pairs
    - T = period of the MEG
    - $\vec{G}$ = gradient strength
    - ξ_0 = peak amplitude of motion
    - k = wave number

MRE Encoding (Visual)

GRE Acquisition

1. **Gradient-recalled echo (GRE)**
   - Oldest method
   - Online reconstruction

- Limitations:
  - Relatively slow

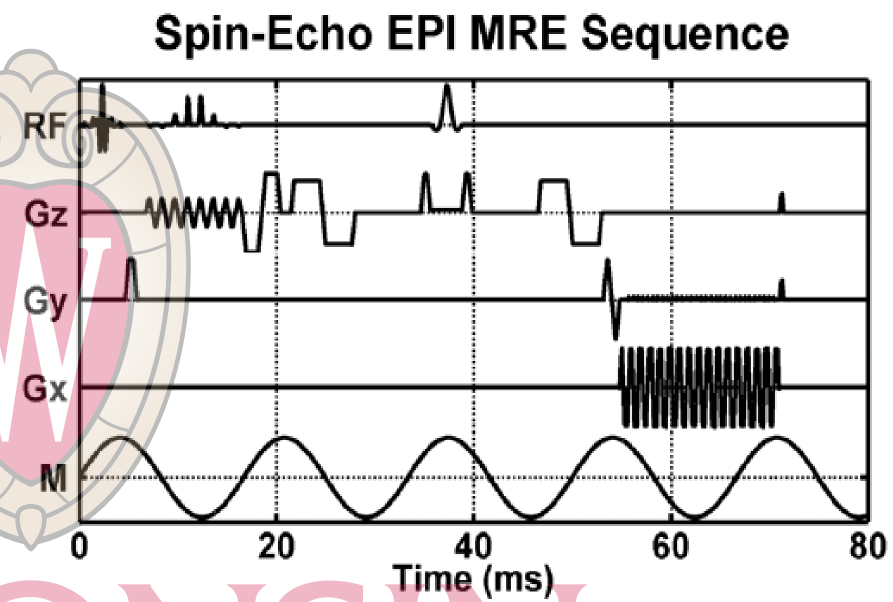


From: Venkatesh, et al. *JMRI* (2013)

SE-EPI Acquisition

2. **Single-shot echo planar imaging (SE-EPI)**
   - Most common
     - What we use here
   - Much faster than GRE
   - Online reconstruction

- Limitations:
  - Long readouts
    - Distortion
    - Reduced SNR

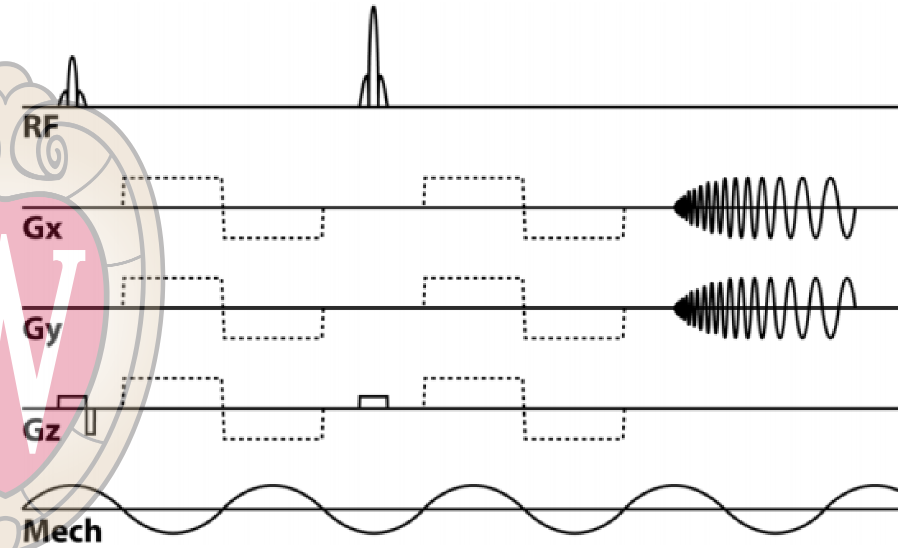


From: Glaser, et al. *JMRI* (2012)

Multi-Shot Spiral Acquisition

3. **Multi-shot, variable density spiral**
   - Relatively new
   - Increased resolution
   - Increased SNR
   - Flexible Tradeoffs

- Limitations:
  - Phase error between shots from bulk motion
  - Offline Recon
  - Increased complexity

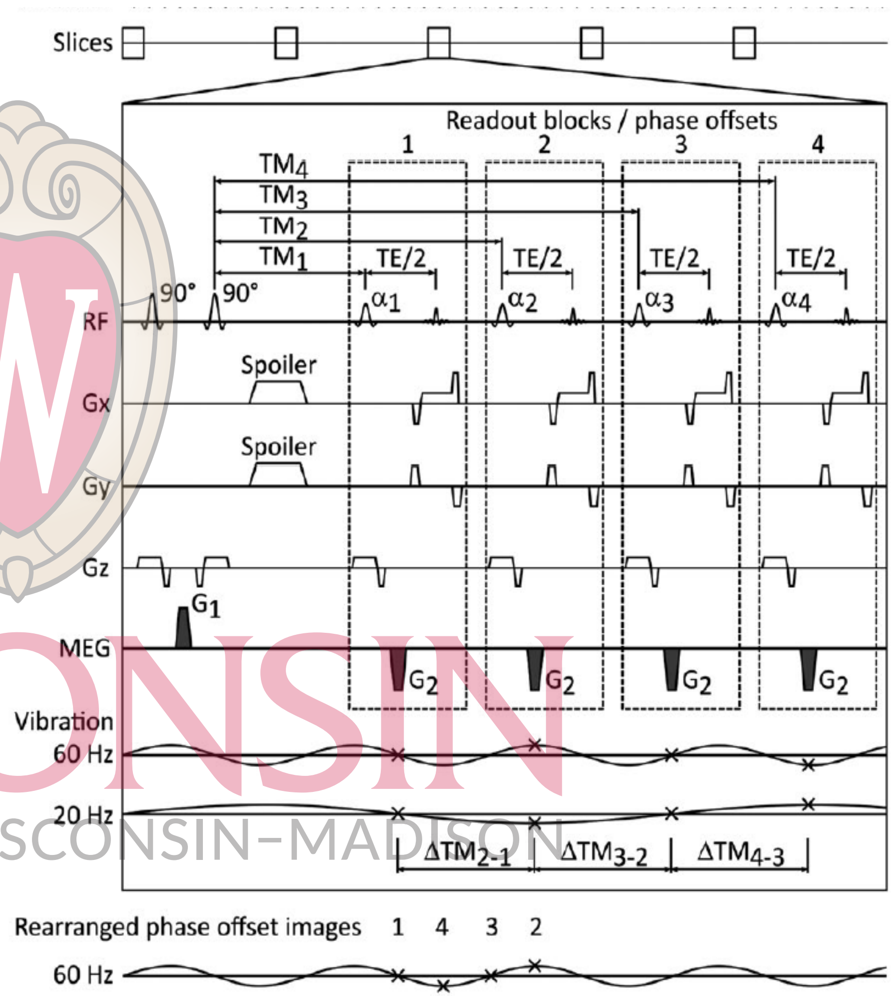


From: Johnson, et al. *MRM* (2013)

DENSE Acquisition

4. **Displacement Encoding Using a Stimulated Echo (DENSE)**
   - Relatively new
   - Allows for imaging with lower driver frequency
   - Fast/Efficient

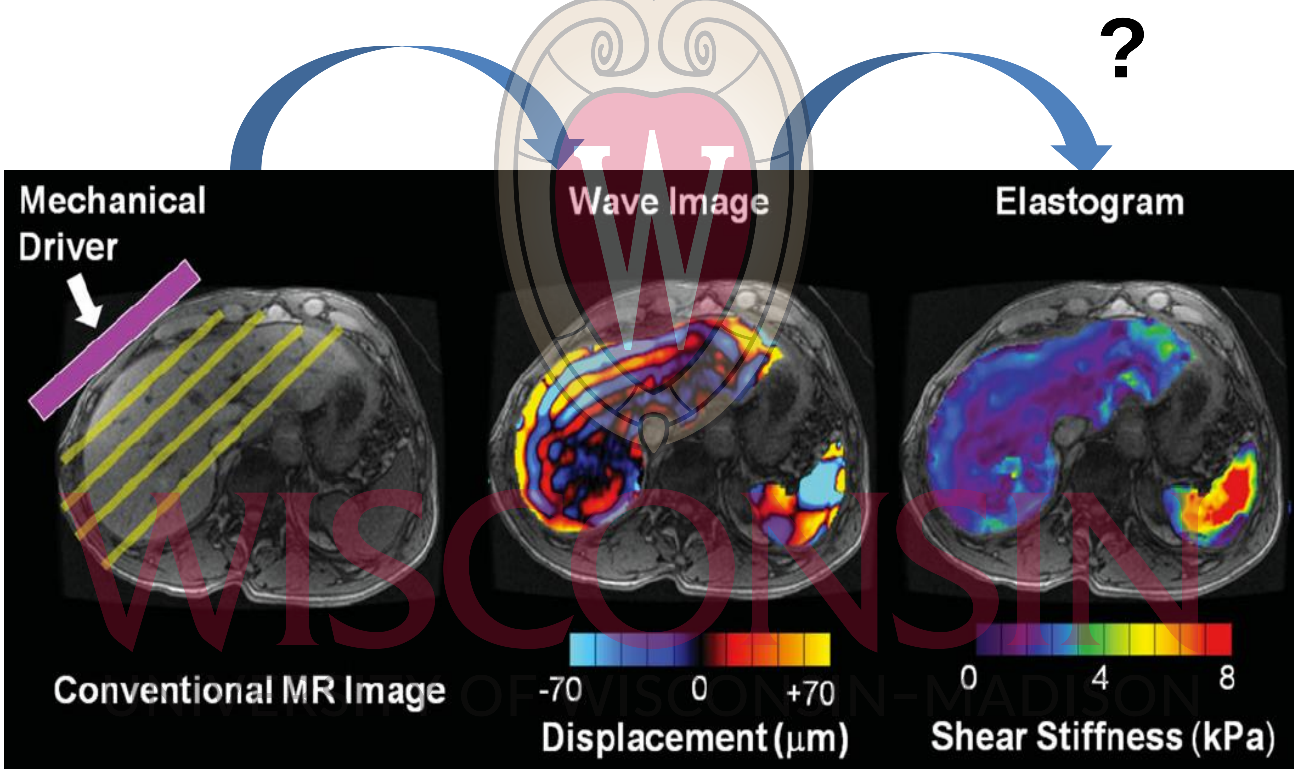
- Limitations:
  - Offline Recon
  - Increased Complexity



From: Strasser, et al. *MRM* (2018)

Reconstruction

- How can we go from wave images to stiffness maps?

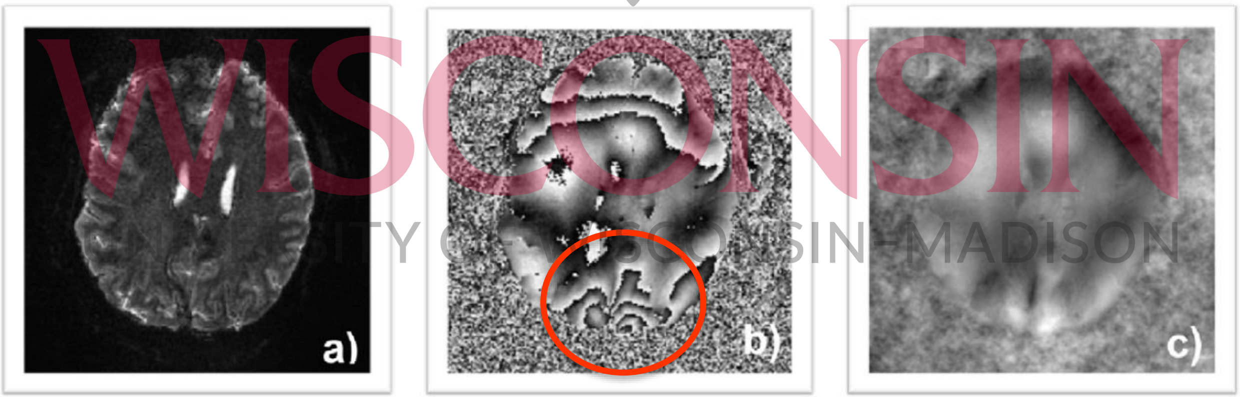


From: Venkatesh, et al. *JMRI* (2013)

Pre-Processing

1) Phase Unwrapping

- Higher amplitude of shear waves allows deeper penetration
- However, this leads to phase-wrapping near brain edges.
- Phase unwrapping algorithms need to be applied before stiffness reconstruction
  - 4D Laplacian-based algorithm

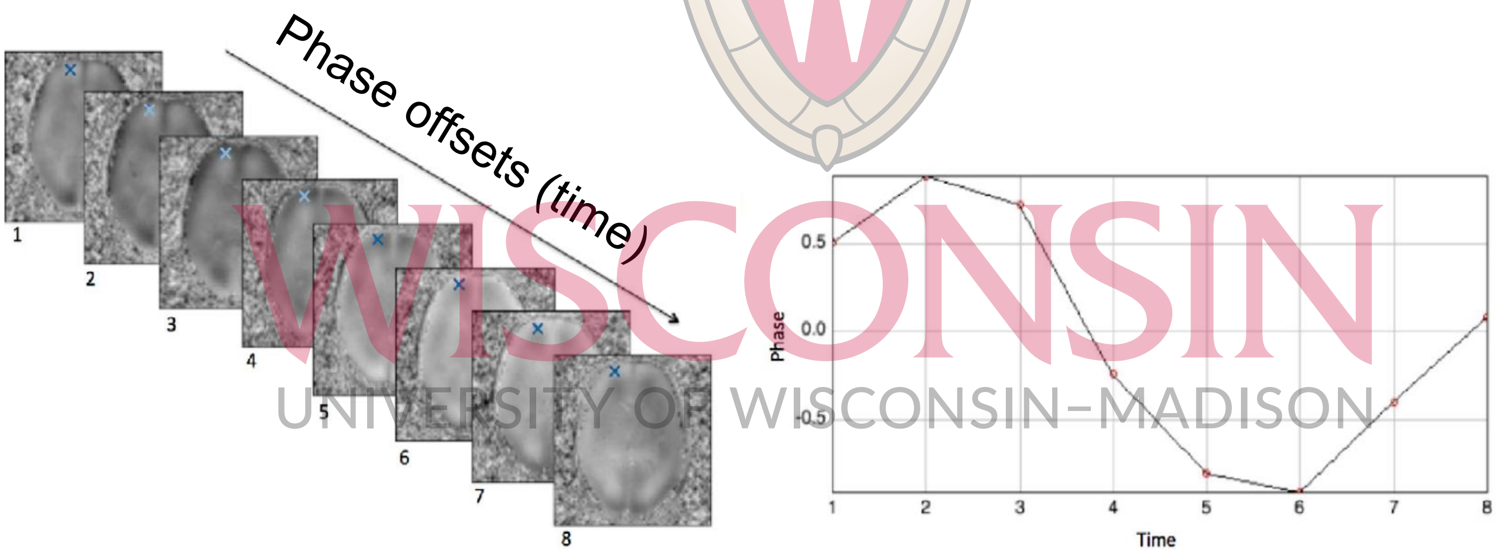


From: Hiscox. *Phys Med Biol* (2016)

Pre-Processing

2) Filtering

- Low frequency bulk waves
  - Occur because brain is not incompressible
- High frequency noise
  - Prevent parameter overestimation



From: Hiscox. *Phys Med Biol* (2016)

LFE Reconstruction

1) Local frequency estimation (LFE)

- Simplest, most-intuitive method
- Uses multiscale filters to estimate spatial wavelengths of shear waves in image.
- $G' = \rho V_S^2 = \rho(\lambda_{sp} f)^2$
  - ρ = tissue density (~1000 kg/m^3)
  - V_s = shear wave speed
  - f = driver frequency
  - λ_{sp} = spatial frequency of shear wave
- Limitations:
  - Get only real part of shear modulus
  - Effected by boundary reflections and dilatational waves

DI Reconstruction

2) Single Frequency Direction Inversion (DI)

- Mechanical properties calculated *directly* through the wave equation.
- Complex inversion problem
  - Requires rank 4 tensor with 21 independent complex quantities to relate applied shear stress to resulting shear strain.
- If we assume tissue isotropy, we can greatly simplify problem.
  - $\tilde{G} = -\rho(2\pi f)^2 \cdot \vec{u}(f)/\nabla^2\vec{u}(f)$
    - $\tilde{G}$ = complex shear modulus
    - f = driver frequency
    - ρ = tissue density (~1000 kg/m^3)
    - $\vec{u}(f)$ = frequency-dependent vector displacement field

DI Reconstruction

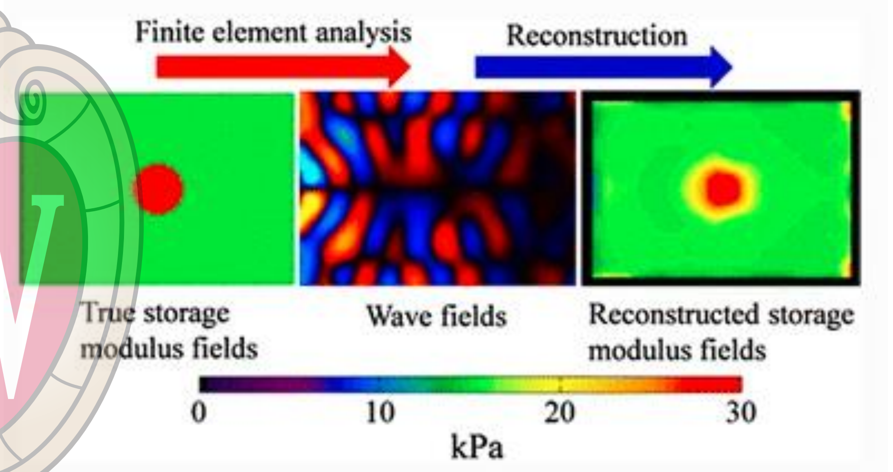
2) Single Frequency Direction Inversion (DI)

- Allows for a very quick calculation
  - Really only need to calculate $\nabla^2 \vec{u}(f)$
- UW scanners use DI
- Limitations:
  - Making many assumptions about material
    - Brain tissue is heterogenous and anisotropic
  - High noise sensitivity
    - Due to second derivative (Laplacian)
  - Susceptible to wave nodes
    - Imaging at single frequency

NLI Reconstruction

3) Non-Linear Inversion with Finite Element Models (NLI)

- Partial differential equations
- Forward problem utilizing prior knowledge
  - Boundary conditions
  - Tissue geometry
  - Mechanical properties



From: Tomita, et al. *J Visual-Japan* (2017)

- Iteratively update heterogenous tissue distribution until difference between experiment and theoretically derived data is minimized.
- Incorporates full equations of motion, nonlinearity, and anisotropy
- Limitations:
  - Speed of processing is on the order of hours

Conclusion

- MRE is a modified phase contrast sequence to encode displacement into image phase.
- Creates shear modulus maps
  - Must mechanically excite tissue
  - Measure/image tissue stress/strain
- Shear modulus has high dynamic range
- Acquisition Strategies:
  - GRE, Spin-echo EPI, Multi-shot spiral, DENSE
- Reconstruction Strategies:
  - Local frequency estimation (LFE), direct inversion (DI), non-linear finite element modelling (NLI)

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