Magnetic Resonance Elastography
Purpose

1. Principles & Techniques
2. MRE Image Acquisition and Pictorial overview
3. Pitfalls and Applications
INTRODUCTION

Magnetic resonance elastography is a technology for measuring the propagation of mechanical waves.

• Invented 20 years ago at Mayo Clinic (US) by Richard Ehman's team.

• It is a form of "virtual palpation" that allows noninvasive and quantitative assessment of mechanical tissue properties.

• Currently the main application is the assessment of liver stiffness a biomarker of fibrosis in chronic liver disease.
Section 1: Principles & Techniques

In the first section, we will review:

• Classification of elastography technique.
• Short Comparison b/w elastography techniques.
• Types of waves and wave generation.
• Key concepts of elastography.
• Mechanical properties & units.
• Components of a MRE system.
CLASSIFICATION OF ELASTOGRAPHIC TECHNIQUES

Static or Quasi-Static techniques

- Manual evaluation of stiffness

Examples:
- eMode (Hitachi)
- eSie Touch (Siemens)
- SonixTOUCH (Ultrasonix)

Dynamic (Shear Wave Imaging)

- Transient
  - Excitation is very short in the range of milliseconds
  - Examples:
    - 1D Transient elastography
    - Fibroscan
    - Shear wave elastography
    - Supersonic Shear Imaging

- Continuous
  - continuous mechanical vibrations
  - Examples:
    - MRE (GE, Philips, Siemens)
Comparison of elastography techniques

<table>
<thead>
<tr>
<th>Modality, Implementations</th>
<th>Brand Name (Manufacturer)</th>
<th>Shear Wave Generation</th>
<th>Shear Wave Duration</th>
<th>Shear Wave Frequency</th>
<th>Imaging</th>
<th>Parameter (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasound</td>
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<tr>
<td>1D Transient elastography</td>
<td>FibroScan (Echosens)</td>
<td>Mechanical</td>
<td>Transient</td>
<td>50 Hz</td>
<td>No anatomic image</td>
<td>Young elastic modulus (kPa)</td>
</tr>
<tr>
<td>Point shear-wave elastography</td>
<td>Virtual Touch Quantification (Siemens Healthcare)</td>
<td>Ultrasound (acoustic radiation force impulse)</td>
<td>Transient</td>
<td>Variable and difficult to precisely control</td>
<td>Location of ROI overlaid on 2D B-mode image</td>
<td>Shear-wave speed (m/s)</td>
</tr>
<tr>
<td>Shear-wave elastography</td>
<td>Shear Wave Elastography (Supersonic Imagine)</td>
<td>Ultrasound (multipoint focalization of acoustic radiation force impulse)</td>
<td>Transient</td>
<td>Variable and difficult to precisely control</td>
<td>Quantitative elastogram within 2D image, with possibility to superimpose ROI</td>
<td>Young elastic modulus (kPa)</td>
</tr>
<tr>
<td>MRI</td>
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<tr>
<td>MR elastography</td>
<td>MR Elastography (GE Healthcare, Philips Healthcare, Siemens Healthcare)</td>
<td>Mechanical</td>
<td>Continuous</td>
<td>60 Hz</td>
<td>Quantitative elastogram of one or more 2D slices</td>
<td>Magnitude of complex shear modulus (kPa)</td>
</tr>
</tbody>
</table>

Table: Tang A. et al
AJR July 2015; 205
MRE

- Built on clinical MR System and as an upgrade to existing MRI systems
- Samples large areas
- Relies on a transducer. Compression waves are produced and are converted to shear waves inside the tissue.
- Sequences are used to obtain wave images and that are converted to elastograms
- Units are in Kilo-pascals Range 0-8kPa.
- In Elastograms, Cool hues represent soft tissues and warm represent stiff
- Acquisition time less than 1 minute
Body Waves used in Imaging Systems

(A) Compression Waves

(B) Shear Waves

Analogy

Tap on a stinky toy.
(faster)

Sideways motion to a stinky toy
(slower)

Image: http://www.ukm.my/rahim/Seismic%20Refraction%20Surveying.html
Wave Generation

- Friction against phantoms
- Red=Crests
  Blue=Troughs

Wave in sideways orientation

Displacement Map (µm)
Waves are represented by two properties viz. Amplitude and wavelength.
Key Concept Of Elastography

1. Acquire Baseline imaging
2. Apply waves at known frequency (60Hz.)
3. Measure Amplitude and Frequency
4. Speed $c$
Elastography techniques do not measure stiffness directly.
Visual Wave Properties

a. Low Elasticity (soft) = Slow
b. High Elasticity (stiff) = Fast
c. High Elasticity and High Viscosity = Fast and dampens (e.g., liver is fatty)

## Mechanical Properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Soft tissue</th>
<th>Unit</th>
<th>Stiff tissue</th>
<th>E.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear wave speed (c)</td>
<td>Slow</td>
<td>m/s</td>
<td>Fast</td>
<td>2m/s</td>
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<tr>
<td>Magnitude of complex shear modulus (G)</td>
<td>Low</td>
<td>Pa</td>
<td>High</td>
<td>4kPa</td>
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<tr>
<td>Young's modulus (E)</td>
<td>Low</td>
<td>Pa</td>
<td>High</td>
<td>12kPa</td>
</tr>
</tbody>
</table>

Shear wave speed: \( c = \lambda \cdot f \)

Shear modulus: \( \mu = \rho \cdot c^2 \)

Young’s modulus: \( E = 3 \cdot \mu \)
# Units in MRE

**Example Readings**

<table>
<thead>
<tr>
<th>Wave images</th>
<th>Tissue Density (kg/m³)</th>
<th>Wavelength (m)</th>
<th>Frequency (Hz)</th>
<th>Shear stiffness (kPa)</th>
<th>Shear Elastogram (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1000 kg/m³</td>
<td>0.0240 m</td>
<td>60 Hz</td>
<td>2.07 kPa</td>
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<tr>
<td>Cirrhotic</td>
<td>1000 kg/m³</td>
<td>0.0479 m</td>
<td>60 Hz</td>
<td>8.25 kPa</td>
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</tbody>
</table>

Images and Readings from Webinar by Dr. An Tang (Sept 2015)
Mechanical Properties

Stiffness types:

Spring (elasticity):
Regains its original shape after it is deformed.
E.g. Spring

Dashpot (viscosity):
Resists movement or dissipated energy or resists flow.
E.g. Oil, Honey
Mechanical properties

• Tissues exhibit both elastic and viscous properties.

• **Various models** that are used to describe these properties

  ![Diagrams](image.png)


  Spring and dashpot  In series  in parallel  in infinite ladders

Reference: Meyers M.A. Mechanical behaviour of materials, Prentice Hall, 2009; 688
Components of MRE system

Image Reference Mariappan YK et al MRE; Review Clin Anat. 2010,23(5); 497-511
Wave Generation
Shown is an example of a gradient-recalled echo MRE pulse sequence diagram. A typical bipolar motion-encoding gradient (MEG) is shown (solid line) as well as the negative MEG (dotted line) used for phase-contrast imaging. The motion waveform and its temporal relationship ($\theta$) with the MEG are also shown.
Key Learning Points in Section 1

1. Elastography built on already existing techniques US and MR systems.
2. The tissue contrast mechanism is different. MRE measures stiffness and other mechanical properties non-invasively.
3. Stiffness cannot be measured directly. Instead, speed of shear waves is measured. Shear waves travel slower in soft tissues and faster in stiff tissues.
4. Various stiffness-related parameters and units:
   - Shear wave speed (m/s)
   - magnitude of complex shear modulus(“shear stiffness”) (Pa)
   - Young’s elastic modulus(“elasticity”) (Pa)
Section 2: MRE Image Acquisition

In this section, we will review:

• The steps involved in **data processing**.
• The **interpretation** of wave images and Elastograms.
• The **diagnostic performance** of MRE for fibrosis staging.
1. Acquired Raw images in a) Phase image and b) Magnitude Image
2. This is then filtered to exclude compression waves and only retain shear images.
3. There are Inversion algorithms that compute stiffness from wave images
4. A confidence map that determines which are the areas of reliable or unreliable measurement.
Wave interactions in media

- a. Attenuation
- b. Absorption
- c. Reflection
- d. Refraction
- e. Mode conversion
- f. Diffraction
- g. Scattering
- h. Constructive Interference
- i. Destructive Interference
Chronic Liver disease, Fibrosis and Cirrhosis

- Leading cause of death worldwide
- Detecting using Biopsy, sampling error
- Conditions that cause hepatic fibrosis:
  - Hepatitis C – appx. 200M people
  - Hepatitis B-especially in Asia
  - Obesity/Fatty Liver Disease- Common in US and western countries
- Fibrosis can be reversed if diagnosed early and treated
Stiffness vs Fibrosis Comparison

Wavelength gradually increasing
Performance of liver MRE

<table>
<thead>
<tr>
<th>Technique, Study</th>
<th>No. of Studies (No. of Patients Included)</th>
<th>Implementation</th>
<th>Cutoff</th>
<th>AUC</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Cutoff</th>
<th>AUC</th>
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<th>Sensitivity</th>
<th>Specificity</th>
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<tr>
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<td>Talwalkar et al. [23]</td>
<td>9 (2083)</td>
<td>1D transient elastography</td>
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<td>7.0 kPa</td>
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<td>0.70</td>
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<td>9.5 kPa</td>
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<td>1.34 m/s</td>
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<td>1.55 m/s</td>
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<td>Bota et al. [25]</td>
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<td>1.80 m/s</td>
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<td>MR elastography</td>
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<td>Wang et al. [2]</td>
<td>5 (398)</td>
<td>Magnitude of complex shear modulus</td>
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<td>0.95</td>
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<td>0.98</td>
<td>0.94</td>
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<td>0.98</td>
<td>0.92</td>
<td>0.96</td>
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<td>0.99</td>
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<tr>
<td>Singh et al. [26]</td>
<td>12 (697)</td>
<td>Complex (G’, G”)</td>
<td>3.45 kPa</td>
<td>0.84</td>
<td>73</td>
<td>79</td>
<td>3.66 kPa</td>
<td>0.88</td>
<td>0.79</td>
<td>0.81</td>
<td>4.11 kPa</td>
<td>0.93</td>
<td>0.85</td>
<td>0.85</td>
<td>4.71 kPa</td>
<td>0.92</td>
<td>0.91</td>
<td>0.81</td>
</tr>
</tbody>
</table>

AUC values close to 1.0 indicate the highest diagnostic accuracy

Pictorial Review: No Fibrosis

Figure. MRI of a 62-year-old female with hepatitis C with fibrosis stage 0 at liver biopsy.

(a) Axial T2-weighted SSFSE image shows an unremarkable liver.
(b) Axial T2-weighted 3D T1-weighted GRE image in portal venous phase after Gd-EOB-DTPA contrast agent in a normal liver.
(c) Axial elastogram cine-loop.
(d) Axial wave image shows a low average liver stiffness of 2.11 kPa, which suggests the absence of liver fibrosis (F0).
Pictorial Review: Fibrosis

- **Observation**: Liver slightly bumpy. No clear signs of fibrosis.

- **Elastogram**: Suggest fibrosis of at least \( \geq F3 \).
Pictorial Review: Inflammation

MRi of 65 year old female with biopsy proven NASH
a) Axial T2 weighted image shows a normal liver
b) Axial fat fraction map indicates FF of 16.8%.
c) Axial cine-loop (gif not available)
d) Axial elastogram shows slightly elevated liver stiffness of 3.88kPa

Observation:-
Liver stiffness may increase in early NASH due to inflammation, even before onset of fibrosis

Non-Alcoholic Steato-Hepatitis
Ascites is the abnormal buildup of fluid in the abdomen.
- Fibroscans does not work in liquid.
- Despite liquid MRE is robust in subjects related to ascites and high BMI.
Section 2: Key Learning Points

1. The main current clinical indications for abdominal elastography techniques are detection and staging of liver fibrosis.

2. MRE samples larger portions of liver and offers excellent diagnostic accuracy that probably slightly exceeds that of ultrasound-based techniques.

3. Emerging indications of elastography include detection of hepatic inflammation, characterisation of focal liver lesions, and assessment of polar hypertension.
Section 3: Pitfalls and other Applications

In this section, we will review:

• Biological and Technical confounders.
• Other applications of MRE
  - MRE of the Brain
  - Alzheimer's disease
Pitfall: Post-prandial vs. Fasting state
Pitfall: Iron Deposition

- MRI of a 62 years old man with biopsy proven cholangiocarcinoma (arrow)

- Iron deposits may degrade the quality of the MRE images and may also mask small lesions.

- Barely detectable
Pitfall: Severe Iron Deposition

- Severe iron deposition can degrade the GRE sequences in patients with marked iron deposits.
MRE of the Brain

Schematic diagram of the magnetic resonance elastography system. Conventional MR imaging gradients and RF pulses that encode spatial positions are shown at the bottom left. The electromechanical actuator (a) applies vertical displacement to the object to be imaged via a cradle or (b) horizontal displacement via a bite block (right). The cyclic motion-sensitizing gradients and the actuator are synchronized using trigger pulses provided by the imager. The phase offset ($\theta$) between the two can be varied to image the waves at various stages of propagation. As shown by the shaded regions, the motion-sensitizing gradients can be superimposed along any desired axis to detect that component of the cyclic motion vector. All data was collected and analyzed using 100 Hz motion.
MRE of the Brain

- Characterization of meningioma.
MRE of the Brain

• Study of \textit{Alzheimer's disease}.
• Stiffness was lower in patients with Alzheimer's disease.
• Significantly stiffer in normal controls but had \textit{beta amyloid deposition}.
• Even stiffer in normal controls.
• Take-home message \textit{brain softens with dementia over time}.
Summary

The major teaching points of this lecture are:

1. MRE is an additional diagnostic tool integrated to MRI systems that requires synchronised vibrations and inversion algorithms to provide stiffness measurements.

2. Mechanical properties (stiffness, elasticity, viscosity) provide new contrast mechanisms.

3. MRE is an emerging clinical tool for the assessment of liver fibrosis and other liver conditions.

4. US elastography techniques are relatively inexpensive, portable, increasingly available. They only sample small portions of the liver and they may be unreliable in obese patients.

5. Rapidly evolving field with other applications: brain, lungs, heart, skeleton muscle and other organs.
Thank You