Applications of Ultrasound Radiation
Force

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Liver Cirrhosis

• **Causes:**
  – Sustain wound healing to chronic liver injury
  – Viral; autoimmune; drug induced; cholestatic; metabolic diseases

• **Prevalence:**
  – Hundreds of millions worldwide
  – 900,000 in USA (number increasing)

• **Risk (50% 5 year mortality):**
  – Hepatic failure
  – Primary liver cancer
Limitation of Liver Biopsy

• Pain (French survey)

• Complications
  – Hospitalization: 1~5%
  – Mortality 1/1,000~1/10,000

• Low reproducibility
  – Inter-observer variability: ~20%
Need for Noninvasive Alternative

• Fibrosis is reversible

• Risk and cost of unnecessary biopsy
  – $2,200
  – HCV: ~25%

• New treatment development
  – Establish effectiveness
  – Optimize dosing
MR Elastography for Fibrosis Staging

- Slow (>20 minutes)
- Expensive
- Precise
MRE of Normal Liver

Figure 6: MR elastographic wave images of a 21-year-old healthy volunteer (transcostal approach, 20-mm orthogonal plane). Rectangle indicates position of driver. Double-headed arrows indicate vibrational motion of driver. (a) Magnitude image. (b) Corresponding Zs phase-difference image shows shear waves (single-headed arrows) propagating in liver.

Ehman R. L. et al.
Figure 7: MR elastographic wave images of a 60-year-old patient (transcostal approach, 20° oblique plane). Rectangle indicates position of driver. Double-headed arrows indicate vibrational motion of driver. (a) Magnitude image. (b) Corresponding Zs phase-difference image shows shear waves (single-headed arrows) in liver. Wavelength is large, which indicates high liver stiffness. On the basis of wavelength measurements, mean liver stiffness was 19.2 kPa. Results of liver biopsy performed 4 months earlier showed cirrhosis.
Olivier Rouvière, Meng Yin, M. Alex Dresner, Phillip J. Rossman, Lawrence J. Burgart, Jeff L. Fidler, and Richard L. Ehman

MR Elastography of the Liver: Preliminary Results
Radiology 2006; 240: 440-448.

Figure 8: Graph of distribution of liver shear stiffness in 12 healthy volunteers and 12 patients with chronic liver disease and varying degrees of liver fibrosis proved with biopsy results.
Ultrasound Elastography for Fibrosis Staging

- Fibroscan™ (Echosens, Paris)
- Sonoelasticity
- Supersonic Imagine™
- ARFI
- SDUV
Ultrasound-based Fibroscan™

\[ V = \sqrt{\frac{\mu_1}{\rho}} \]

(Not 2D!)
Sonoelastographic image of shear wave interference patterns induced in a tissue-mimicking phantom using externally applied mechanical vibration.

Robert M. Lerner, M.D. and Kevin J. Parker, P.

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Liver Elastography with Ultrasound

Real-Time Elastography for Noninvasive Assessment of Liver Fibrosis in Chronic Viral Hepatitis

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AJR:188, March 2007

Fig. 1—Tissue elasticity distribution represented as color-coded images over conventional B-mode image. Image presents example of 34-year-old healthy female subject.
Vibrometry Measurements of Liver Stiffness in Humans

Fig. 2—Box plots show correlation between noninvasive tests and histologic results from liver biopsy. Top and bottom of boxes represent first and third quartiles, respectively. Length of box represents interquartile range within which 50% of values are located. Thick line through each box represents median. Error bars mark minimum and maximum values (range). Small circles represent outliers.

A. Real-time elastography. Skewed data for control subjects might be explained by inhomogeneous group of patients, whereas skewed data for fibrosis stage F2 can be explained by small number of patients in this group.

B. Aspartate transaminase–to–platelet ratio index (APRI). Skewed data are equalized when using log scale for APRI score.

C. Elasticity–laboratory combination values for each fibrosis stage.
Supersonic Shear Imaging

Pushing mode
3% - 3% Agar-Gelatin Elastic phantom

Imaging mode
Plane wave insonification at 3000 Hz

Processing
Beam-forming
US images
1D Cross-correlation

Uz(x,t)

Mathias Fink, University Paris VII, France
Proposed Method (SDUV)

Viscoelastic Medium

\[ \partial_t^2 \phi + c_s \nabla^2 \phi = 0 \]

- Depends only on local \( \mu_1 \) and \( \mu_2 \) (Voigt model)
- Device independent (beam shape, Tx)
- Independent of ultrasound intensity

\[ c_s = \sqrt{\frac{2(\mu_1^2 + \omega^2 \mu_2^2)}{\rho(\mu_1 + \sqrt{\mu_1^2 + \omega^2 \mu_2^2})}} \]

\[ c_s(\omega) = \frac{\omega \cdot \Delta r}{\phi_2 - \phi_1} \]
Advantages of SDUV

- Shearwave Dispersion Ultrasound Vibrometry SDUV
- Truly quantitative
- Elasticity & viscosity
- Does not require direct inversion
- Applicable to ascites patients
- “Virtual biopsy” guided by 2D B-scan
Test of Accuracy

Shear wave speed vs. frequency

LMS fit: $\mu_1 = 2220 \pm 80 \text{ Pa}$, $\mu_2 = 0.24 \pm 0.03 \text{ Pa s}$

Validation: $\mu_1 = 2350 \text{ Pa}$, $\mu_2 = 0.32 \text{ Pa s}$
Beef Muscle Results

Mechanical vibration results:

\[ \mu_1 = 29 \, \text{kPa}, \quad \mu_2 = 9.9 \, \text{Pa} \cdot \text{s} \]

<table>
<thead>
<tr>
<th>Vibration frequency (Hz)</th>
<th>Shear wave speed (m/s)</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>4</td>
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<td>200</td>
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<td>300</td>
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<tr>
<td>400</td>
<td>8</td>
</tr>
<tr>
<td>500</td>
<td>9.2</td>
</tr>
</tbody>
</table>

LMS fit: \( \mu_1 = 24 \, \text{kPa}, \mu_2 = 9.7 \, \text{Pa} \cdot \text{s} \)
Rabbit Liver Results

Dispersion in healthy rabbit liver

Shear wave speed (m/s)

Vibration frequency (Hz)

LMS fit: $\mu_1 = 1.6$ kPa, $\mu_2 = 0.76$ Pa*s
SDUV with a Single Array Tx

Array Tx

Tissue
SDUV with a Single Array Tx

Array Tx

Tissue
SDUV with a Single Array Tx
Intermittent Vibration and Detection
SDUV Vibrometry “Biopsy” of Liver
SDUV Summary

• SDUV is not dependent on instrument characteristics.
• SDUV is fast.
• SDUV can be done with software alterations of modern ultrasound scanners.
• SDUV measures both elasticity and viscosity.