Acoustic Radiation Force Based Imaging: An Overview

Kathy Nightingale, Michael Wang, Stephen Rosenzweig, Veronica Rotemberg, Samantha Lipman, Ned Rouze, Mark Palmeri

Department of Biomedical Engineering
Duke University

Disclosures

Intellectual Property related to radiation force based imaging technologies

Siemens Medical Solutions, Ultrasound Division – research agreement providing equipment and technical support

Learning objectives

- To understand the differences between acoustic images, qualitative elasticity images, and quantitative shear wave images
- To understand the tradeoffs between resolution and accuracy in shear wave imaging
- To understand the limitations of the assumptions made by time-of-flight based algorithms

Elasticity Imaging

Generate images portraying information about the stiffness (elasticity) of tissue:

1) Mechanical excitation
   - External
   - Physiological
   - Focused acoustic radiation force
2) Image tissue response
   - Ultrasound
   - MRI
   - Optical
3) Generate image of tissue stiffness
   - Relative stiffness
   - Quantify tissue stiffness (shear wave speed or elastic moduli)

Why image mechanical properties?

- Manual palpation by clinicians – what do they feel?
  - Masses (e.g. breast, liver, prostate)
  - Pathology (e.g. cirrhotic liver)
  - Large inherent mechanical contrast between soft tissues
- Palpation has limitations:
  - Physical location
  - Size of palpable structure
  - Doctor-to-doctor variability (“hard”, “soft”)
  - Repeatability

Why use acoustic radiation force?

- Focused within organ of interest
- Small strain

Typical soft tissue material properties

Young's Modulus, E (kPa)	Shear Modulus, μ (kPa)	Shear Wave Speed (m/s)	Bulk Modulus, K (GPa)	Ultrasonic Wave Speed (m/s)	Example
~1	~0.3	~0.5	2-2.5	1490-1540	Fat
1-24	0.3-8	0.5-2.8	2-2.5	1490-1540	Liver
3-30	1-10	1-3.2	2-2.5	1490-1540	Skeletal Muscle
6-45	2-15	1.4-3.9	2-2.5	1490-1540	Prostate
20-150	6.7-50	2.6-7.1	2-2.5	1490-1540	Myocardium
30-300	10-100	3.2-10	2-2.5	1490-1540	Fibrotic Liver

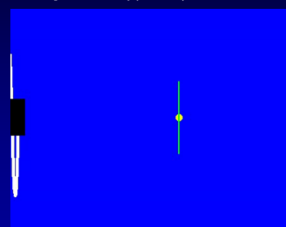
Shear modulus and shear wave speed provide more inherent contrast than bulk modulus and ultrasonic wave speed.

•Sarvazyan, A.P. (2001). Elastic Properties of Soft Tissue. *Handbook of Elastic Properties of Solids, Liquids, and Gases*. 3: 107-127
•Skovoroda et al., (1995). Quantitative analysis of the mechanical characteristics of pathologically changed soft biological tissues. *Biophysics,* 40(6)1359-1364.
•Duck, F.A. (1990). Physical Properties of Tissue, a Comprehensive Reference Book. Academic Press.
•Sandrin et al, (2003) Transient elastography: a new noninvasive method for assessment of hepatic fibrosis. *UMB* 29(12)1705-1713.

Acoustic Radiation Force

Force generated by a transfer of momentum from an acoustic wave to the medium through which it is propagating, caused by absorption (predominantly) and scattering in soft tissue. Force magnitude typically ~3 g/cm^3

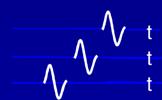
$$F = \frac{2\alpha I_{ta}}{c}$$



α=absorption coefficient

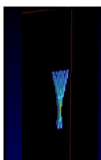
I_{ta} = temporal average intensity

c = speed of sound



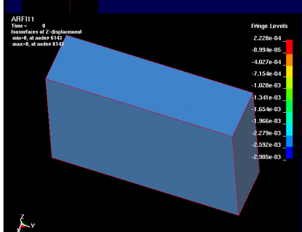
Nyborg, W. *Acoustic Streaming*, in Physical Acoustics Vol. IIB, editor: Mason W.P., Academic Press,1965.

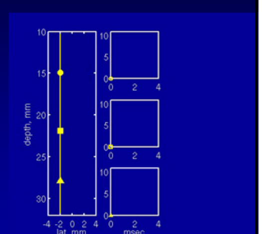
FEM: Homogeneous Medium



$$F = \frac{2\alpha I_{ta}}{c}$$

ARFI - look where you push



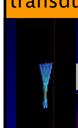


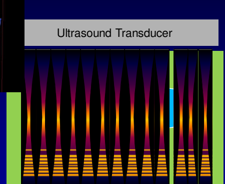
μ=1 kPa, movie duration = 10 ms

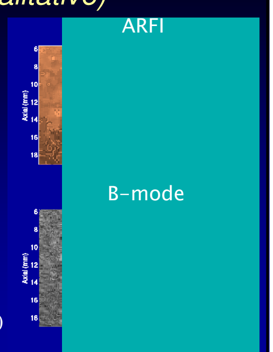
Palmeri et al "A finite element method model of soft tissue response to impulsive acoustic radiation force", *IEEE UFFC*, 52(10): 1699-1712, 2005.

Acoustic Radiation Force Impulse (ARFI) Imaging (qualitative)

transducer







- Displacement inversely proportional to stiffness
- Relative stiffness (as with strain images)
- Not operator dependent

Nightingale et al, "ARFI imaging: in vivo demonstration of clinical feasibility", *UMB*, 28(2): 227-235, 2002

- Radiation force occurs with all wave propagation
- Increased intensity to move microns
- Diagnostic or HIFU transducers

Typical ARFI excitation:

Frequency = 2-6 MHz

Intensity (sppa$_{.5}$, linear) = 1500 - 3000 W/cm^2

Mechanical Index = 1.5-3.0

Duration < 1 msec

Temperature rise = 0.03-0.1 °C

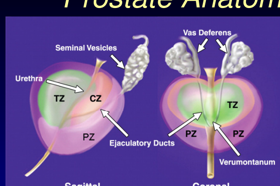
Tissue Displacement = 10-15 µm

ARFI – Prostate Imaging

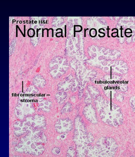
- Prostate cancer (PCA) facts
  - Affects 1/6 men in the US
  - 2nd leading cause of cancer death in men
- Prostate cancer diagnosis
  - Initially screened through DRE and PSA
  - Confirmed through TRUS guided needle biopsy
    - PCA not visualized in ultrasound
    - Random or systematic sampling
    - Low detection rates
- ARFI imaging a potential tool for targeting needle biopsy and monitoring lesion growth/response to treatment

http://www.cancer.org/Cancer/ProstateCancer/DetailedGuide/prostate-cancer-key-statistics

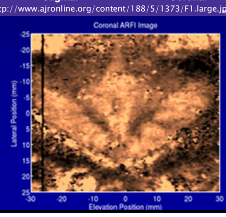
Prostate Anatomy and Pathology



http://www.ajronline.org/content/188/5/1373/F1.large.jpg

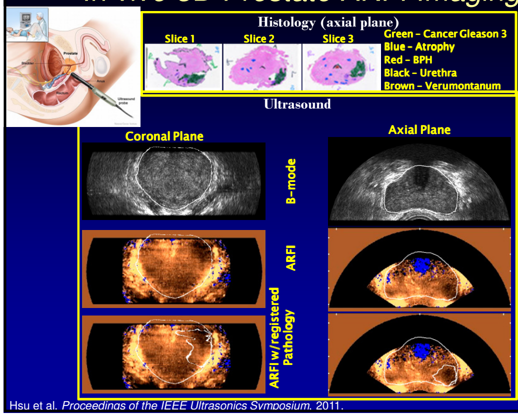


http://www.lab.anhb.uwa.edu.au/mb140/corepages/malerepro/Images/pro04he.jpg



http://visualsonline.cancer.gov/preview.cfm?imageid=2720&fileformat=jpg

In vivo 3D Prostate ARFI Imaging

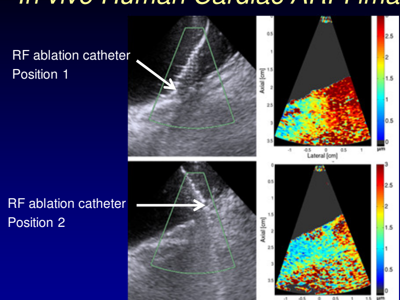


Hsu et al. *Proceedings of the IEEE Ultrasonics Symposium*, 2011.

ARFI - Monitoring Thermal Ablation

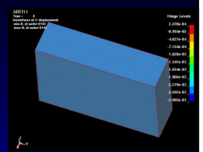
- Thermal ablation increases tissue stiffness
  - Ablated tissues no distinct in ultrasound images
- Elasticity methods can monitor thermal ablation processes:
  - Radio Frequency ablation (RFA)
  - High intensity focused ultrasound (HIFU) ablation
- Cardiac ablations are commonly performed to eliminate aberrant electrical conduction pathways

In vivo Human Cardiac ARFI imaging of RFA



- Human Left Atrium (Roof-line)
- AcuNav intra-cardiac transducer and separate RF ablation catheter
- AcuNav imaging catheter in fixed position, moved ablation catheter for ARFI imaging
- Images courtesy of Dr. Pat Wolf

Shearwave Speed Quantification



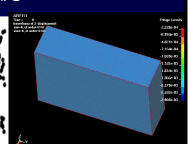
- Excite tissue with a dynamic stress:
  - Vibrating table or punch[1-3]
  - Acoustic radiation force[4, 5-7]
- Evaluate resulting tissue response/shear wave propagation
- Shear wave speed related to shear modulus (i.e. material stiffness), and structures within tissue

[1]Lerner et. al., 1988; [2]Muthupillai et. al., 1995; [3]Sandrin et al, UMB, 2003;
[4]Sarvazyan et al, UMB, 1998
[5]Nightingale et al, UMB, 2003; [6]Bercoff et al, IEEE UFFC, 2004; [7]Chen et al, JASA, 2004

Wave Propagation in Soft Tissues

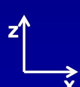
Ultrasound (Pressure)
1540 m/s

Transverse (Shear) 1-5 m/s



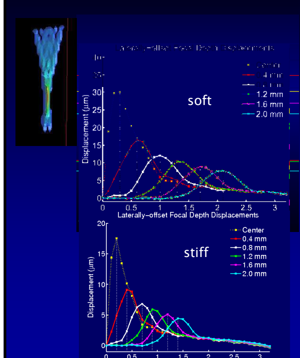
Particle motion ↕
Wave propagation →

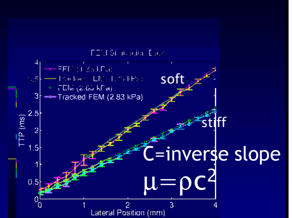
Particle motion ↕
Wave propagation ↓



http://www.kettering.edu/%7Edrussell/Demos/waves/wavemotion.html

Estimate shear wave speed with linear regression





Assumptions:
- Known direction of propagation
- Linear, isotropic, homogeneous material

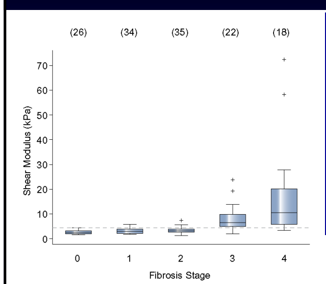
Palmeri et al. UMB, 2008.

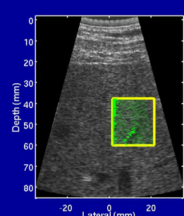
Liver Biopsy

- Diagnostic gold-standard
  - Invasive
    - Infection
    - Hemorrhage
    - Pain
  - Limited sampling
  - Costly (time and money)
  - Not suitable for longitudinal monitoring of disease progression / resolution
- Can a non-invasive liver stiffness estimate be used as a surrogate measure of liver fibrosis?

http://www.medandlife.ro/assets/images/Vol%20II%20NO%204/generalarticles/fierbinteanu/image005.jpg

Shear Modulus vs. Fibrosis Stage





- 4.24 kPa F0-2:F3-4 threshold
- 90% sensitivity
- 90% specificity
- 0.90 AUC

Palmeri et. al., J Hepatology (55), 2011

Commercial Radiation Force Methods

Products now in commercial market (not in US):

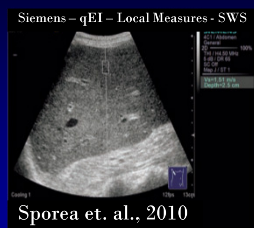
- Siemens 'Virtual Touch Tissue Quantification'®
  - rEI® (qualitative (ARFI) images)
  - qEI® (quantitative SWS measurements)
  - SVI® (quantitative images)
  - Initial release – abdominal probe, now additional probes
- Super Sonic Imagine, SSI Aixplorer® (quantitative images)
  - Initial release - breast probe, now additional probes

Liver Stiffness/SWS Quantification/Fibrosis

Over 400 articles in clinical literature evaluating performance of qEI ™ in the context of liver fibrosis staging

Good diagnostic accuracy for the noninvasive staging of liver fibrosis

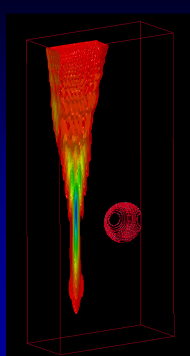
Friedrich-Rust, J. Viral Hepatitis, 2012
Toshima, J. Gastroenterol, 2011
Crespo, J. Hepatology, 2012
Sporea, Med. Ultrason, 2010

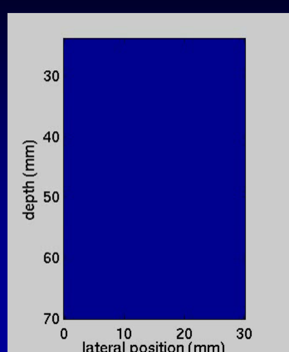


Heterogeneity in thresholds – why?

- Depth within Liver
- Disease etiology (CHC, CHB, NASH/NAFLD)
- Other sources of increases in stiffness (i.e. inflammation, congestion)

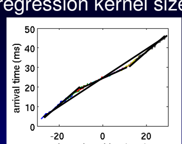
SWS Behavior in Heterogeneous Material



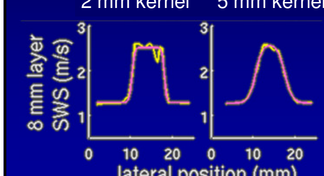


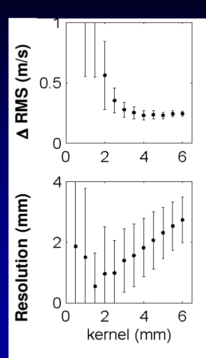
Vertical Layer – resolution and precision

regression kernel size:



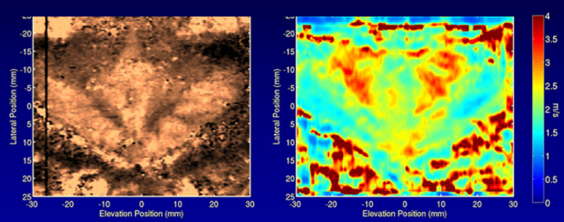
2 mm kernel 5 mm kernel





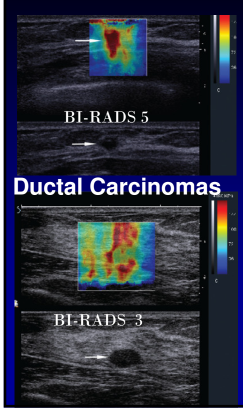
Matched C-plane In Vivo Prostate Images

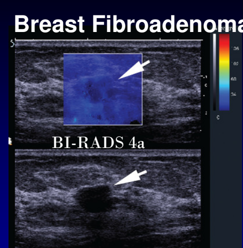
ARFI (Qualitative) | SWS (Quantitative 0-4 m/s)



- Quantitative SWS image is lower resolution
- Concordance between darker ARFI regions and higher SWSs

SSI – Multi-center Breast Lesion Evaluation





939 breast masses; limited SSI to evaluation of BIRADS 3 and 4a:

- Increased specificity of breast mass assessment from 61.1% (397 of 650) to 78.5% (510 of 650), with *P*<.001
- Insignificant improvement in sensitivity

Berg et. al, ***Radiology:*** 262(2); 2012

Summary – Radiation Force Based Elasticity Imaging

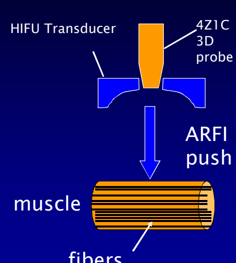
- Clinically available
  - Qualitative methods (ARFI imaging)
  - Quantitative methods (shear wave speed)
- Need large-scale clinical studies and research validation of the quantitative methods
  - monitoring disease progression?
  - monitoring response to therapy?
- Standardization among manufacturers – RSNA/QIBA efforts

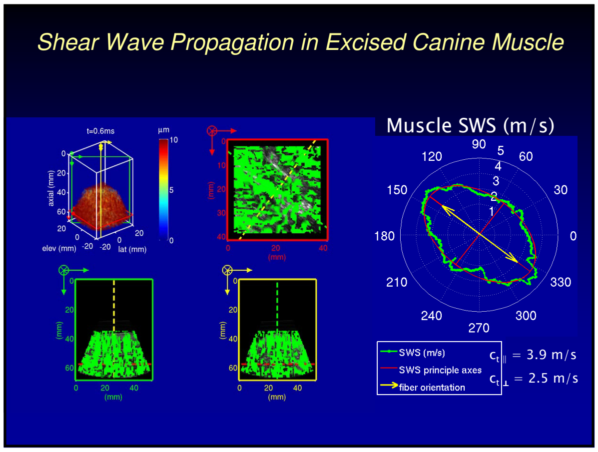
Acknowledgements

- NIH NIBIB R01EB002132
- NIH NCI R01CA142824
- Siemens Medical Solutions, USA, Inc., Ultrasound Division

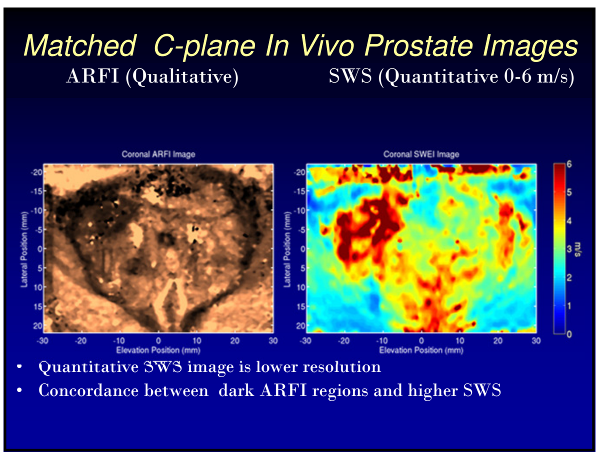
Duke ARFI/Ultrasound Team

3D Shear Wave Imaging Setup





Shear Wave Propagation in Excised Canine Muscle
t=0.6ms
axial (mm)
elev (mm)
lat (mm)
Muscle SWS (m/s)
90
120
60
150
30
180
0
210
330
240
300
270
SWS (m/s)
SWS principle axes
fiber orientation
$c_{t\parallel}$ = 3.9 m/s
$c_{t\perp}$ = 2.5 m/s



Matched C-plane In Vivo Prostate Images
ARFI (Qualitative)
SWS (Quantitative 0-6 m/s)
Coronal ARFI Image
Coronal SWEI Image
Lateral Position (mm)
Elevation Position (mm)
m/s
• Quantitative SWS image is lower resolution
• Concordance between dark ARFI regions and higher SWS