Quasi-Static Elastography

Timothy J. Hall
Professor

Medical Physics Department

University of Wisconsin-Madison

Overview – Quasi-static Elastography

- Fundamental concepts in palpation elastography
  - Elasticity image formation
- Applications of palpation elastography
  - Successes and failures
- Quantitative elastography
- Phantoms for elastography

Palpation & Disease

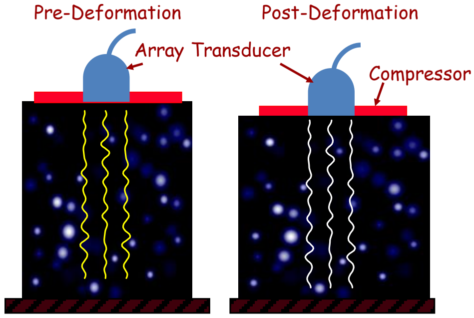
- Many disease processes are associated with changes in tissue stiffness
- Palpation has been used in medical investigations for millennia
- Palpation is a common tool for diagnosis
  - Clinical breast exam
  - Testicular exam
  - Digital rectal (prostate) exam

Quasi-Static Elasticity Imaging

- Use a standard clinical imaging system
  - Ultrasound or MRI
- Acquire a map of anatomy
- Deform the tissue (at surface or remotely)
  - Deformations are tiny
    - Quasi-static systems use about 1% strain in 4cm of breast tissue (0.4mm displacement)
- Acquire another map of anatomy
- Track relative motion due to deformation
- Extract information about tissue viscoelastcity…

Quasi-Static Elasticity Imaging

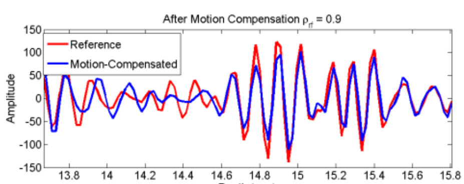
How Do We Create Elasticity Images?



Quasi-Static Elasticity Imaging

How Do We Create Elasticity Images?

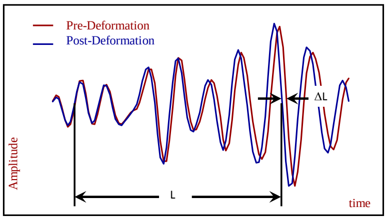
- Deformation of tissue causes the echo signal to change
  - Use that change to track tissue motion



Quasi-Static Elasticity Imaging

How Do We Create Elasticity Images?

RF Echo (A-mode) Signals with 2% Compression

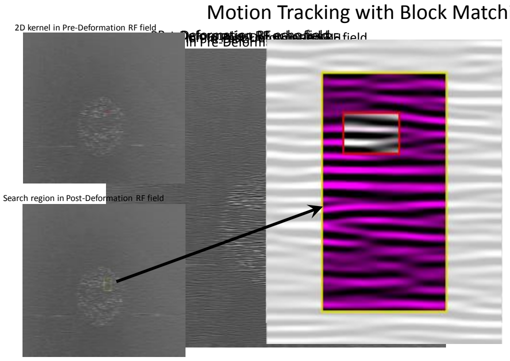


A small deformation (strain) of the tissue results in a small deformation of the signal

Strain = ΔL/L

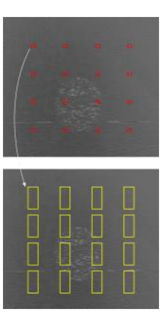
Quasi-Static Elasticity Imaging

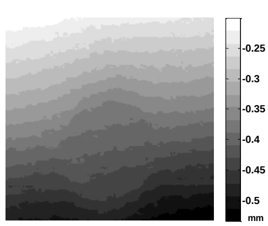
Motion Tracking with Block Matching



Quasi-Static Elasticity Imaging

Motion Tracking with Block Matching

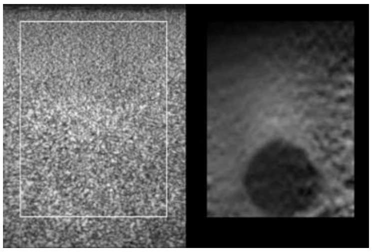




Displacement map

Quantitative Ultrasound Theory

Real-time Freehand Scanning



B-mode Ultrasound | Elasticity (Mechanical Strain)

Applications of Quasi-Static Elastography

New Imaging Modalities For Early Detection and Classification of Breast Masses

- 1 in 8 women get breast cancer
  - 2nd most common cancer among women
- Changes in collagen microstructure and mechanical (stiffness) properties accompany pathologic changes
  - 70% of breast cancers (ages 20—44) detected by self-examination (palpation)
- More quantitative information from imaging…
  - might help increase clinician confidence and reduce biopsy rate of benign lesions
  - improve communication among providers

Breast Quasi-Static Elastography

In widespread use

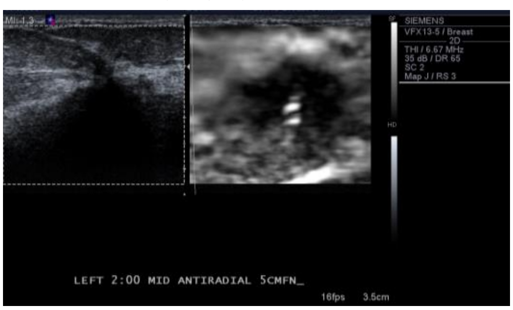
- Initial clinical research literature on breast elastography started nearly 20 years ago
- Hundreds of publications reporting diagnostic utility of strain imaging in breast
  - Many comparing methods of image interpretation
- Recent consensus documents by professional organizations
  - 2013 European Federation of Societies for Ultrasound in Medicine and Biology (EFSUMB)
    - Cosgrove, et al. Ultraschall in Med 34: 238–253, 2013
  - 2013 Japan Society of Ultrasonics in Medicine (JSUM)
    - Nakashima, et al. J Med Ultrasonics 40:359–391, 2013
  - 2014 World Federation of Ultrasound in Medicine and Biology
    - Barr, et al. Ultrasound Med Biol (2014) in press

Breast Quasi-Static Elastography

Invasive Lobular Carcinoma
Malignant lesions are typically larger in strain than B-mode

Breast Quasi-Static Elastography

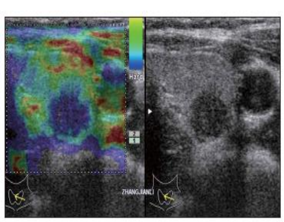
Lesion boundary is more clearly defined
in the elasticity image – provides new information



Applications of Quasi-Static Elastography

Thyroid Elastography

- Lesion detection
- Biopsy guidance
  - Which to biopsy
- Treatment monitoring
- Two recent meta-analyses
  - ROC AUC for differentiating benign v. malignant lesions >0.90

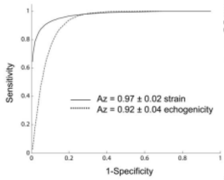


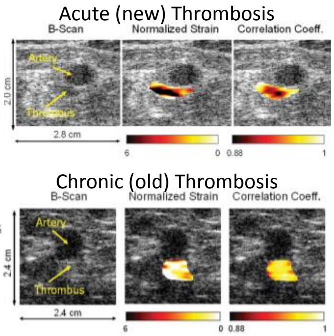
Bojunga J, et al. Thyroid. 20(10):1145-50, 2010 (639 nodules)

Sun J, et al. J Ultrasound Med. 33(3):495-502, 2014 (1063 nodules)

Applications of Quasi-Static Elastography

Deep Vein Thrombosis



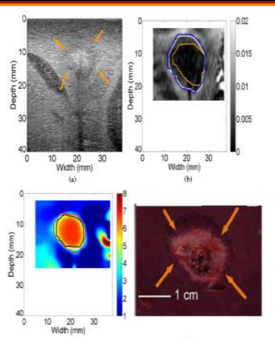


Rubin, et al. J Ultrasound Med 25:1179–1186, 2006

Applications of Quasi-Static Elastography

Ablation Therapy Monitoring

- Ablation zone barely visible on ultrasound (or CT without contrast)
- Easily seen in strain images
- Size and shape of ablation zone in modulus reconstruction closely matches histology

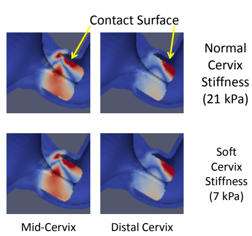


Jiang, et al. Phys Med Biol 55(8):2281-306, 2010

Applications of Quasi-Static Elastography

Cervical Assessment During Pregnancy

- Cervical softening is part of the progression from conception to delivery
- A soft cervix early in pregnancy is a risk factor for preterm birth
  - How soft is 'soft'???



Jiang, et al. World Congress on Biomechanics Boston, MA July, 2014

Strain imaging is a poor approach to estimate organ softness
Feltovich and Hall Ultrasound Obstet Gynecol. 42(2): 121-128, 2013.

Breast Quasi-Static Elastography

- Strain imaging is an option on ultrasound systems from nearly all manufacturers
- Easiest to use and interpret using linear arrays
  - Available on some curved linear and phased arrays
- Methods for image display vary among manufacturers
  - Side-by-side grayscale images (B-mode & strain) provide separate interpretation
  - Color overlay (strain on B-mode) provide relative deformation in the context of relative anatomy
    - Color lookup tables vary among manufacturers so interpret with caution!

Quasi-static (palpation-type) elastography is ***not*** well suited to evaluating:

13%	1.	Breast massess
13%	2.	Thyroid masses
23%	3.	Deep vein thrombosis
20%	4.	Ablation monitoring
30%	5.	Uterine cervix softness

Quasi-static (palpation-type) elastography is ***not*** well suited to evaluating:

1. Breast masses

Quasi-static elastography (strain imaging) is good at displaying variations in tissue stiffness but not well suited to estimating overall stiffness.

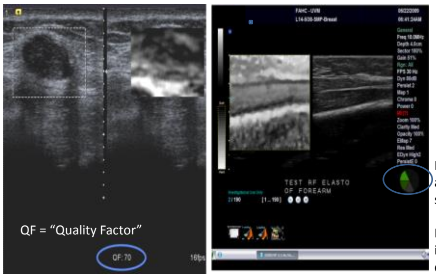
2. Thyroid masses

Accurate modulus reconstructions require detailed information about boundary conditions which are quite complicated in the cervix.

3. Deep vein thrombosis
4. Ablation monitoring
5. Uterine cervix softness

- SOURCE:
  - Feltovich and Hall. Ultrasound Obstet Gynecol. 42(2): 121-128, 2013.
  - Jiang, et al. World Congress on Biomechanics, Boston, MA July, 2014

Tools to Aid in Elasticity Image Analysis



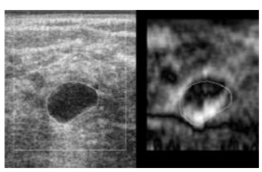
Frame-average strain

Not image quality

Measures of elasticity image quality

Tools to Aid in Elasticity Image Analysis

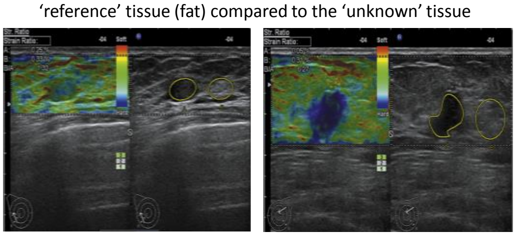
- Automated boundary segmentation
- Mirroring segmentation
  - Trace in one image, display in both



Quantitative Elastography

Strain Ratio

'reference' tissue (fat) compared to the 'unknown' tissue

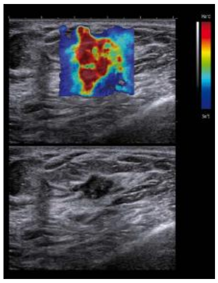


Zhi, et al. Acad Radiol 17: 1227-1233, 2010

Quantitative Elastography

Shear Wave Speed

- Induce a shear wave with acoustic radiation force
- Measure shear wave speed
- Relate shear wave speed to shear modulus
  - "Stiffness" on an absolute scale



Shear wave speed

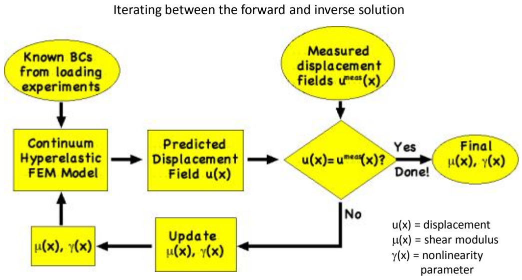
B-mode

Quantitative Elastography

Elastic Modulus Reconstruction

Iterative Algorithm for Nonlinear Reconstruction

Iterating between the forward and inverse solution

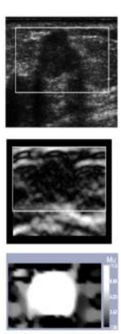


u(x) = displacement
$\mu(x)$ = shear modulus
$\gamma(x)$ = nonlinearity parameter

Quantitative Elastography

Elastic Modulus Reconstruction

- "Stiffness" on an absolute scale
  - Comparison from one study to the next
  - Direct comparison among patients
  - Monitor therapy



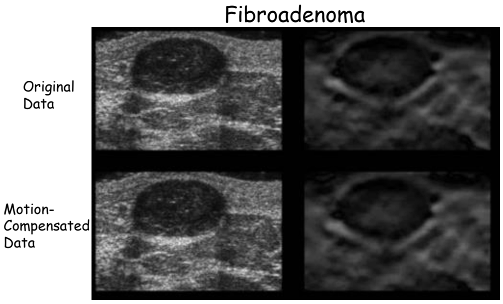
B-mode

Strain

Shear Modulus

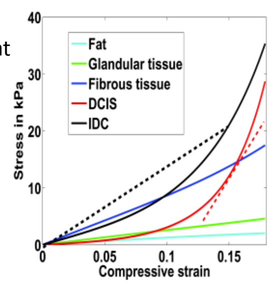
Quasi-Static Elastography

Deformation-Dependent Contrast

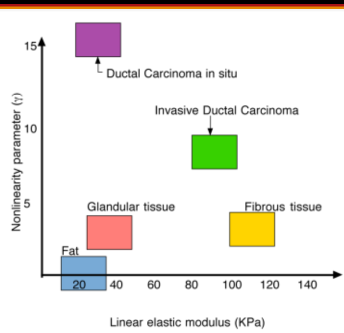


Elastic Nonlinearity

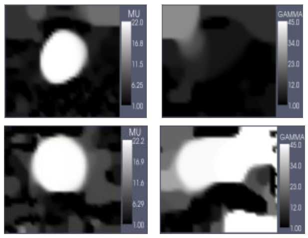
- Tissues become stiffer at large deformation
  - Estimate the slope (modulus) at very small strain
  - Estimate the rate of stiffening (nonlinearity parameter)



Elastic Properties of Breast Tissues



Elastic Nonlinearity



Fibroadenoma

Invasive ductal carcinoma

Small strain shear modulus

Elastic nonlinearity parameter

Elastic Nonlinearity

Summary measures of
small-strain shear modulus (Mu) and nonlinearity parameter (Gamma)

	FA1	FA2	FA3	FA4	FA5	Mean	STDDEV
Mu	22	6.5	4	17	9	11.7	6.7
Gamma	5	19.5	6.6	2.5	3	7.3	6.3
	IDC1	IDC2	IDC3	IDC4	IDC5	Mean	STD DEV
Mu	22.2	7.5	7	22	14.5	14.6	6.6
Gamma	47	41	34	28	20	34	9.5

TAKE AWAY POINTS
1. Unknown preload for these data – likely a larger difference in Mu values
2. Nonlinearity parameter appears highly dependent on tissue type
3. Elasticity imaging systems suffer in clinical trials without control for preload

Methods for Elasticity Imaging

- Advantages of quasi-static (palpation-like) elastography
  - Conceptually simple
  - Can be implemented on most any ultrasound system
  - Generally easy to perform with training and practice
  - Can be converted to absolute elasticity (Young's modulus) with contact pressure measurement and a mathematical model
- Disadvantages of quasi-static elastography
  - Strain is a relative parameter (relative displacement)
    - Not an absolute measure of elasticity
  - Can be challenging to perform in some cases

Methods for Elasticity Imaging

Both quasi-static and radiation force elastography…

- Subject to boundary conditions of data acquisition
  - Both use standard ultrasound imaging systems but have their own limitations
  - Quasi-static elastography is easiest to perform when boundary conditions can be controlled; otherwise can be difficult
  - Radiation force elastography cannot "push" deep into tissue
- Subject to tissue elastic nonlinearity (tissues stiffen when deformed enough)
  - The image obtained will depend on the initial preload (how hard you press)
  - Large preload can reduce elastic contrast
- Both methods have unique image artifacts
  - Decorrelation 'noise' in strain images due to poor motion tracking
  - Odd patterns in strain images with more than one inclusion
  - Complicated shear wave propagation in heterogeneous media (breast)
    - Shear wave reflection, other artifacts not well characterized in the literature
    - Requires further study
- Both methods have demonstrated benefits in many clinical trials

A major advantage of quasi-static elastography v. shear wave elastography is:

13%	1.	The use of standard ultrasound transducers
13%	2.	Imaging any organ in the body
30%	3.	Doesn't depend on boundary conditions
13%	4.	Ability to estimate elastic nonlinearity
30%	5.	Same image no matter how hard I press

A major advantage of quasi-static elastography v. shear wave elastography is:

1. Use of standard ultrasound transducers

Only quasi-static elastography has been shown to objectively estimate the nonlinear elastic properties of tissues.

2. Imaging any organ in the body

3. Doesn't depend on boundary conditions

➔ 4. Ability to estimate elastic nonlinearity

5. Same image no matter how hard I press

- SOURCE:
  - Oberai, et al. Phys. Med. Biol. 54:1191–1207, 2009.
  - Hall, et al. Current Medical Imaging Reviews 7(4):313-327, 2011.

Phantoms for Elastography

- What is the difference between a "phantom" and a "test object"?
  - A "test object" is a tool that might not be "known" from first principles but is used for investigating imaging system performance
    - A grape in Jello
  - A "phantom" is a test object who's behavior can be predicted from first principles and results compared with theory
    - Glass beads in agar to study acoustic scattering theory

Phantoms for Elastography

- Most ultrasound phantoms are made from water based gels
  - Gelatin, agar, polyacrylimide (Zerdine™)
  - Non-water based: Urethane or oil-based gels
- Materials added to control acoustic properties
  - Sound speed; attenuation; scattering properties; acoustic nonlinearity (B/A), etc.
- Long history of controlling acoustic properties with great precision
- These materials are also compatible with MRI

Phantoms for Elastography

- Most ultrasound elastography phantoms are made from variants of the same materials
  - Polyacrylimide
  - Agar, gelatin, agar-gelatin combinations
- For elastography, its necessary to control the cross linking among these polymers
  - Control stiffness
  - Provide temporal stability in elastic properties
- Relatively recent developments:
  - Control elastic nonlinearity
  - Control viscous response over specific frequency ranges
- No current material known to mimic both elastic nonlinearity and viscous response of tissue

Which of the following is ***not*** true regarding tissue-mimicking phantoms for elastography:

23%	1.	They have the same properties as tissue (that's what it means to be "tissue mimicking")
17%	2.	Specific material properties of phantoms can closely match those of tissue
10%	3.	No known tissue-mimicking material closely matches tissue for all elastography experiments
30%	4.	Most phantom materials are water-based gels with additives to control elastic and acoustic properties
20%	5.	Some phantoms are compatible with both ultrasound and MR elastography

Which of the following is ***not*** true regarding tissue-mimicking phantoms for elastography:

1. They have the same properties as tissue (that's what it means to be tissue-mimicking).
2. Specific material properties of phantoms can closely match those of tissue.
3. No known tissue mimicking material closely matches tissue for all elastography experiments.
4. Most materials are water-based gels with additives to control elastic and acoustic properties..
5. Some phantoms are compatible with both ultrasound and MR Elastography

- SOURCE:

  - American Institute of Ultrasound in Medicine (AIUM) Recommended Terminology 3rd Edition. (2008)
  - Hall, et al. IEEE UFFC 44(6):1355-1365, 1997
  - Pavan, et al. Phys Med Biol 57:4787–4804, 2012
  - Browne, et al. Ultrasound Med Biol 27(7): 1053-1060, 2003

Summary

- Palpation-type elastography continues to show great promise for improving diagnosis
- Continuing development of new approaches
  - Tools for image selection and interpretation
  - Quantitative elastography to reduce ambiguity
  - Nonlinear elasticity imaging to increase specificity
- International consensus documents on the appropriate use of the technology now available

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