Imaging Elastographic Properties of Soft Tissues Using Ultrasound

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Presentation Outline

- Motivation
- Definitions & Basic Principles
- Young's Modulus Contrast For Strain Imaging
- Methods for Strain Imaging
  - Elastography
  - Palpation Imaging
  - Physiological Stimuli
  - Sonoelasticity Imaging
  - Radiation Fore Imaging
- Clinical Ultrasound Systems

Motivation

- Most pathological changes are associated with changes in tissue stiffness.
- Palpation is an effective method for lesion detection.
- Many cancers (breast, prostate) are isoechoic, and hence difficult to detect by ultrasound.

Definitions

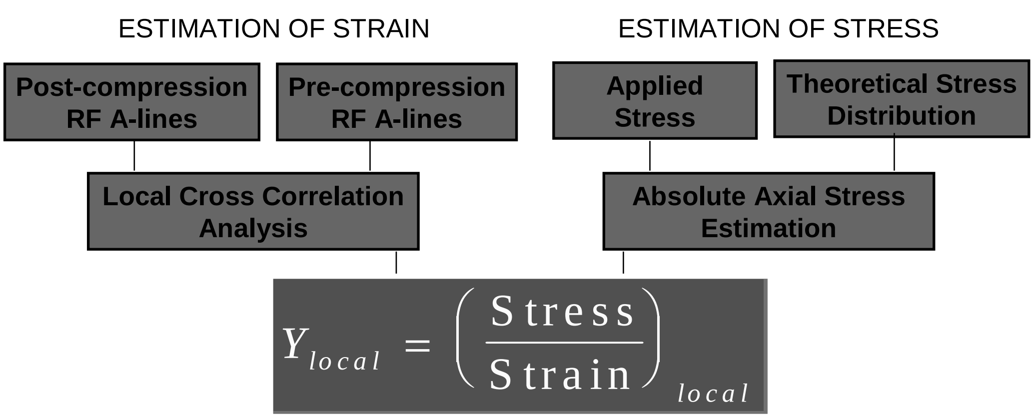
- **Stress** is defined as force per unit area.
- **Shear stress** has the same units as normal stress but represents a stress that acts parallel to the surface (cross section).
- **Strain** is the change in length per unit length. Computed as $(L_f - L_0) / L_0$ where L_f is the final length and L_0 is the initial length.
- **Strain Rate,** specifies how quickly (or slowly) a material is being deformed or loaded, i.e. the amount of strain that occurs in a unit of time. Since strain is dimensionless, units are *1/time*.

Definitions (cont)

- **Young's Modulus** is the constant of proportionality between stress and strain. Units are the same as stress (i.e., force per unit area) and the most commonly used are psi, Pa (Pascal), kPa, and MPa.

- **Poisson's Ratio**, is the ratio of lateral strain to longitudinal strain. Typical range of values is between zero and 0.5.

Basic Principles



Strain Imaging

- Quasi Static Methods (Ophir et al. 1991, O'Donnell et al. 1991)
- Dynamic Methods (Parker et al. 1990, Krouskop et al. 1987, Sandrin et al. 1999)
- Radiation Force (Walker 1999, Fatemi & Greenleaf 1999, Nightingale et al. 2002, Lizzi et al. 2003)

Stress Imaging

- Mechanical or Tactile Imaging (Sarvazyan et al. 1998, Wellman et al. 2001)
  - Computational models
  - Finite Element Modeling
  - Using Surface Pressure Information

Modulus Imaging

- Iterative Modulus Reconstruction (Kallel et al. 1995)
- Direct Methods (Solving PDE's) (Emelianov et al. 2000, Sumi et al. 1995)
- Finite Element Inversion (Zhu et al. 2003)

Young's Modulus As the Contrast Mechanism

Background

- Tissue Elasticity Imaging methods are based on imaging differences in stiffness or Young's Modulus between normal and abnormal tissue conditions.
- Literature reports on stiffness variations between different tissue types is limited.
- However, these results demonstrate significant stiffness variations between normal and pathological tissue.

Measurements of breast tissues *in-vitro**

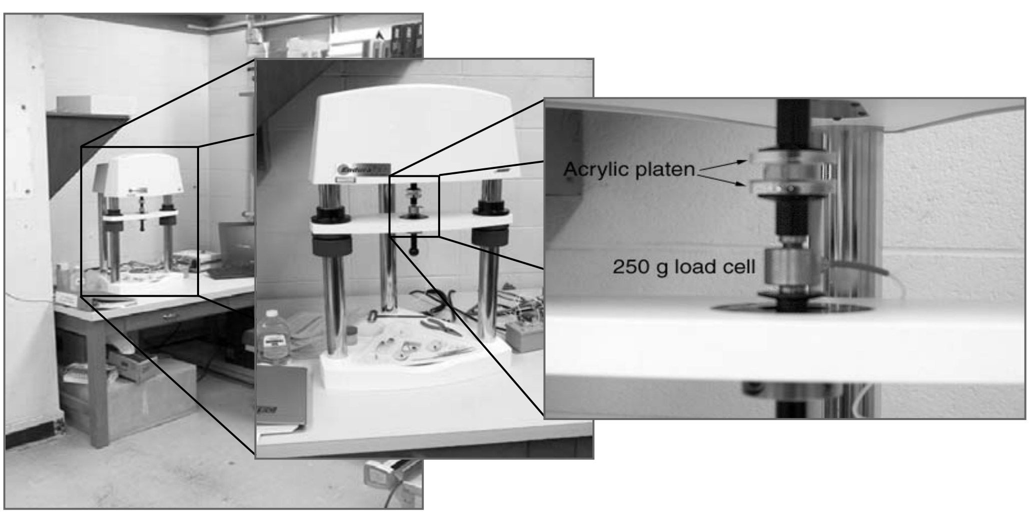
Tissue Type	Number Of Patients	Tissue Stiffness (kPa) 20% Pre-compression 20%/sec Strain Rate
Normal Fat	40	20 ± 6
Normal Glandular	31	57 ± 19
Fibrous	21	233 ± 59
Ductal Tumor	23	301 ± 58
Infiltrating Ductal Tumor	32	490 ± 112

**Krouskop TA, Wheeler TM, Kallel F, Garra BS, Hall T., Elastic moduli of breast and prostate tissues under compression, Ultrason Imaging, 1998; 20(4): 260-74.*

Basic data on Breast tissues

Krouskop TA, Wheeler TM, Kallel F, Garra BS, Hall T., Elastic moduli of breast and prostate tissues under compression, Ultrason Imaging, 1998; 20(4): 260-74.

ELF 3220 at UW-Madison

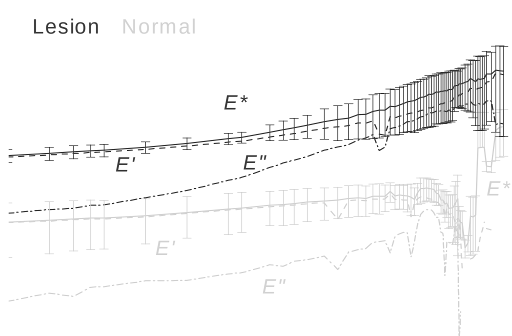


Experimental Methods

- Tissue samples prepared as cylinders 20 mm diameter x ~5 mm height
- Samples compressed to 4 % strain at varying frequencies
- Load response measured with 50 Lb load cell
- Thermal lesions prepared by RF ablation (70°, 90° C for 10 minutes)

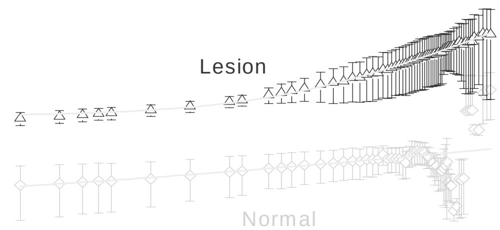
Experimental Results

In Vitro Canine Liver – Comparison



Experimental Results

In Vitro Canine Liver – Comparison, Model Fits



Normal	Lesion
E_0 = 2.54 x 10^3 Pa	E_0 = 2.66 x 10^4 Pa
E_1 = 3 x 10^3 Pa sec$^\alpha$	E_1 = 2.2 x 10^3 Pa sec$^\alpha$
α = 0.154	α = 0.555

Discussion

- Pathology generally exhibits ***large elastic contrast*** with normal background.
- Reliable ***small elastic contrast*** *exists among normal soft-tissue* components
- Results show that the complex modulus is dependent on frequency, but is explained well by ***fractional derivative*** Kelvin-Voigt model
- High frequency results may be better represented by measuring shear modulus

Methods for Strain Imaging

Methods for Strain Imaging

- ☆ Mechanical Stimuli used for perturbation
  - ➢Quasi-Static Methods (Ophir et al., O'Donnell et al.)
    - ❖Quasi Static Compression (Elastography)
    - ❖Palpation Imaging (Hall TJ) or Freehand Compression
    - ❖Low frequency Oscillatory Compression (Ermert H)
  - ➢Dynamic Methods
    - ❖Low frequency Vibration (Sonoelasticity imaging)
    - ❖Physiological Stimuli
  - ➢Radiation Force Based Techniques (static & dynamic)
- ☆ Imaging Modality Utilized
  - ➢Ultrasound
  - ➢Magnetic Resonance Imaging
  - ➢Optical Coherence Tomography
- ☆ Time Domain or Frequency Domain Processing

Quasi-Static Methods

Algorithms

- Cross-Correlation (Ophir et al. 1991)
- Phase shift correlation (O'Donnell et al. 1991)
- Phase-root seeking (Pesavento et al. 2000)
- Block-matching methods (Chaturvedi et al. 1998; Bohs et al. 1995)
- Decorrelation methods (Bamber et al. 1995; Varghese & Ophir 1996)
- Envelope processing (Varghese & Ophir 1998)
- Envelope + RF (Shiina et al. 1995; Alam et al. 1997)

Quasi-Static Methods

Elastography

(cross-correlation)

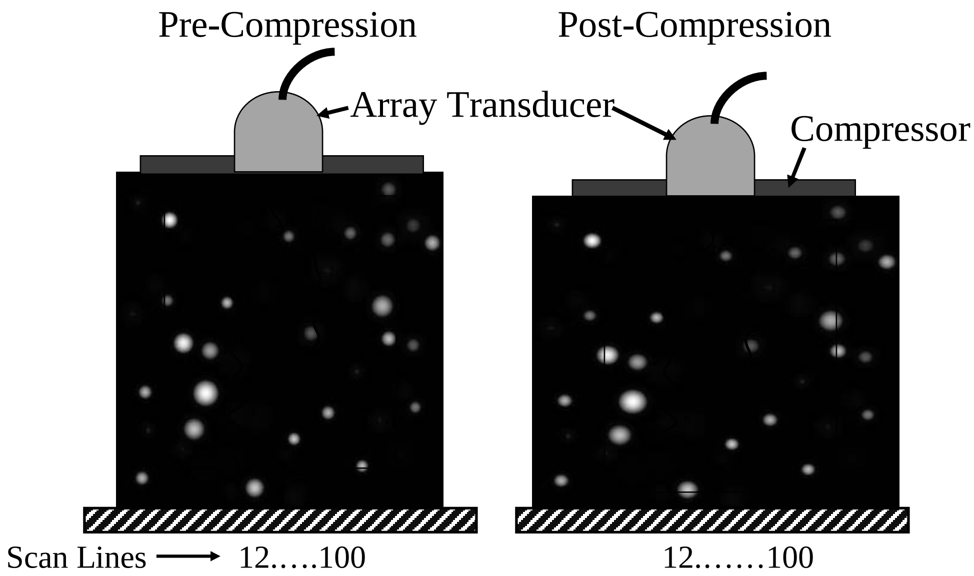
Definition

Elastography:

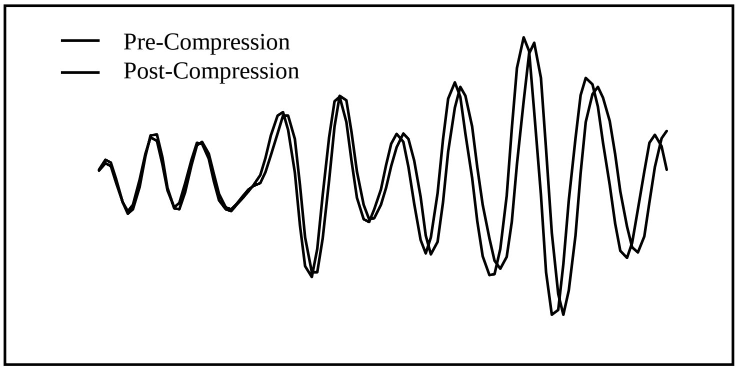
An imaging technique whereby local tissue strains are measured from differential ultrasonic speckle displacements. These displacements are generated by a weak, quasi-static stress field.

The resultant axial-strain, lateral-strain, modulus or Poisson's ratio images are all referred to as **Elastograms.**

ELASTOGRAPHY



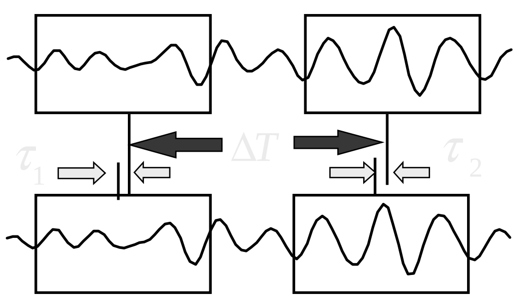
RF Signal Compression: 2% applied strain



Notice that a small compression (strain) of the tissue results in a small compression of the signal (similar to frequency modulation)

Basic Principles: Estimation of Strain

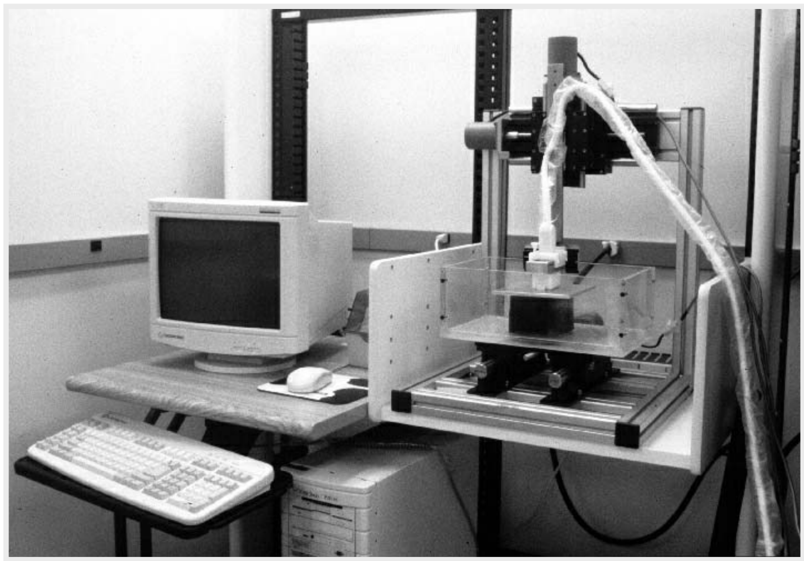
Pre-compression RF line



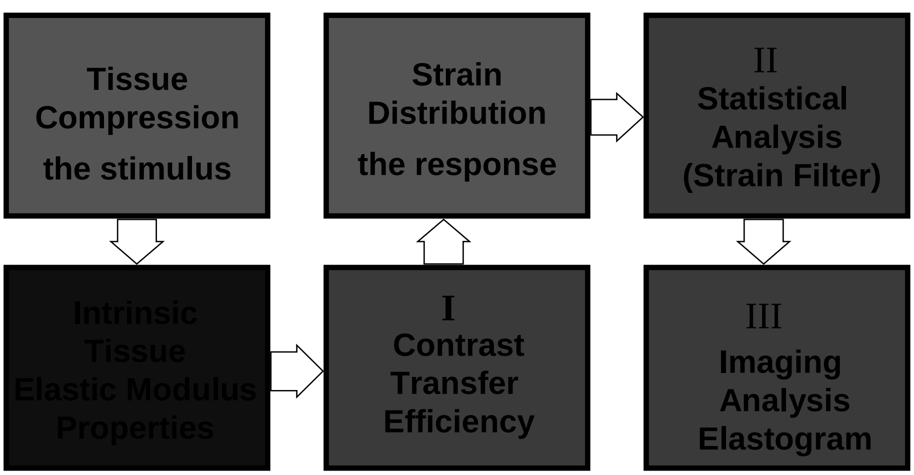
Post-compression RF line

$$Strain = \frac{\tau_2 - \tau_1}{\Delta T}$$

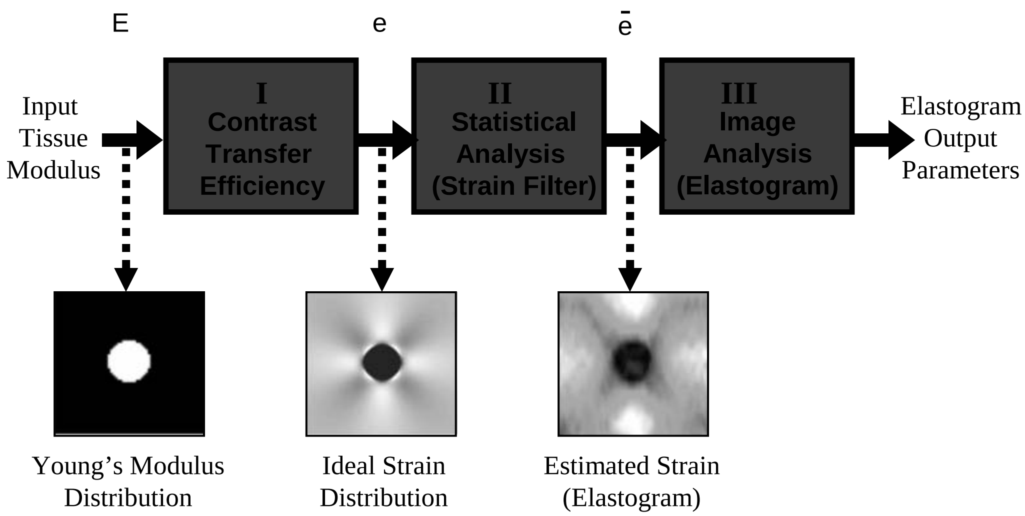
Elastography Data Acquisition System



The Elastographic Process



The Elastographic Process



In-vivo Applications of Elastography

- Breast Imaging (Garra et al. 1997; Hiltawsky et al. 2001; Hall et al. 2003)
- Prostate Imaging (Lorenz et al. 2000; Souchon et al. 2002, 2003)
- Thyroid Imaging (Meixner et al. 2002)
- Liver Imaging (Varghese et al. 2002; Merritt et al. 2002; Kolen et al. 2002)
- Treatment Monitoring (Varghese et al. 2002; Merritt et al. 2002; Souchon et al. 2003)
- Intravascular Strain Imaging (de Korte et al. 2000; 2002a; 2002b; 2003)
- Cardiac Elastography (Konofagou et al. 2000; Varghese et al. 2002)
- Deep Vein Thrombosis (Emelianov et al. 2002)
- Kidney Transplant Monitoring (Emelianov et al. 2002)

Breast Imaging

- Cancers are statistically significantly darker (stiffer) than benign fibroadenomas and other benign lesions.
- The transverse dimension of cancers is larger on the elastograms than their size estimates on the sonogram.
- Freehand and real-time implementation on an US scanner.

*Garra, B.S., Céspedes, E.I., Ophir, J., Spratt R.S., Zuurbier R.A., Magnant, C.M., Pennanen, M.F., Elastography of breast lesions: Initial clinical results, Radiology, 1997, 202, 79-86.

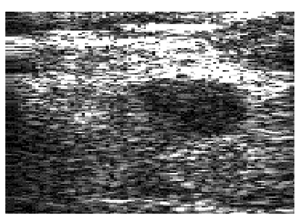
*Ophir, J., Alam, K.,Garra, B., Kallel, F., Konofagou, E., Krouskop, T., Varghese T., Elastography: Ultrasonic estimation and imaging of the elastic properties of tissues, Invited Paper & Review, Proc. Inst. Mech. Eng., Part H J Engg. Med., Vol. 213, pp. 203-233,1999.

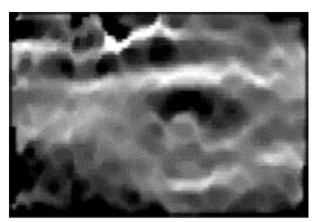
*Hiltawsky KM, Kruger M, Starke C, Heuser L, Ermert H, and Jensen A, Freehand ultrasound elastography of breast lesions: clinical results, Ultrasound Med Biol. 27 (11), 1461-1469., 2001

*Hall TJ, Zhu Y, and Spalding CS, In vivo real-time freehand palpation imaging, Ultrasound Med Biol. 29 (3), 427-435., 2003 .

Breast tumors *in-vivo* (1999)

Fibroadenoma

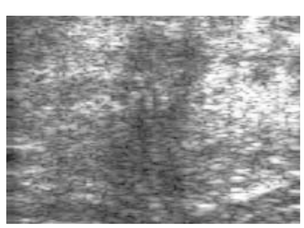


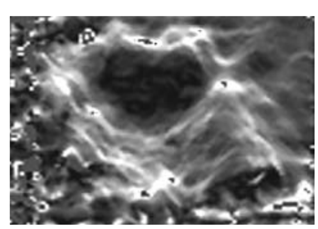


Sonograms

Elastogram

Infiltrating Ductal Carcinoma





Prostate Imaging

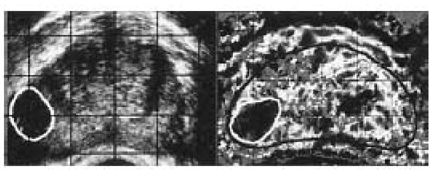
- Elastograms obtained using a balloon to provide the compressive force.
- The transducer probe also has been used as the compressor.
- Real-time implementation has been demonstrated.

Lorenz A, Ermert H, Sommerfeld HJ, Garcia-Schurmann M, Senge T, and Philippou S, [Ultrasound elastography of the prostate. A new technique for tumor detection], Ultraschall Med. 21 (1), 8-15., 2000.

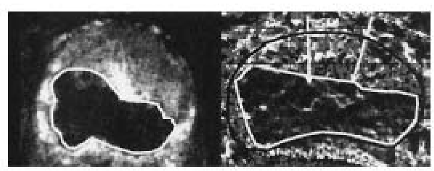
Souchon R, Soualmi L, Bertrand M, Chapelon JY, Kallel F, and Ophir J, Ultrasonic elastography using sector scan imaging and a radial compression, Ultrasonics. 40 (1-8), 867-871., 2002 .

Souchon R, Rouviere O, Gelet A, Detti V, Srinivasan S, Ophir J, and Chapelon JY, Visualisation of HIFU lesions using elastography of the human prostate in vivo: preliminary results, Ultrasound Med Biol. 29 (7), 1007-1015., 2003.

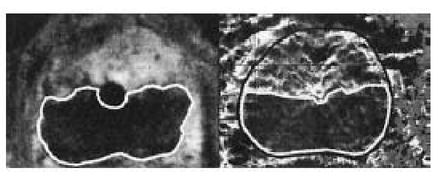
In-vivo Prostate Elastograms



Ultrasound B-Mode Elastogram
Before HIFU Ablation



Ultrasound Elastogram
During HIFU Ablation



MRI Elastogram
After HIFU Ablation

Souchon R, Rouviere O, Gelet A, Detti V, Srinivasan S, Ophir J, and Chapelon JY, Visualisation of HIFU lesions using elastography of the human prostate in vivo: preliminary results, Ultrasound Med Biol. 29(7), 1007-15., 2003.

Treatment Monitoring

- RF ablated lesion *in-vivo* in an animal model
  - Use the RF electrode as the compressor
  - Use compression induced due to diaphragmatic stimuli
- HIFU lesions in prostate imaged using a balloon to provide the compressive stimuli.
- Using a stepper motor controlled compression on an open chest animal model on RF ablated lesions.

***Varghese T, Zagzebski JA, and Lee FT, Jr., Elastographic imaging of thermal lesions in the liver in vivo following radiofrequency ablation: preliminary results, Ultrasound Med Biol. 28 (11-12), 1467-1473., 2002.*

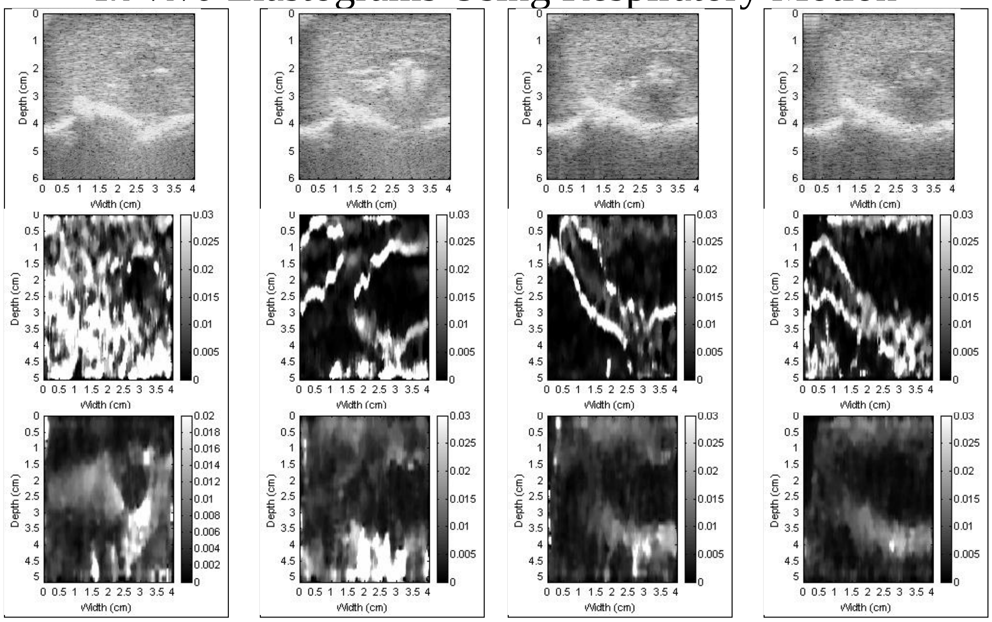
*** *Souchon R, Rouviere O, Gelet A, Detti V, Srinivasan S, Ophir J, and Chapelon JY, Visualisation of HIFU lesions using elastography of the human prostate in vivo: preliminary results, Ultrasound Med Biol. 29 (7), 1007-1015., 2003.*

***Merritt CR, Forsberg F, Liu J, and Kallel F, In-vivo elastography in animal models: Feasibility studies, (abstract), J. Ultrasound Med.. 21 S98, 2002.*

In Vivo Study

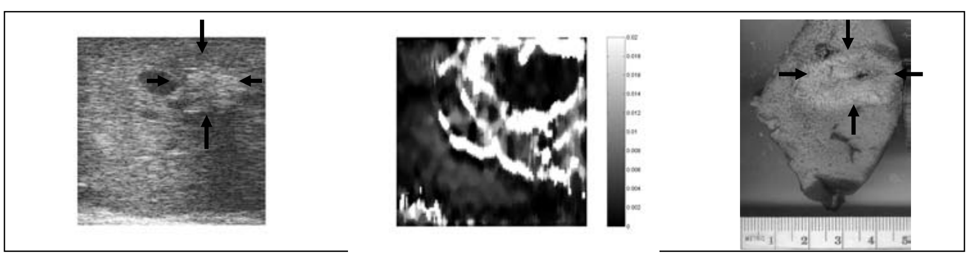
- 75 kg Female Yorkshire Pig
- Approved RARC Protocol
- Liver tissue exposed by laparatomy
- RITA 1500 electrosurgical device for ablation
  - 50W; 100^{o}C; 10min
- Acuson scanner with 12 Bit Gage Board at 50 MHz sampling rate to acquire RF echo signals at 2 f/s.
- Liver removed, sliced following procedure

In-vivo Elastograms Using Respiratory Motion

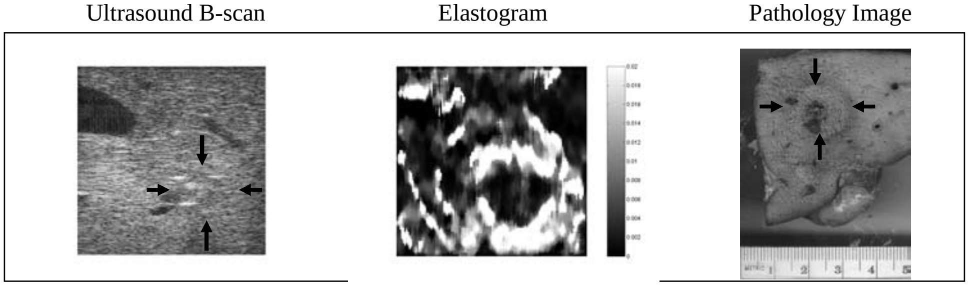


t = 51 Seconds | t = 3.78 Minutes | t= 8.13 Minutes | t = 12.03 Minutes

In-vivo Elastograms Using the Ablation Probe



Ultrasound B-scan | Elastogram | Pathology Image



Ultrasound B-scan | Elastogram | Pathology Image

Thyroid Imaging

- Freehand and real-time elastographic imaging of thyroid
- Tumor slippage is believed to occur in many benign masses, while slippage appears to be absent in malignant masses.

***Meixner D, Hangiandreou NJ, Charboneau JW, Hall TJ, Zhu Y, and Farrell MA, Initial Clinical Experience with Real-time Ultrasound Strain Imaging of the Thyroid, (abstract) RSNA. 225 713, 2002*

*** *Wilson et al. (personal communication).*

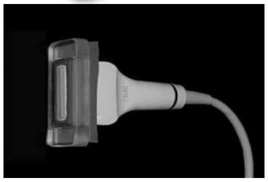
Quasi-Static Methods

Palpation Imaging

(block matching)

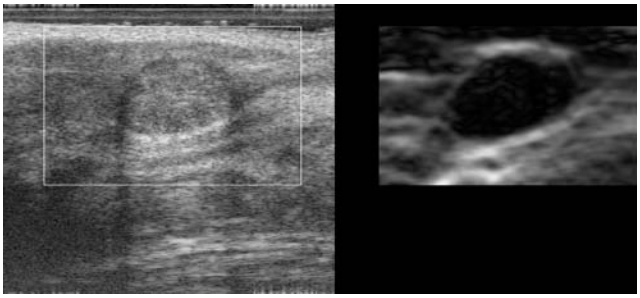
Palpation Imaging System

- Implemented on the Siemens Elegra
  - Acquisition, Processing, and Display
- Uses Any Linear Array Transducer
- Displays B-mode and Strain Images Side-by-Side in Real-Time (~7fps)
- Performed with Freehand Scanning
  - Technique almost identical to standard breast sonography with compression
- Only modification to the Elegra (other than our software) is a small compressor plate attached to the array



Fibroadenoma

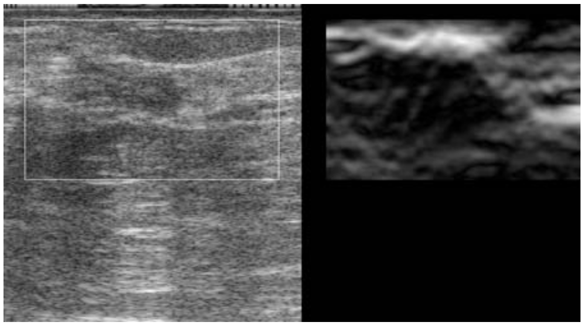
(Example from Charing Cross Data)



- Typical Strain Patterns in Fibroadenoma
  - Compression-dependent strain image contrast
  - Smooth boundaries
  - Lesion area comparable to that in B-mode images

Invasive Ductal Carcinoma

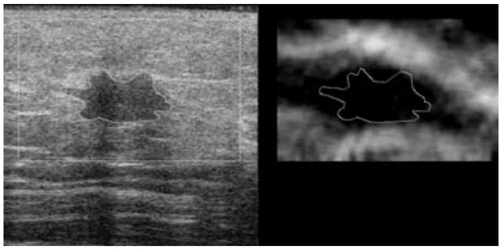
(Example from Charing Cross Data)



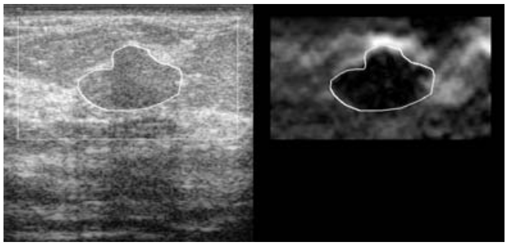
- Typical Strain Patterns in IDC
  - High negative contrast (dark) lesion regardless of compression
  - Lesion area larger than seen in B-mode image

Relative Size of Lesions

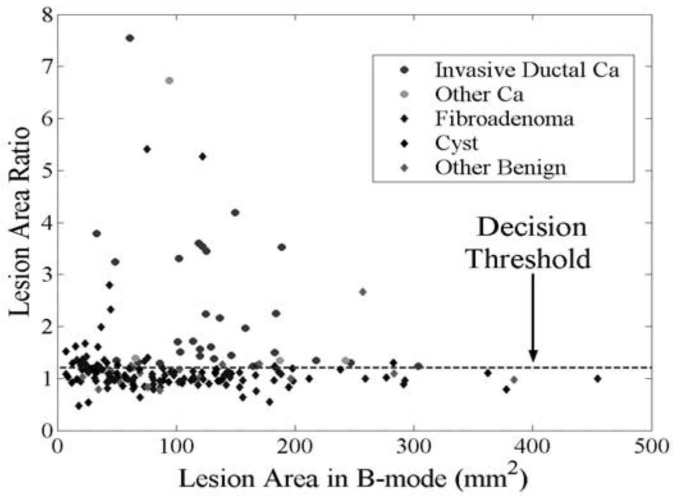
Invasive Ductal Carcinoma



Fibroadenoma



Combined KUMC and Charing Cross Results



Results of ROC (1 observer)

	Area Ratio	B-mode Sono (Stavros, et al.)	1st Screen Mammo (Baines, et al)
ROC Area	0.930	0.729	---
Sensitivity	100%	98.4%	69%
Specificity	75.5%	67.8%	94%
PPV	56.9%	38%	8.6%
NPV	100%	100%	99.7%

Dynamic Methods

Sonoelasticity Imaging

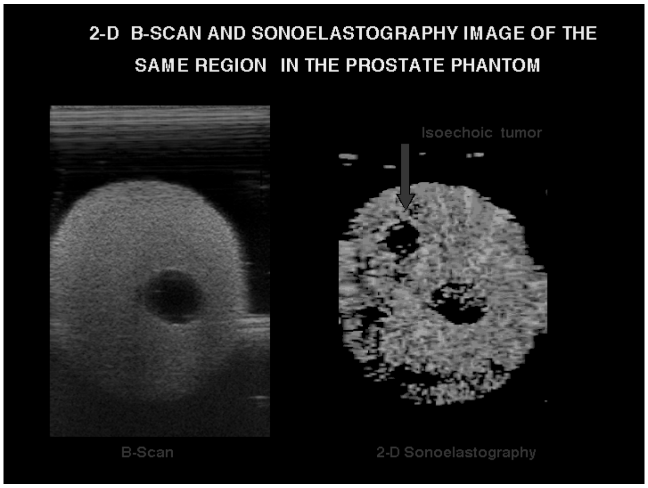
Sonoelasticity Imaging

Definition

Sonoelasticity imaging is a method for assessing the stiffness, or elastic constants, of tissues. This is a hybrid imaging technique which uses Doppler ultrasound to map out, or image, the local vibrations within tissues or structures which are excited by externally applied oscillations at low frequencies (10-1000 Hz typically.) The concept is that stiff tumors surrounded by soft tissues will present abnormal vibration amplitudes and can therefore be detected.

Robert M. Lerner and Kevin J. Parker, University of Rochester, 1986.

Sonoelasticity Imaging



Robert M. Lerner and Kevin J. Parker, University of Rochester, 1986.

Dynamic Methods

Physiological Stimuli

Cardiac Elastography

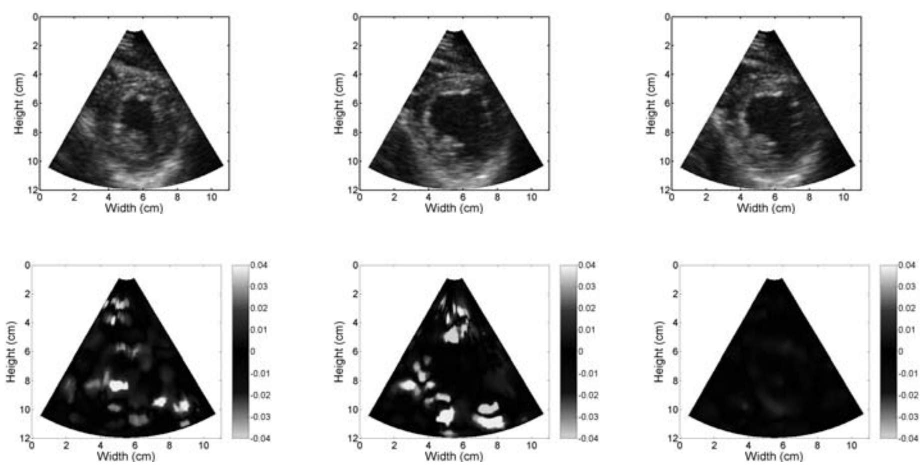
- Cardiac-elastography can provide a 2-D quantitative and translation independent measure of myocardial strain.
- Cardiac elastography provides strain information with excellent spatial resolution (dependent on window length and overlap), with the same temporal resolution provided by 1-D SRI.
- Motion artifacts due to the translation and rotation of the heart are minimized with the high frame rates available.

**Konofagou EE, D'Hooge J, and Ophir J, Myocardial elastography--a feasibility study in vivo, Ultrasound Med Biol. 28 (4), 475-482., 2002.*

** Varghese T, Zagzebski JA, Rahko P, and Breburda CS, Ultrasonic imaging of myocardial strain using cardiac elastography, Ultrason Imaging. 25 (1), 1-16., 2003.*

Short Axis View

Patient with Coronary Artery Disease



End Systole　　End Diastole　　Diastasis

Intravascular Elastography

- Reproducible intravascular elastograms *in-vivo* are obtained near end-diastole.
- Elastograms can also be obtained using a balloon to provide the compressive force.

deKorte, C. L., Van der Steen, A. F. W., Céspedes, E.I., Pasterkamp G., Carlier S G., Mastik F., Schoneveld A H., Serruys P W., and Bom, N, Characterization of plaque components and vulnerability with intravascular ultrasound elastography, Phys. Med. Biol., 25, 1465-1475, 2000.

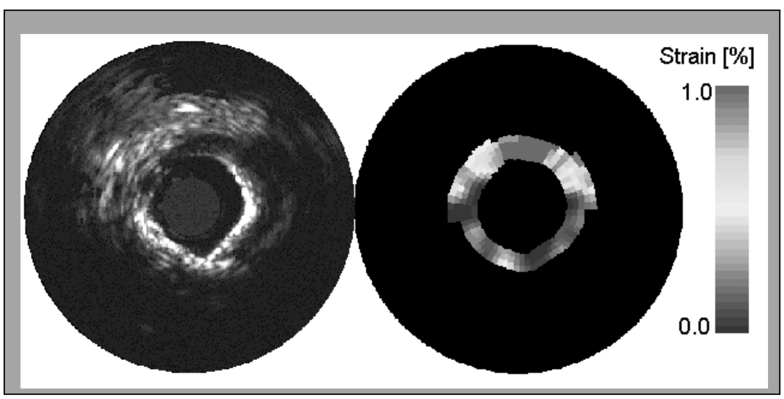
** Shapo, B.M., Crowe, J.R., Skovoroda, A.R., Eberle, M.J., Cohn, N.A., and O'Donnell, M., Displacement and strain imaging of coronary arteries with intraluminal ultrasound, IEEE Trans. Ultrason. Ferroel. Freq. Cont., 43(2), 234-246, 1996.*

**de Korte CL, Carlier SG, Mastik F, Doyley MM, van der Steen AF, Serruys PW, and Bom N, Morphological and mechanical information of coronary arteries obtained with intravascular elastography; feasibility study in vivo, Eur Heart J. 23 (5), 405-413., 2002*

**de Korte CL, Sierevogel MJ, Mastik F, Strijder C, Schaar JA, Velema E, Pasterkamp G, Serruys PW, and van der Steen AF, Identification of atherosclerotic plaque components with intravascular ultrasound elastography in vivo: a Yucatan pig study, Circulation. 105 (14), 1627-1630., 2002.*

**de Korte CL, Schaar JA, Mastik F, Serruys PW, and van der Steen AF, Intravascular elastography: from bench to bedside, J Interv Cardiol. 16 (3), 253-259., 2003*

In-vivo Intravascular Elastograms
Coronary Artery



de Korte CL, Carlier SG, Mastik F, Doyley MM, van der Steen AF, Serruys PW, and Bom N, Morphological and mechanical information of coronary arteries obtained with intravascular elastography; feasibility study in vivo, Eur Heart J. 23 (5), 405-413., 2002

Radiation Force Imaging

Radiation Force Based Imaging

- Quasi-static methods
  - Acoustic Radiation Force Imaging (ARFI)
    - Duke University (Trahey GE, Nightingale K)
    - University of Virginia (Walker W)
  - Radiation Force Imaging
    - Riverside Research Institute (Muratore R, Lizzi F)
    - Brigham & Women's Hospital (Hyunen K, Konofagou E)
- Dynamic Methods
  - Vibro-acoustography
    - Mayo Clinic (Greenleaf J, Fatemi M)
  - Supersonic Shear Imaging
  - Transient Elastography
    - Laboratoire Ondes et Acoustique (Fink M, Catheline S)

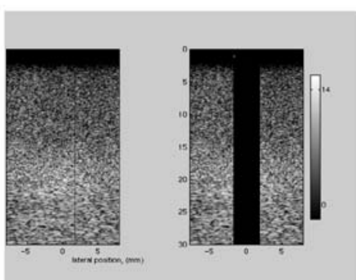
Acoustic Radiation Force Based Imaging (ARFI)

Definition

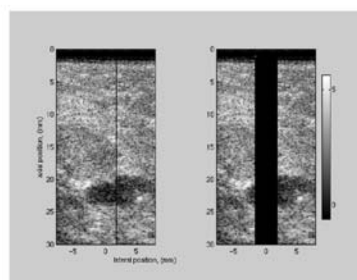
Acoustic radiation force is a phenomenon associated with the propagation of acoustic waves through a dissipative medium. It is caused by a transfer of momentum from the wave to the medium, arising either from absorption or reflection of the wave. This momentum transfer results in the application of a force in the direction of wave propagation. The magnitude of this force is dependent upon both the tissue properties and the acoustic beam parameters. The duration of the force application is determined by the temporal profile of the acoustic wave.

Source: Duke University web-site: Nightingale K, Trahey GE

ARFI Images



Uniform Phantom



in-vivo Breast Tissue

Source: Duke University web-site: Nightingale K, Trahey GE et al.

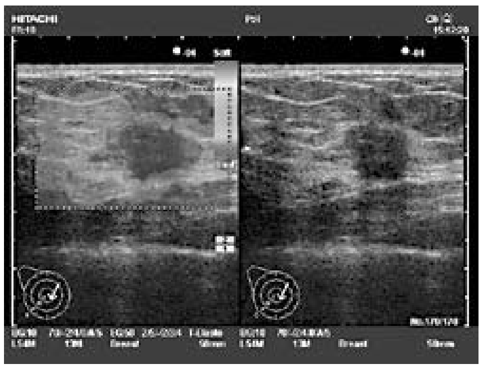
Clinical Systems For Strain Imaging

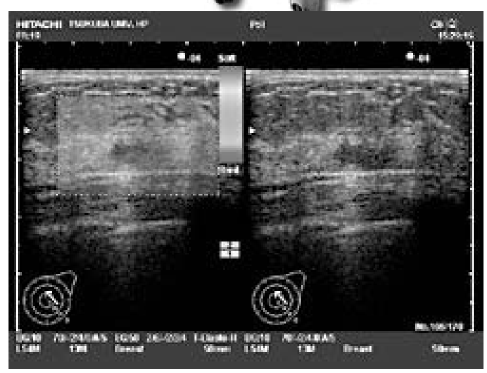
Siemens SONOLINE®
Antares Platform

- Generic Description
  - 192 element beamformer
  - 100-base-T network port
  - CD writer onboard
- Ultrasound Research Interface

Hitachi EUB-8500 Platform

Real-time Tissue Elastography





Conclusions & Future Directions

- The tradeoffs among engineering/elastographic image parameters are now reasonably well understood.
- Reliable small elastic contrast exists among normal soft-tissue components; good CNR allows its visualization.
- Pathology generally exhibits a large elastic contrast.
- *In-vivo* elastography is rapidly developing in many areas
- Freehand and real-time *in-vivo* elastography is now being practiced

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MEDICAL PHYSICS