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Advances in Ultrasound-mediated Imaging

Richard Bouchard, Ph.D.
Department of Imaging Physics
The University of Texas MD Anderson Cancer Center

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Talk Disclaimer

- Brief overview of recent applications given
- Most of the technical slides removed or moved to the end
- Talk meant to give a general overview of two ultrasound-mediated imaging modalities

Talk Outline

- Introduction
  - Why ultrasound-mediated imaging?
  - What is ultrasound-mediated imaging?
- Photoacoustic (PA) Imaging
  - Background
  - Current PA imaging applications
- ARF-Based Shear Wave Imaging
  - Background
  - Cardiac ARF-based shear wave imaging
- Conclusions

Driving Question

What should a medical imaging solution offer to meet the healthcare needs of today and tomorrow?

Imaging Needs

- Easy to use
- Good penetration depth
- Good resolution
- Good soft tissue contrast
- Function vascular imaging (Doppler & microbubbles)

✔ (Past Needs)

- Low cost
- Point-of-care implementation

✔ (Current Needs)

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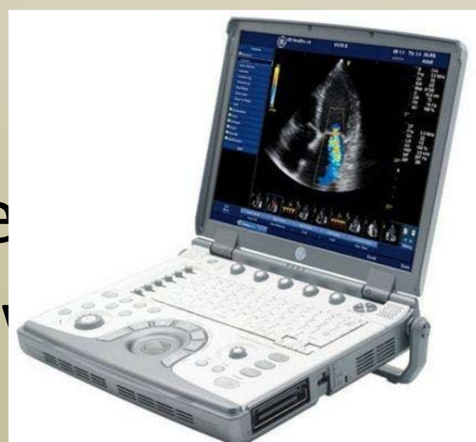
...but ... e futu...



Full Functionality
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Future Needs

- Sensitivity to cellular/molecular dynamics
  - Targeted plasmonic nanoparticles
  - Metabolic imaging based on oxygen saturation
  - Early detection of cancer
  - “Personalized Cancer Therapy
- Contrast for therapy planning and guidance
  - Visualization of surgical implants/tool and contextual anatomy
  - Photoacoustic-based thermography
  - Quantitative tissue characterization
- Quantification of material tissue properties
  - Tissue stiffness characterization for improved diagnosis
  - Endpoint for ablation therapy

✔ (with Ultrasound-Mediated Imaging)

✗ (with Conventional Ultrasound)

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Ultrasound-mediated Imaging

“Advances in Ultrasound-mediated Imaging”

Advantages of conventional B-mode (i.e., same hardware and basic sig... ...ess... added fun...

To meet current/future imaging needs:

- Photoacoustic-Ultrasonic Imaging
- Sensitivity to cellular/molecular dynamics
- ARFI-Based Shear Wave Imaging
- Contrast for therapy planning and guidance
- Ultrasound-Based Thermography
- Quantification of related tissue properties
- Magnetomotive ...
- Vibroacoustography
- Ultrasound RF Analysis for Tissue Charact...
- Ultrasound Current Source Density Imaging

Basic

Engineering Phantom

Chemistry In Vitro

Bench

Preclinical

Large

Small

Bedside

Clinical

Clinic

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Conventional Ultrasound

- Acoustic pulse transmitted into soft tissue from focused transducer
- Energy scatters at acoustic impedance mismatches

$$Z = \rho c = \sqrt{\rho K}$$

- Transducer receives backscattered energy ("echo")
- Beamforming/post-processing
- B-mode image typical format
- Tx pulse few cycles long

$$\text{Res}_{\text{Axial}} = \frac{\text{pulse length}}{2}$$

- Tx pulse 1-60 MHz

$$\text{Res}_{\text{Lat}} \propto \text{F\#} \times \lambda$$

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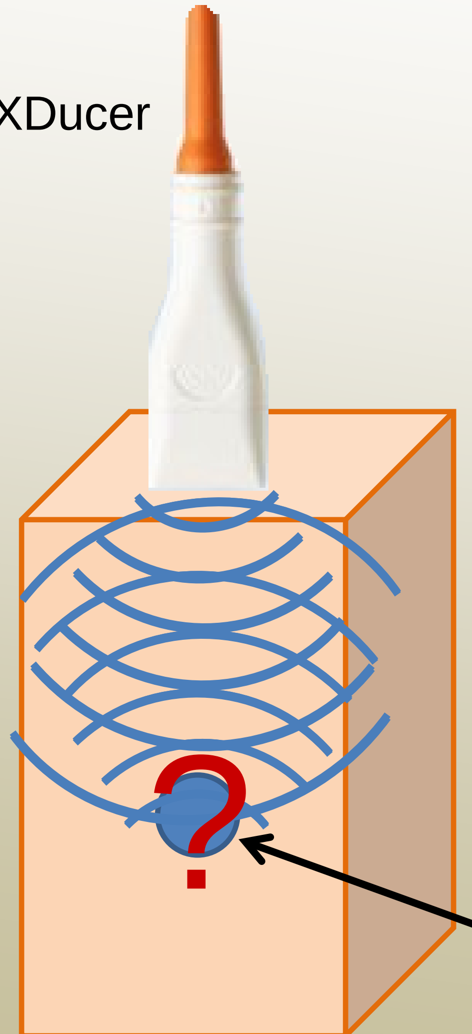
Ultrasound-Mediated Imaging

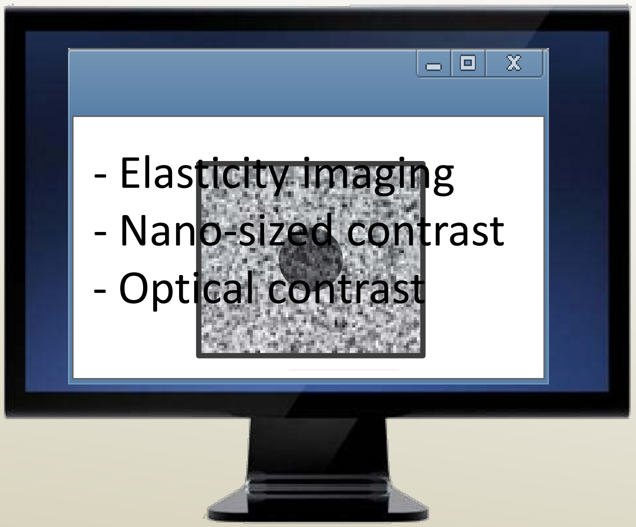
Ultrasound XDucer



ROI

Tissue

Ultrasound Image



Display

What if we induce a local mechanical perturbation in the ROI and THEN apply conventional ultrasound imaging methods?

Induce gross motion or create cell/molecule-specific acoustic sources.

Integration Simplicity

- Can be implemented with a conventional ultrasound scanner
- Image presentation same of clinically accepted B-mode schemes
- Relies on conventional beamforming for image acquisition
- Induce a local mechanical perturbation:
  - Photoacoustic Approaches –> Optical Contrast
  - ARFI-based Approaches –> Elasticity Imaging

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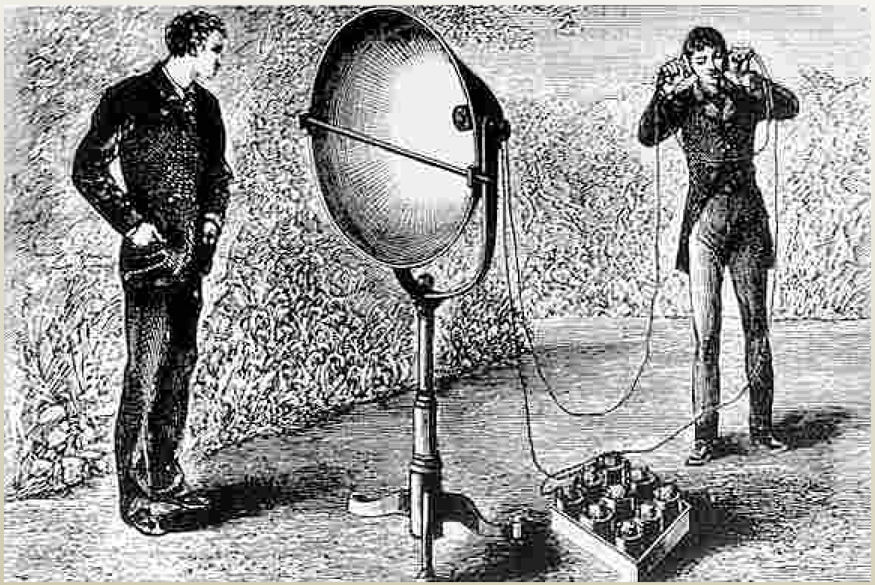
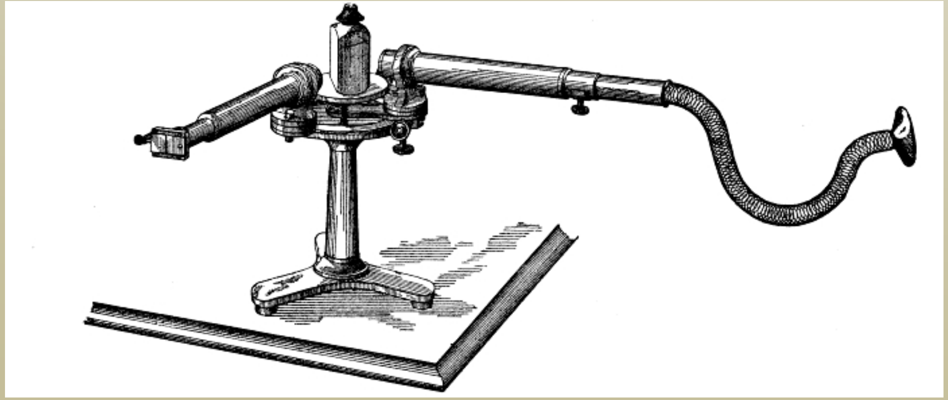
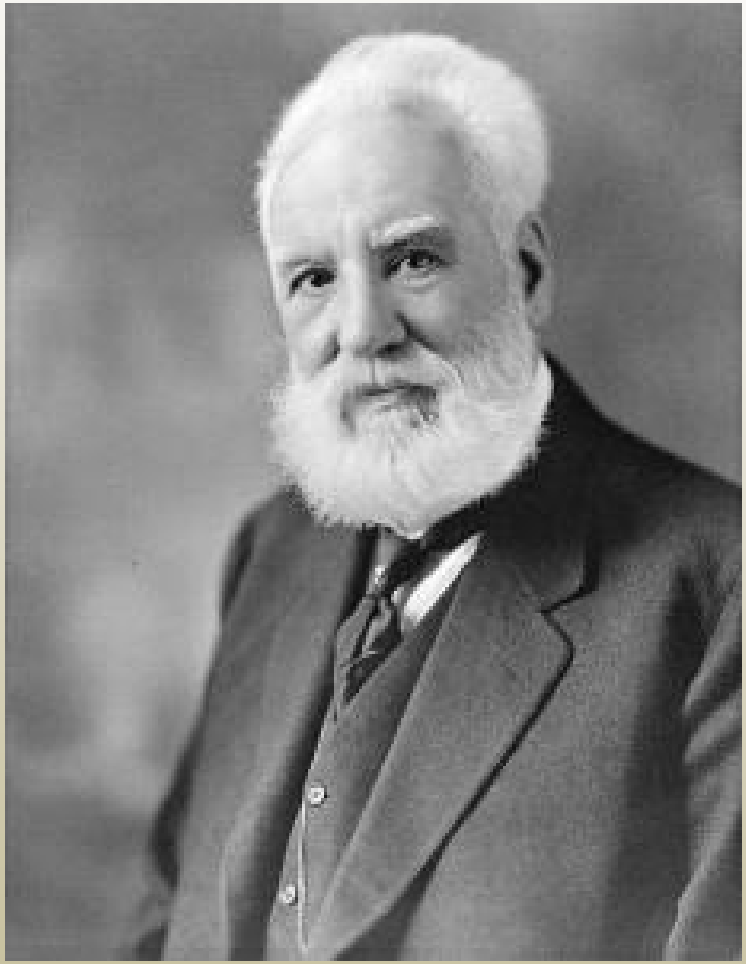
Birth of Photoacoustics

(Alexander Bell and Charles Tainter, 1880)







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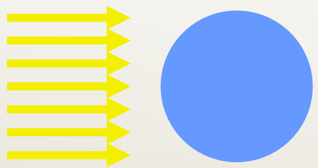
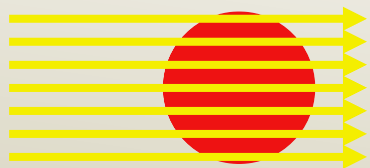
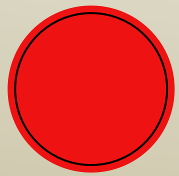
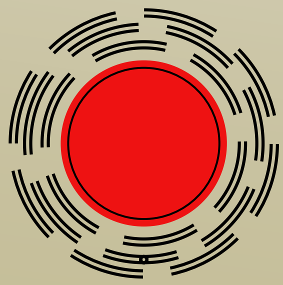
Lighting and Thunder


Tissue is irradiated with a near-infrared laser pulse


Optical energy is absorbed by tissue and converted into thermal energy


Optical absorption of nanosecond light leads to rapid thermal expansion of tissue and generation of acoustic (pressure) transients


The acoustic signal, recorded using an ultrasound transducer, is used to form an image

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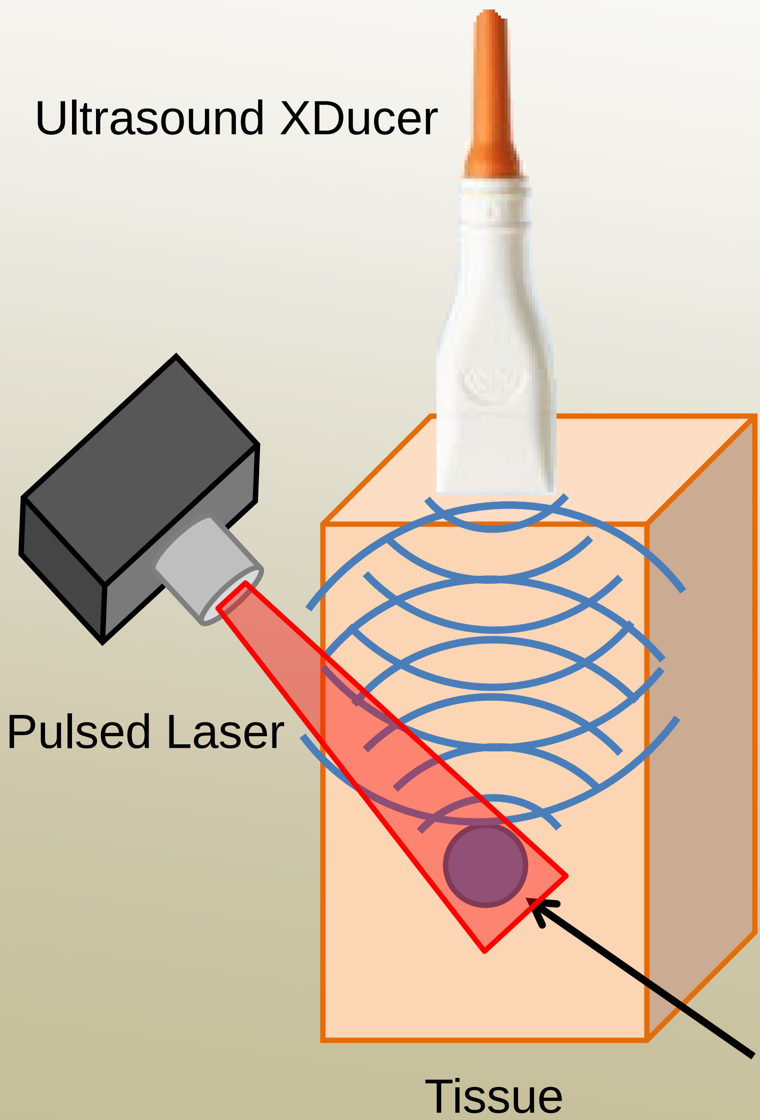
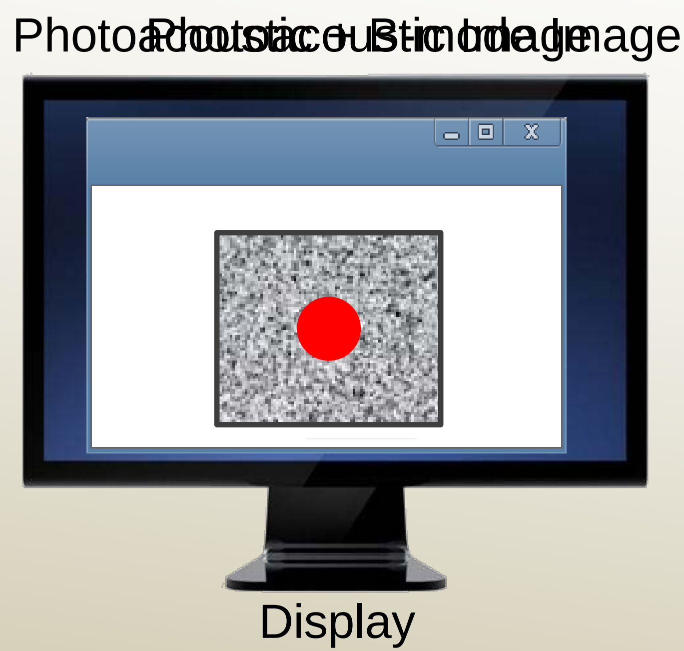
Photoacoustic Imaging





1) Irradiate the ROI with nanosecond laser.
2) Form an image from the acoustic source.
3) Obtain a co-registered B-mode image.

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Capabilities

- **Quantification of hemoglobin content**
  1) Anemia assessment
- **Calculation and quantification of oxygen saturation**
  1) Tumor and tissue hypoxia assessment
  2) Stroke/ischemia assessment
- **Detection of contrast agents or near IR-absorbing compounds**
  1) Molecular and cellular quantification
  2) Cellular specificity
  3) Biomarker studies
  4) Sentinel lymph node detection
  5) Tumor detection through uptake of targeted nanoparticles
  6) Tumor visualization through increased vascularization
  7) Visualization of metallic implants or tools
- **Noninvasive Temperature monitoring**
  1) Monitor progression and extent of therapeutic hyperthermia

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Photoacoustic Imaging of Prostate Brachytherapy Seeds

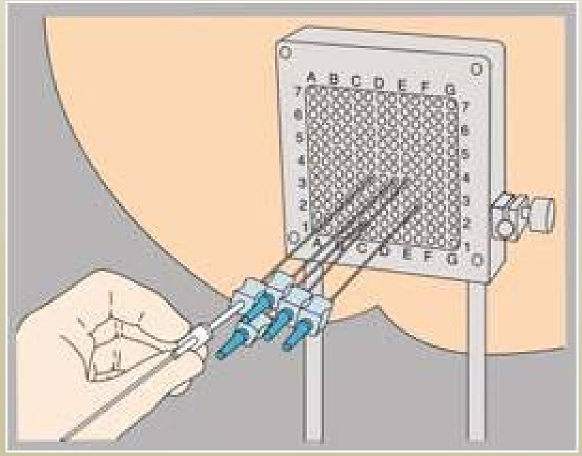
Standard of Care

The use of **brachytherapy seeds** is a common treatment option for low-to-intermediate risk patients.

- Seeds are placed according to a pre-established treatment plan.
- Image-guidance and monitoring is conducted using ultrasound and x-ray.

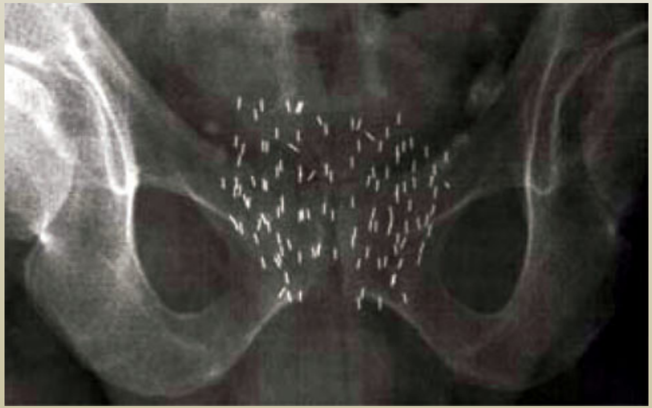
Use of transrectal ultrasound (TRUS) is the **current standard of care** during the procedure.

- Allows for determination of prostate boundary (CT imaging does not provide).
- Monitoring of seed insertion procedure in real-time.



Limitations of Current Technology

- TRUS has many visualization issues
- Seeds can be too small for detection - location often achieved indirectly by visualization of insertion needles
- Echogenicity of tissue can be similar to seeds (poor contrast)
- Acoustic signal of seed is dependent on orientation
- Fluoroscopy provides excellent contrast but cannot used for real-time guidance because of ionizing radiation



Fluoroscopy Image

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Clinical Need

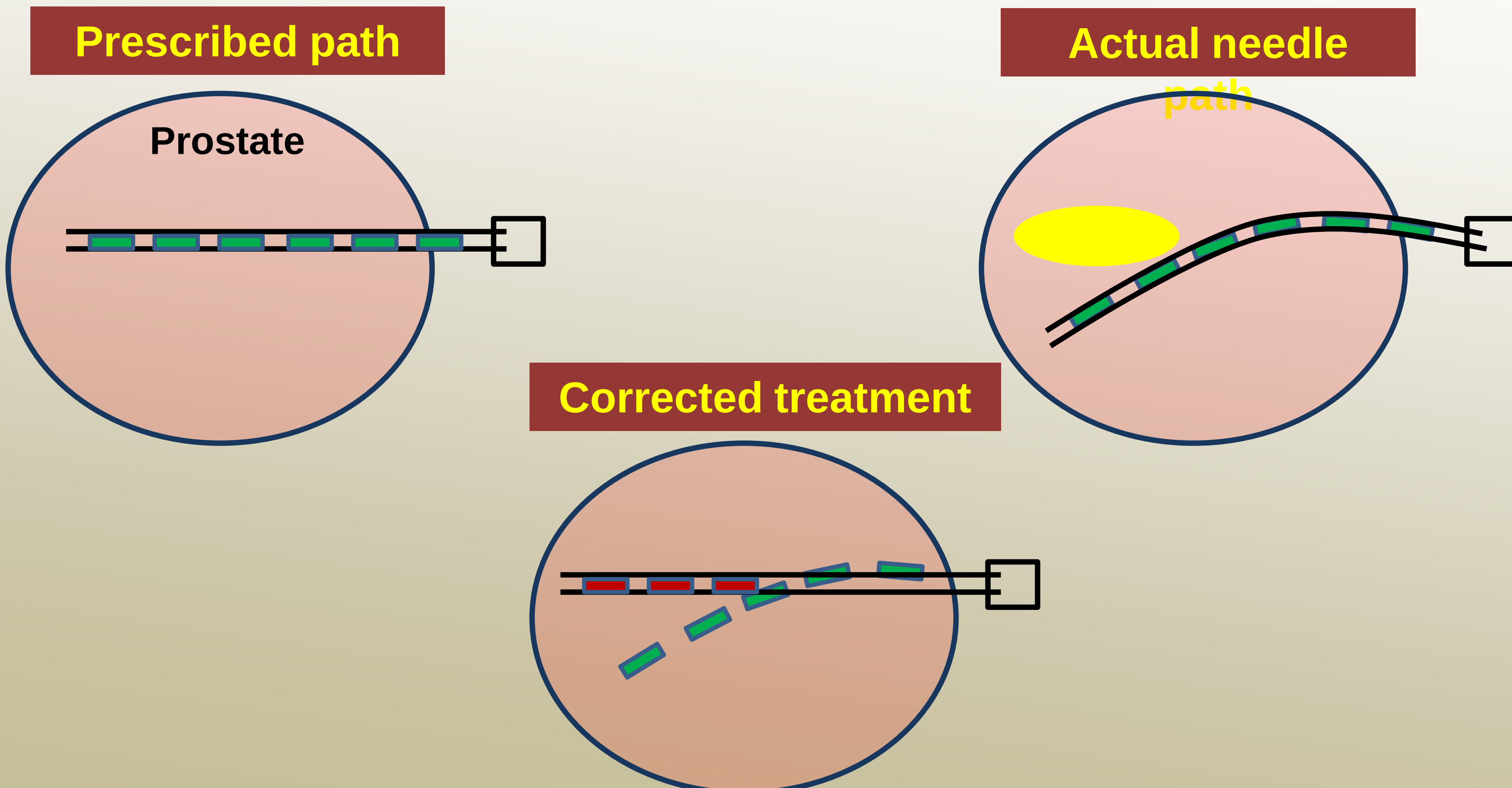
- Seed misplacements require post-op dose corrections with external beam radiation or a revision implantation
- Needle deflections of 5° can reduce dose by 10% and increase tumor-cell survival by 200x†
- Overdosing can lead to multiple complications, including urinary retention (14.5%) and/or rectal bleeding (13.7%)††

†S. Nath, Z. Chen, N. Yue, S. Trumpore, and R. Peschel, “Dosimetric effects of needle divergence in prostate seed implant using 125I and 103Pd radioactive seeds,” Med. Phys. 27, 1058–1066 (2000).
††R. Benoit, M. Naslund, J. Cohen, “A comparison of complications between ultrasound-guided prostate brachytherapy and open prostate brachytherap,” International Journal of Radiation*Biology*Physics 47, 909-913 (2000).

Addressing the Clinical Need

What is needed: An ADAPTIVE treatment plan during the procedure

Requires real-time visualization of seeds AND anatomy!!



Figures: Fichtinger, G. "Research Issues in Robot-Assisted Needle Interventions" 2003.
http://miccai.irisa.fr/Program/description/G-Fichtinger.pdf

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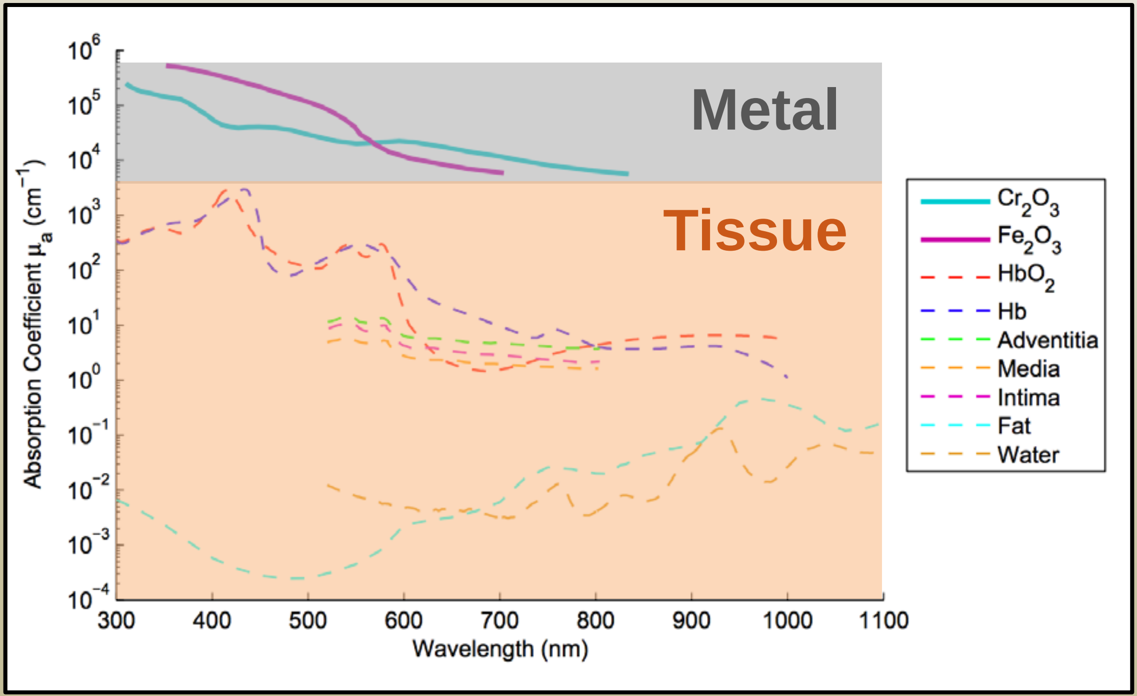
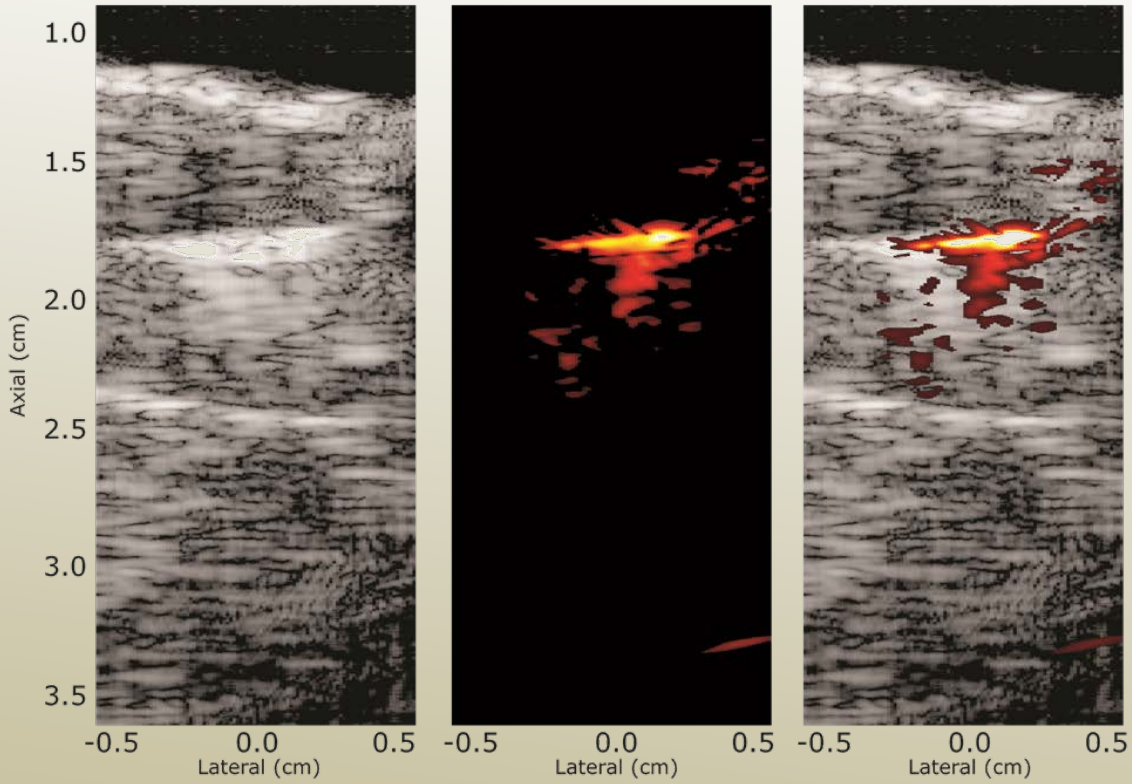
Photoacoustic Imaging

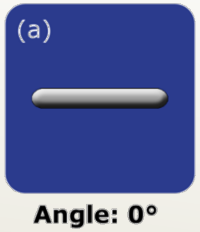
- Photoacoustic imaging uses laser pulses to generate acoustic sources in tissue through absorption and thermoelastic expansion.
- Provides contrast (optical absorption) and spectroscopic capabilities of optical technique with depth penetration of acoustic technique.
- Combined with ultrasound (PAUS) to achieve real-time imaging of absorbers (e.g., hemoglobin or plasmonic nanoparticles) and anatomy.



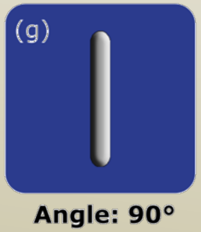
Contrast Improvement Result

Seed shallowly embedded in prostate tissue





28-dB contrast improvement
Photoacoustic over Ultrasound



24-dB contrast improvement

1) Su JL*, **Bouchard RR***, Karpiouk AB, Hazle JD, Emelianov SY. “Photoacoustic imaging of prostate brachytherapy seeds,” Biomedical Optics Express, 2(8): 2243-2254, 2011. (*authors contributed equally)

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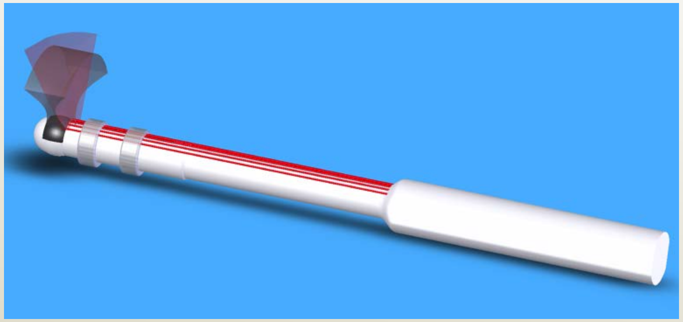
Transrectal PAUS Imaging

A



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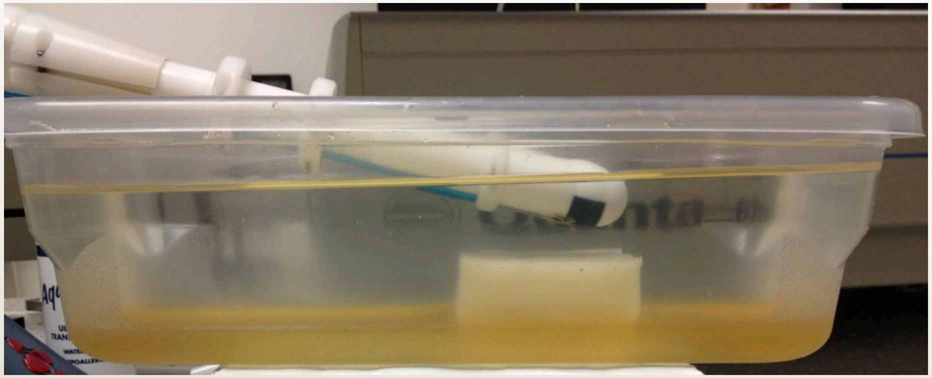
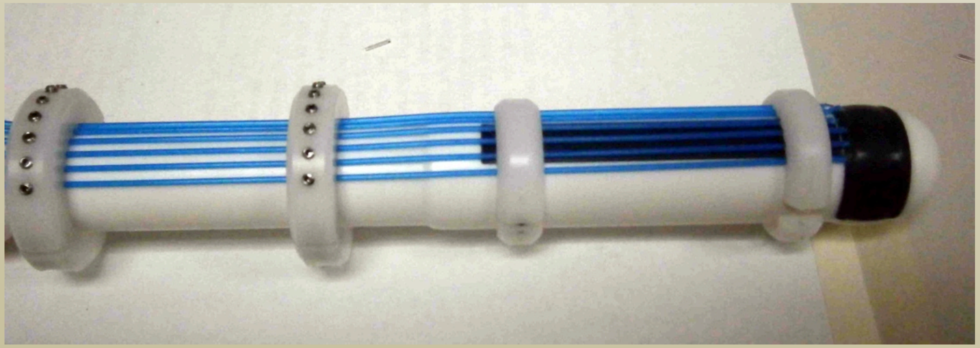
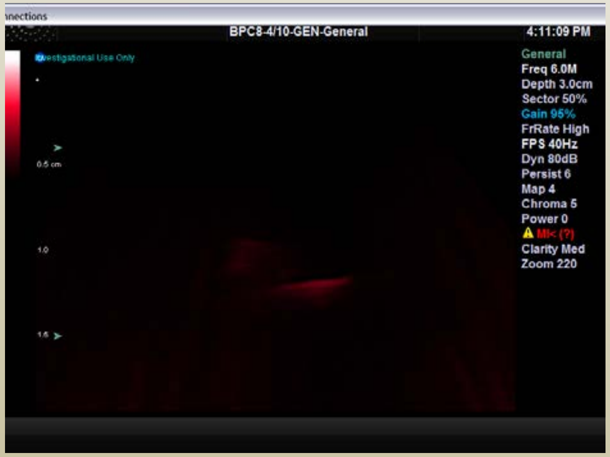


D

B





1) Mitcham T, Homan K, Frey W, Chen Y, Hazle, J, Emelianov SY, **Bouchard RR**. "Modulation of Photoacoustic Signal Generation from Metallic Surfaces," *Journal of Biomedical Optics,* 18(5): 056008, 2013.

Photoacoustic Imaging of RFA Lesions in Myocardium

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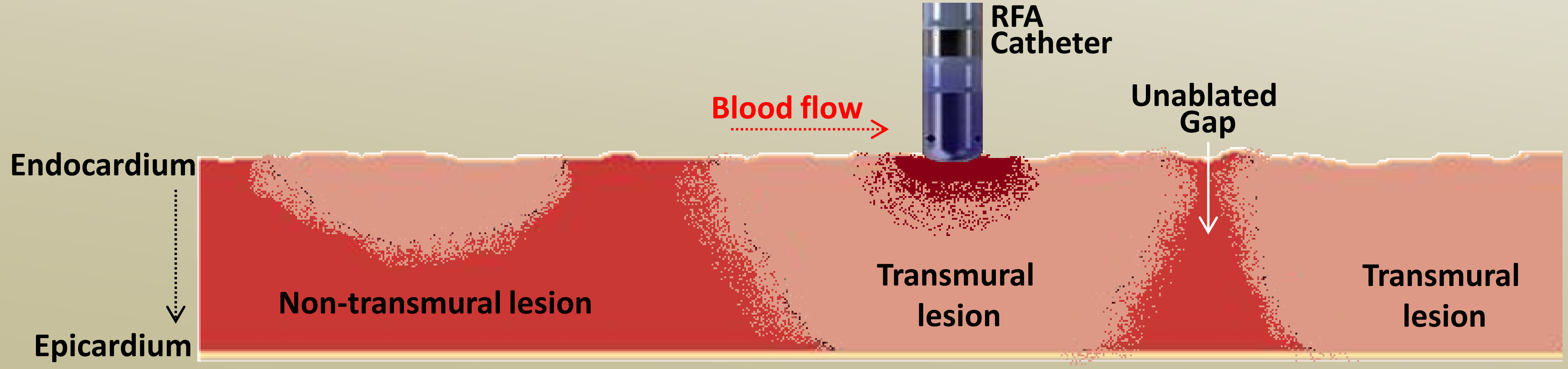
PA Imaging of RFA Lesions

Radiofrequency Ablation

- Single RFA lesions and lines of RFA lesions must be transmural and continuous to block conduction
- Electrical reconnection occurs at unablated gaps
  - Gaps cause the arrhythmia to resurface
- Blood flow around catheter tip and tip-tissue contact affect lesion formation
  - Lesion size is unpredictable with delivery parameters
- *Ideally, a real-time visual inspection would confirm RFA lesion transmurality and line contiguity*



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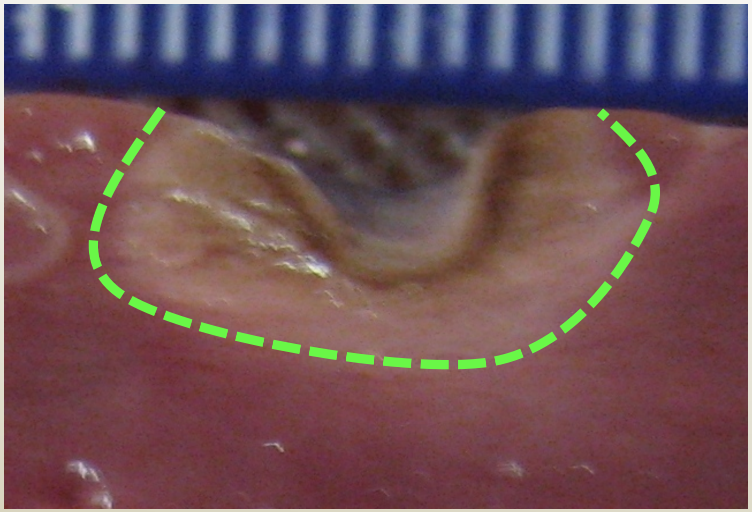
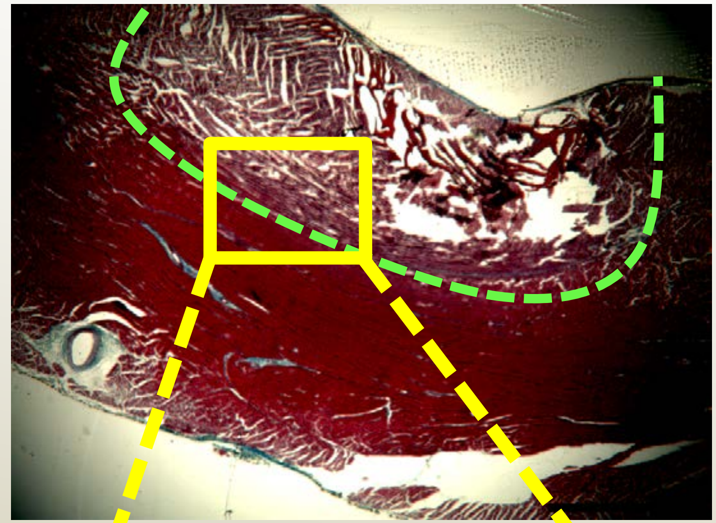
Single-Wavelength Imaging

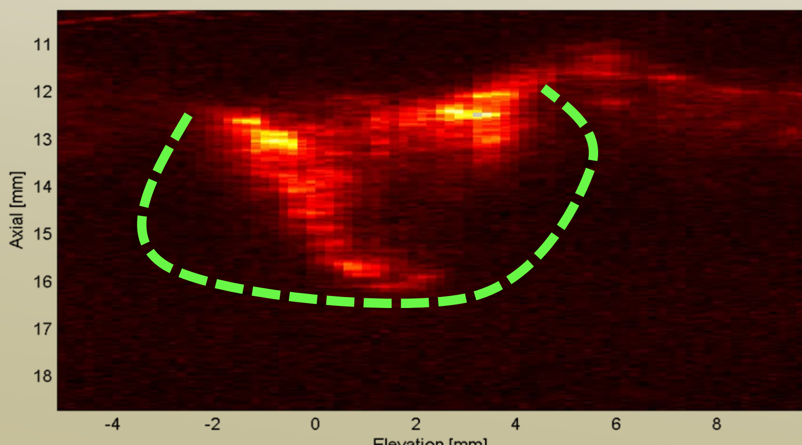
Photograph of Ablation Cross Section



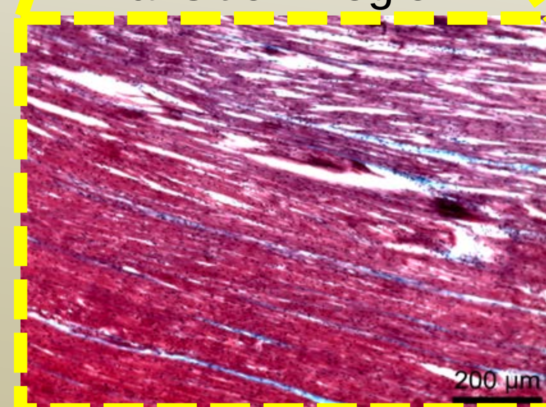
Histology (Gomori's Trichrome Stain)



PA Image of Ablation Cross Section

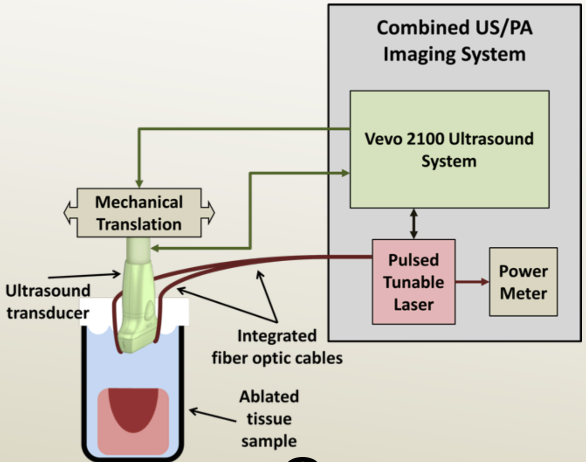


Transition Region



Multi-wavelength PA Imaging

A



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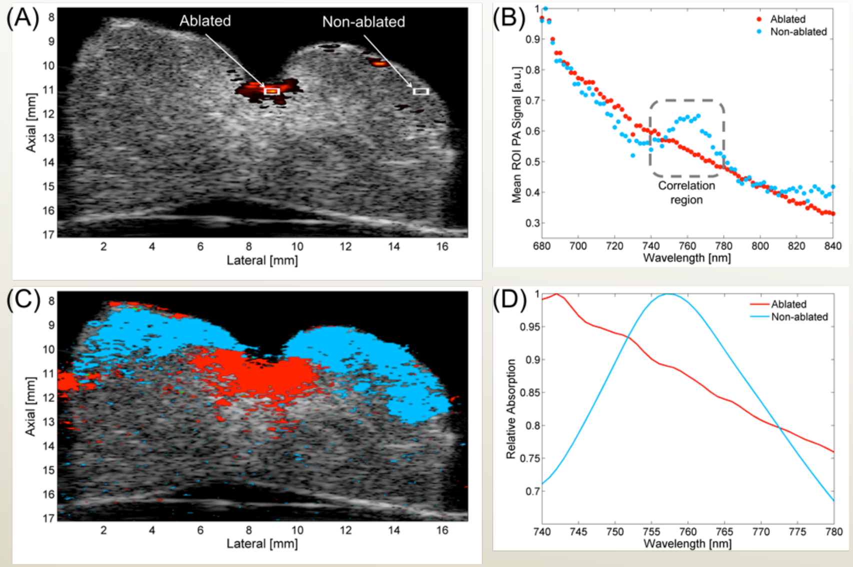

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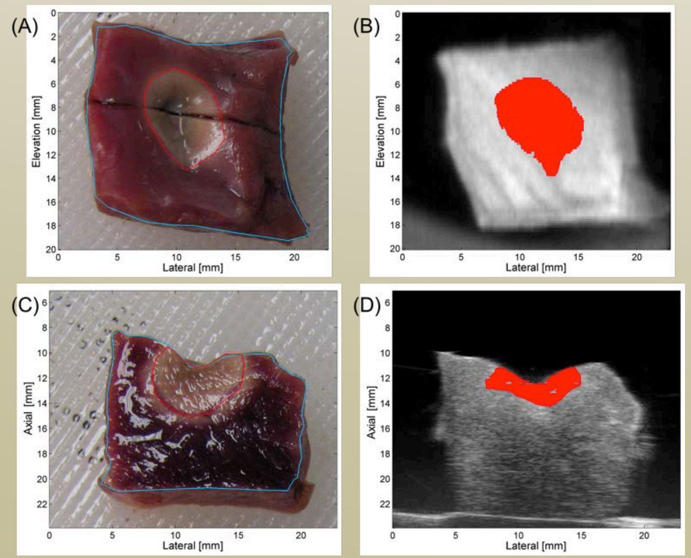

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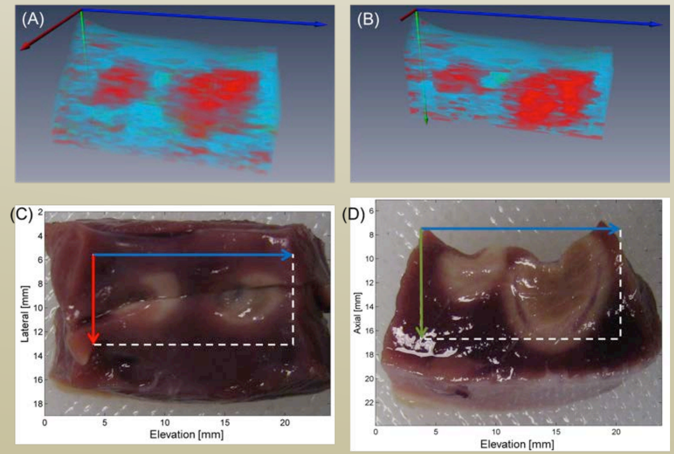

1) Dana N, Di Biase L, Natale A, Emelianov SY, **Bouchard RR**. “In-vitro Photoacoustic Visualization of Myocardial Ablation Lesions,” *Heart Rhythm*, 11(1): 150-157, 2014.

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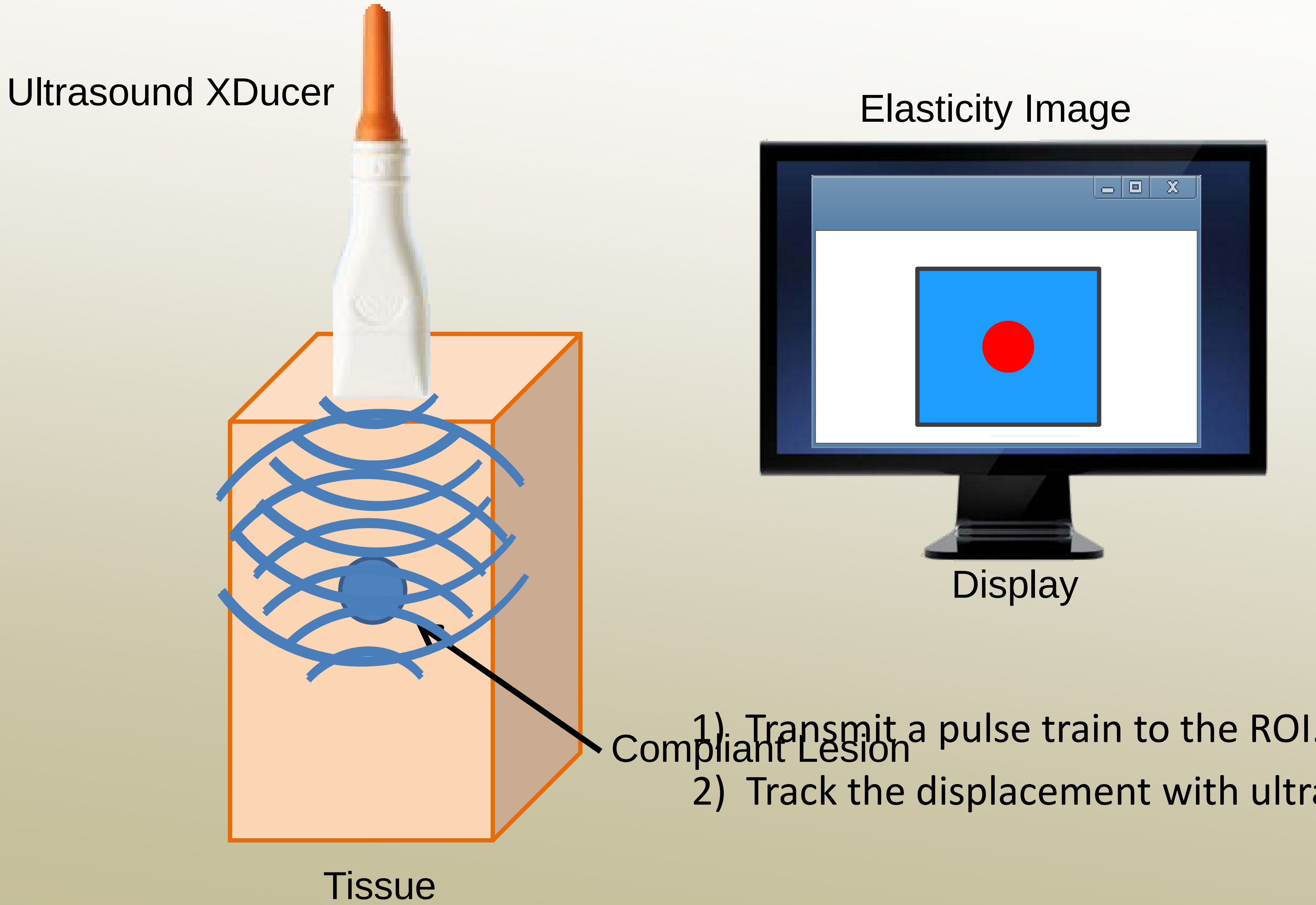
Stiffness = Disease

- Manual palpation around for ages
- Diseased tissues becomes stiffer or “harder”
- Palpation *qualitative* and *superficial*
- Imaging method capable of **quantitative** stiffness assessment **at depth** in tissue?

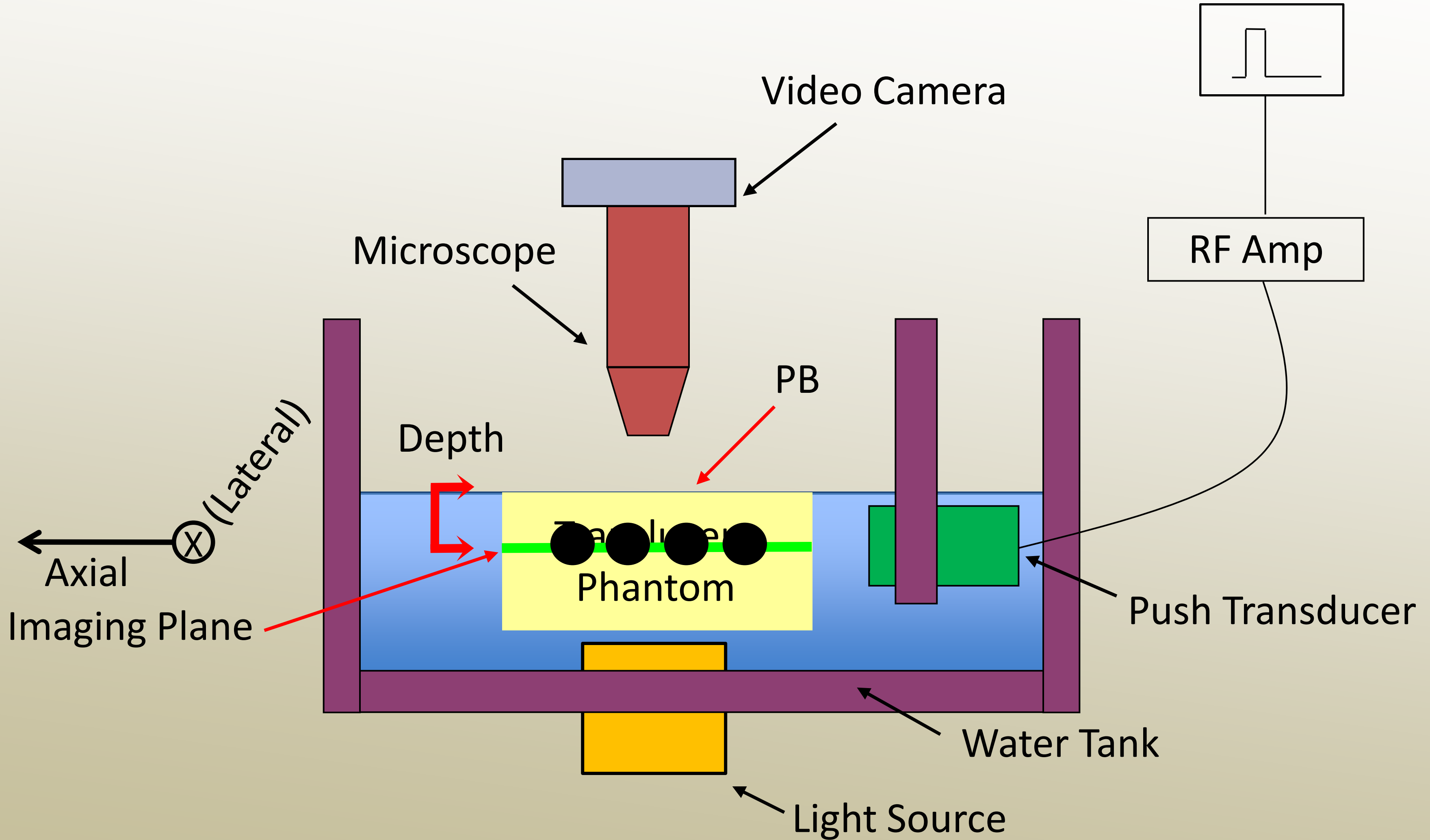
ARF-Based Elasticity Imaging!!

ARF-Based Elasticity Imaging



1) Transmit a pulse train to the ROI.
2) Track the displacement with ultrasound.

Phantom Example



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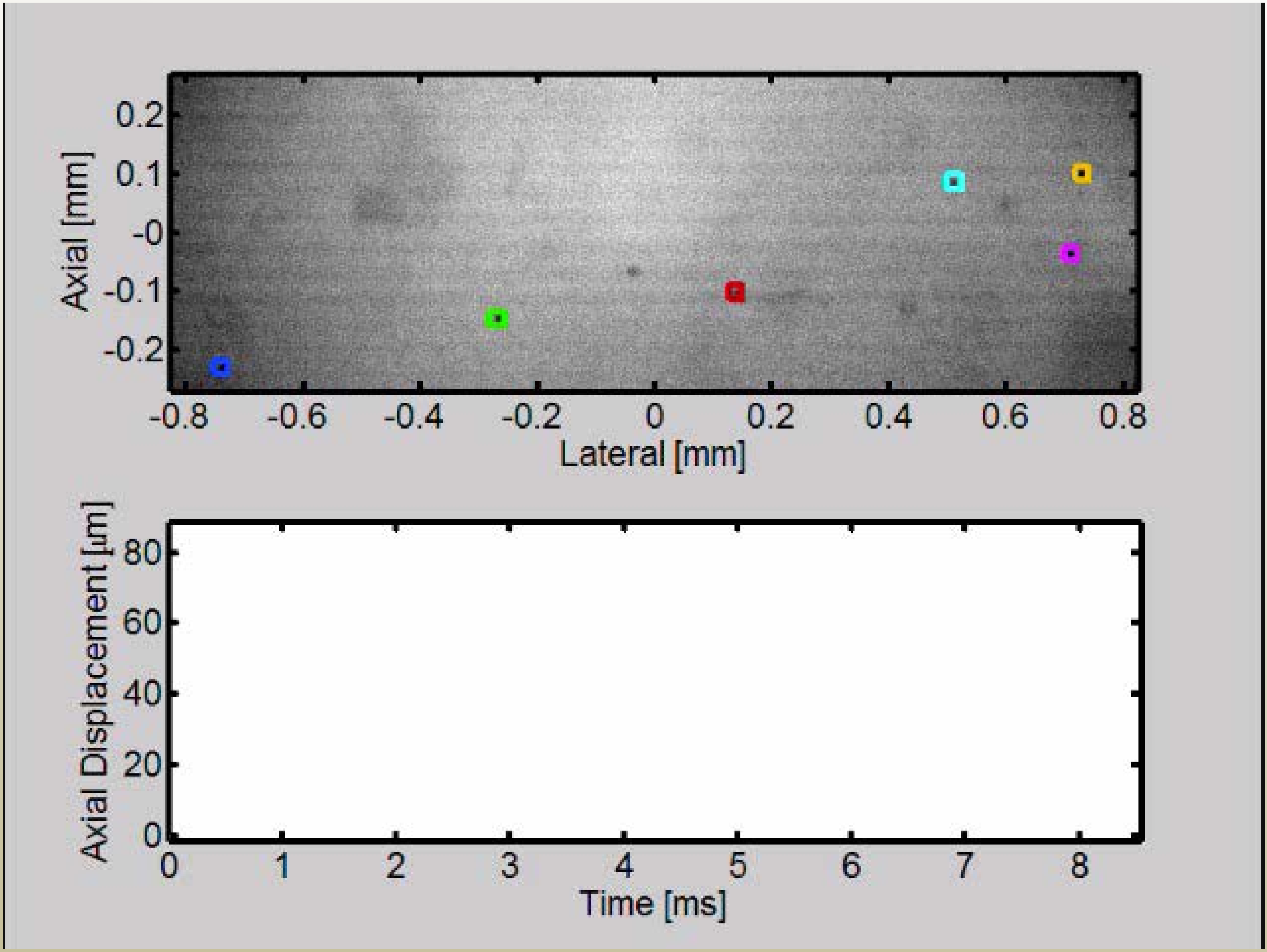
Dynamic Response



1) **Bouchard RR**, Streeter JE, Palmeri ML, Pinton GF, Trahey GE, Dayton PA. "Optical tracking of acoustic radiation force impulse-induced dynamics in a tissue-mimicking phantom," *Journal of the Acoustical Society of America*, 126(5): 2733-2745, 2009.

Shear Wave Imaging

- Acoustic radiation force $$\left|\vec{F}\right| = \frac{2\alpha I}{c}$$
- ARFI excitation induces shear waves in tissue
- Waves are tracked with ultrasonic-based methods
- Stiff: > Velocity Compliant: < Velocity
- Assess stiffness of soft tissues: breast, liver, vessels, etc.
- Shear wave speed relates to Young's modulus:

$$c_T = \sqrt{\frac{E}{2(1+\nu)\rho}}$$

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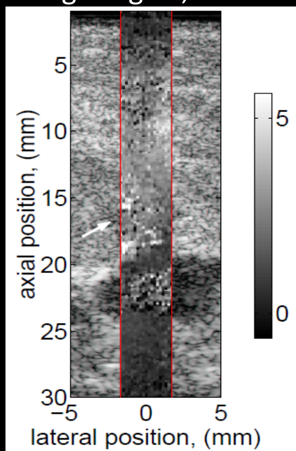
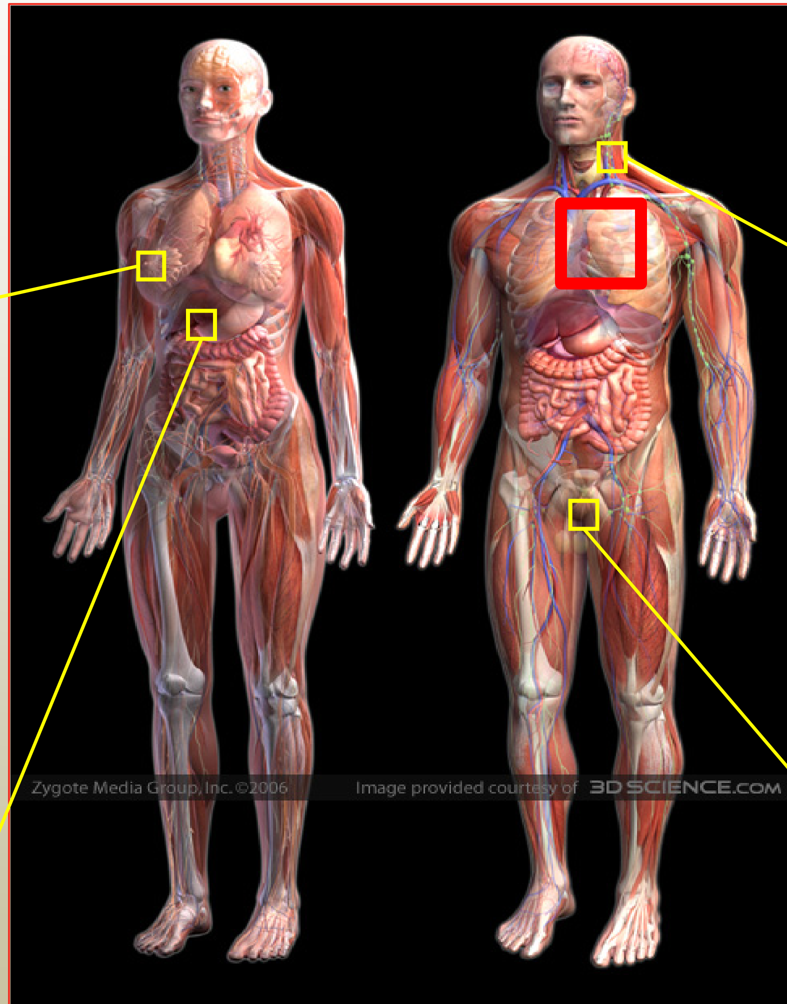
Clinical Possibilies

Nightingale, *et al.*

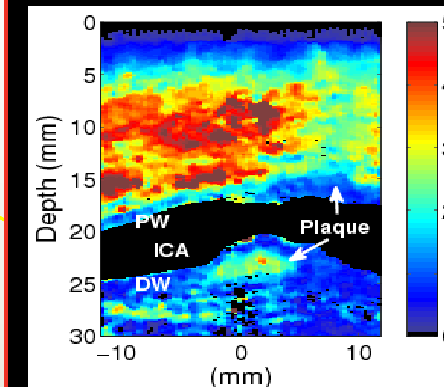


20-60 kPa

2-4 cm depth

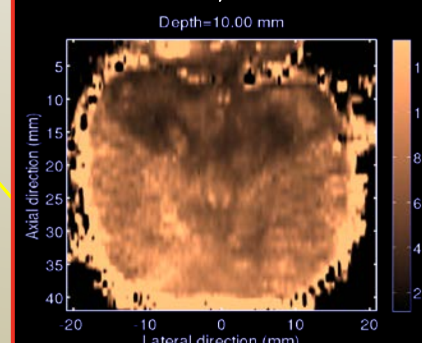


Dumont, *et al.*



80-110 kPa

Zhai, *et al.*



50-70 kPa

Fahey, *et al.*

1-5 kPa

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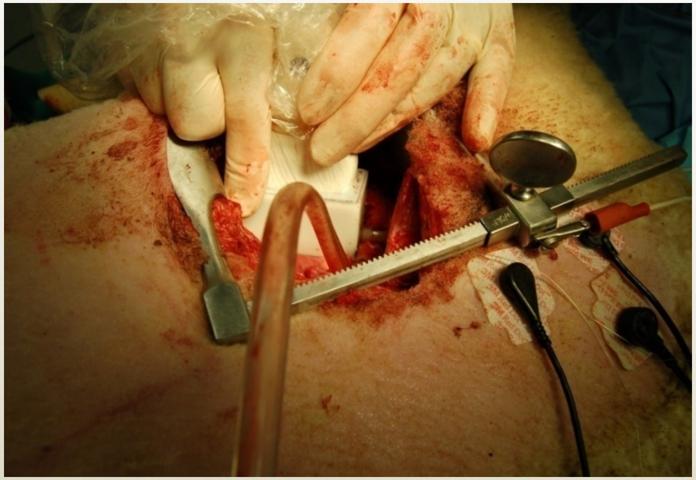
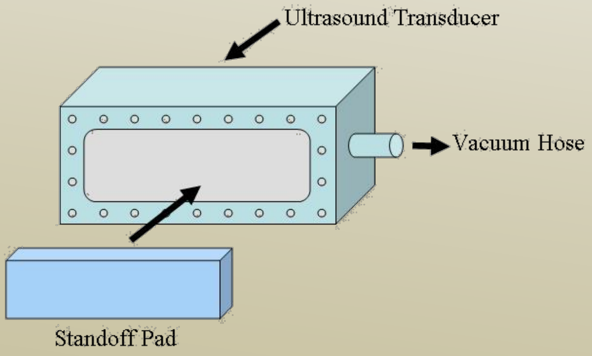
Cardiac Imaging Configuration

- VF10-5 linear array
  - 5.7 MHz (ARFI); 10 MHz (Track)
- Canine subjects
- Thoracotomy performed
- Imaging on epicardium
- Vacuum-coupling device used
- Heart rate 92-110 BPM





1) Hsu SJ, **Bouchard RR**, Dumont DM, Wolf PD, Trahey GE. "In vivo assessment of myocardial stiffness with acoustic radiation force impulse imaging." *Ultrasound in Medicine and Biology*, 33(11): 1706-1719, 2007.

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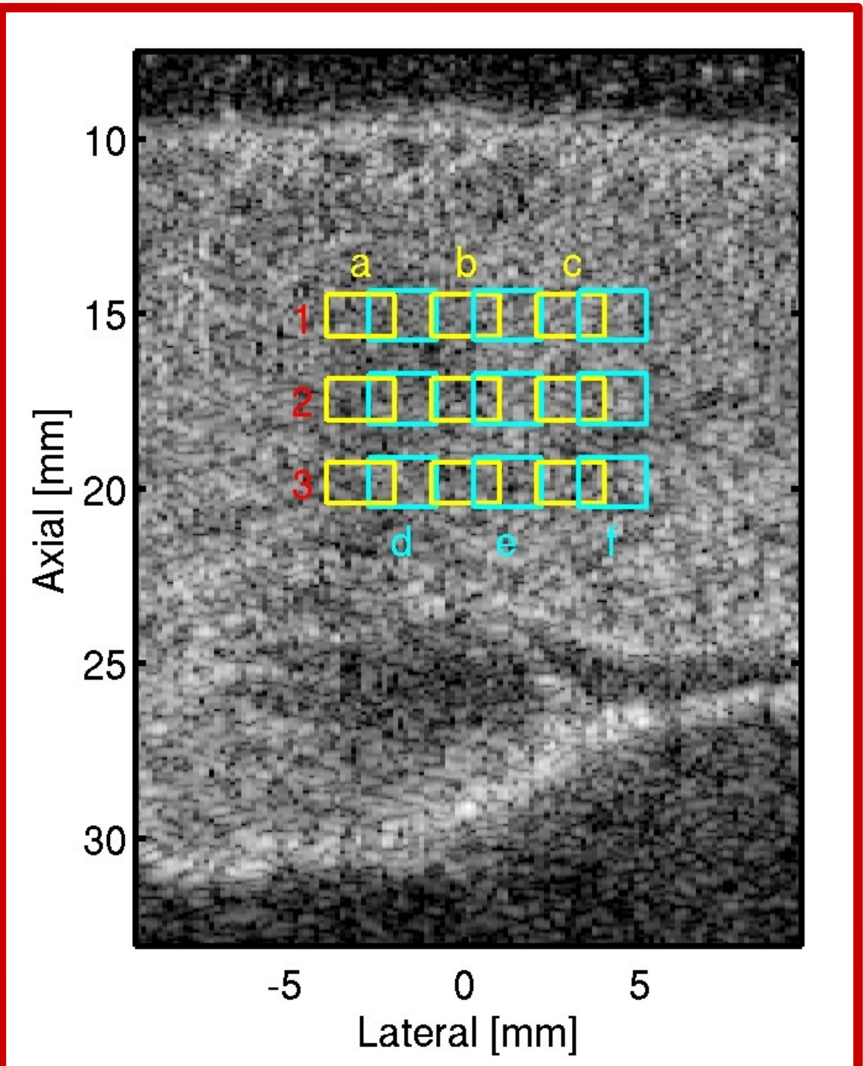
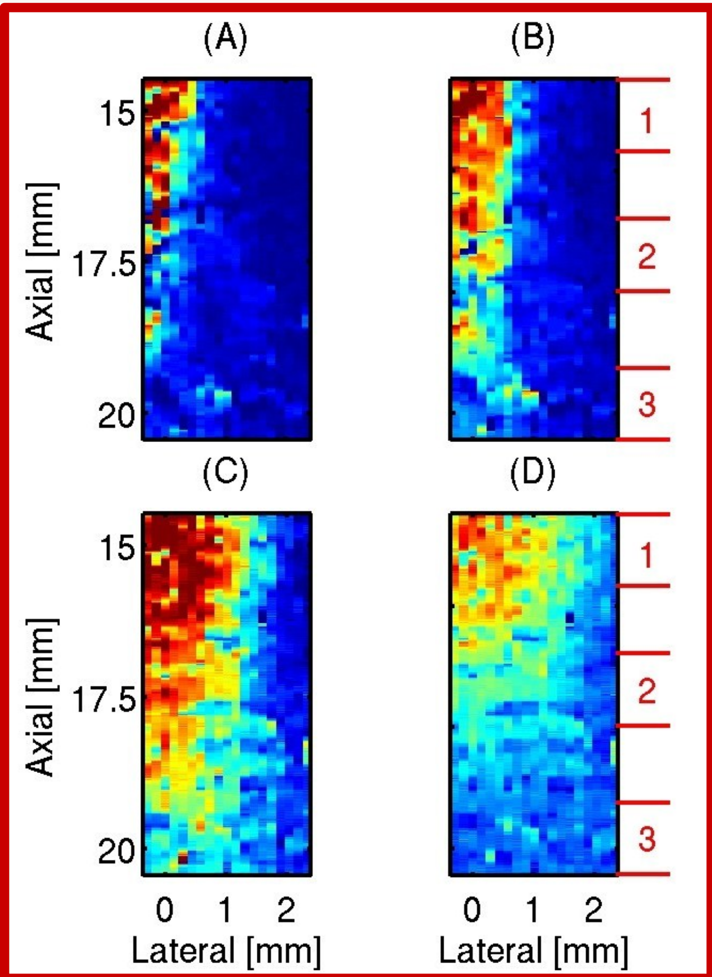
In Vivo Results

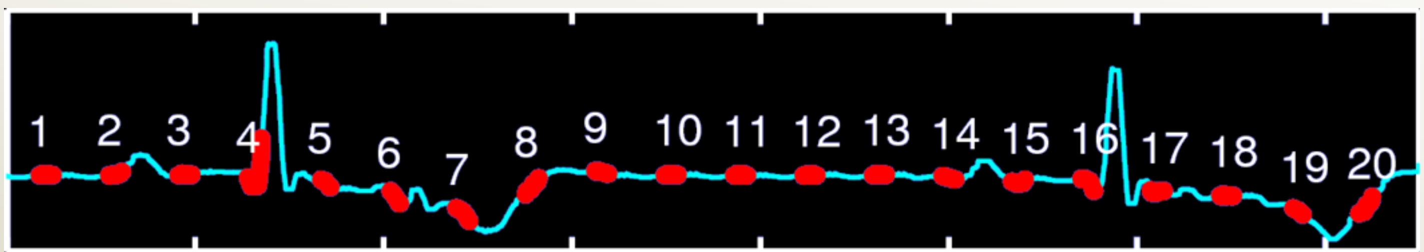




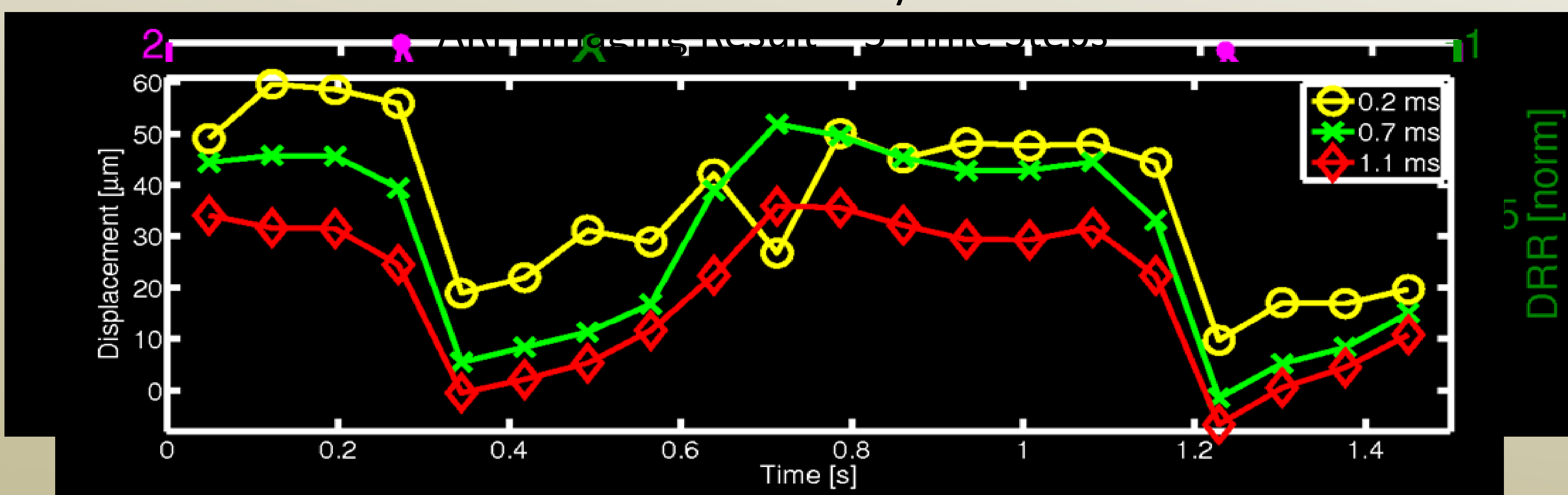
1) **Bouchard RR**, Hsu SJ, Wolf PD, Trahey GE. "*In vivo* cardiac, acoustic-radiation-force-driven, shear wave velocimetry," *Ultrasonic Imaging*, 31(3): 201-213, 2009.
2) Hsu, Stephen J.**, Richard R. Bouchard**, Douglas M. Dumont, Cheng W. Ong, Patrick D. Wolf, and Gregg E. Trahey. "Novel acoustic radiation force impulse imaging methods for visualization of rapidly moving tissue." Ultrasonic imaging 31, no. 3 (2009): 183-200.

Cyclic Elasticity

ECG Trace w/Acquisition Numbers



Shear Velocimetry Plot



1) **Bouchard RR**, Hsu SJ, Palmeri ML, Rouze NC, Nightingale KR, Trahey GE. “Acoustic Radiation Force-Driven Assessment of Myocardial Elasticity using the Displacement Ratio Rate (DRR) Method,” *Ultrasound in Medicine and Biology*, 37(7): 1087-1100, 2011.

Talk Outline

- Introduction
  - Why ultrasound-mediated imaging?
  - What is ultrasound-mediated imaging?
- Photoacoustic (PA) Imaging
  - Background
  - Current PA imaging applications
- ARF-Based Shear Wave Imaging
  - Background
  - Cardiac ARF-based shear wave imaging
- Conclusions

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Conclusions

- Clinical potential for PAUS imaging
  - Molecular specificity
  - Therapy guidance (e.g., brachytherapy, ablation)
  - Image targeted nanoparticles -> early detection
- ARFI-Based SWEI already in the clinic
  - Cardiac stiffness characterization
  - Fibrosis/ablation characterization possible
- Ultrasound-mediated imaging solutions can meet many of our future healthcare needs

Thank You!

- National Institutes of Health
- National Science Foundation Graduate Fellowship
- Whitaker International Fellowship
- Odyssey Fellowship Program at MD Anderson
- Laura and John Arnold Foundation at MD Anderson
- Siemens Healthcare USA, Inc.
- VisualSonics, Inc.
- IsoAid, LLC

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Advances in Ultrasound-mediated Imaging

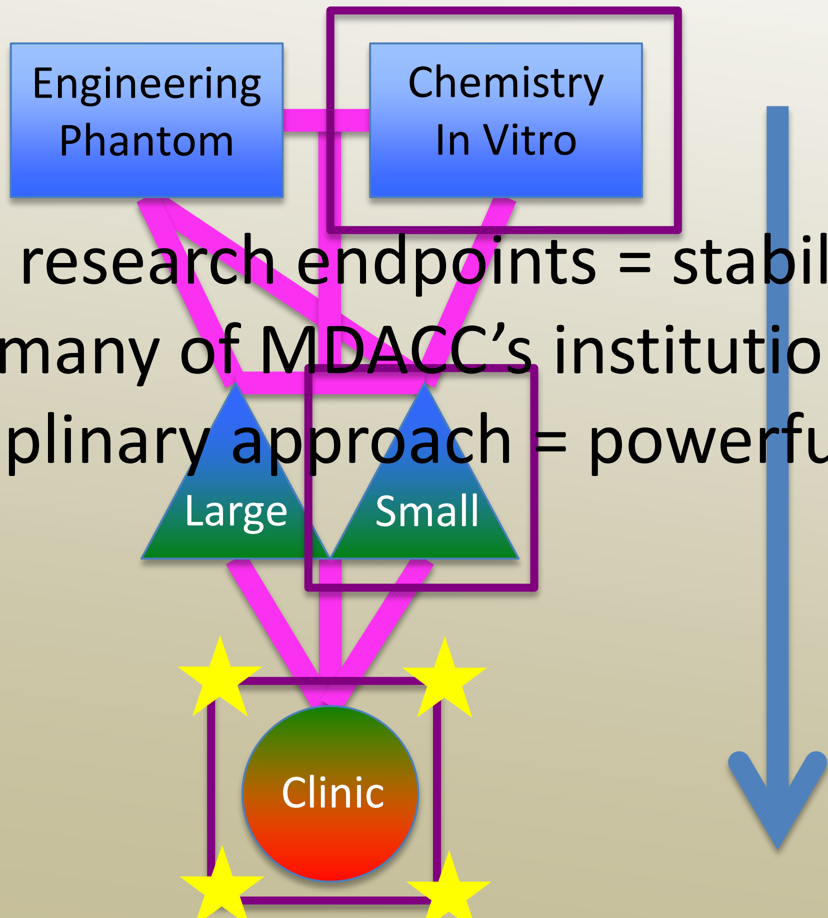
Richard Bouchard, Ph.D.

Department of Imaging Physics

The University of Texas MD Anderson Cancer Center

Title Dissection

- 3 imaging research endpoints = stability and robustness
- Leverage many of MDACC's institutional resources
- Multidisciplinary approach = powerful approach



Bench

Bedside

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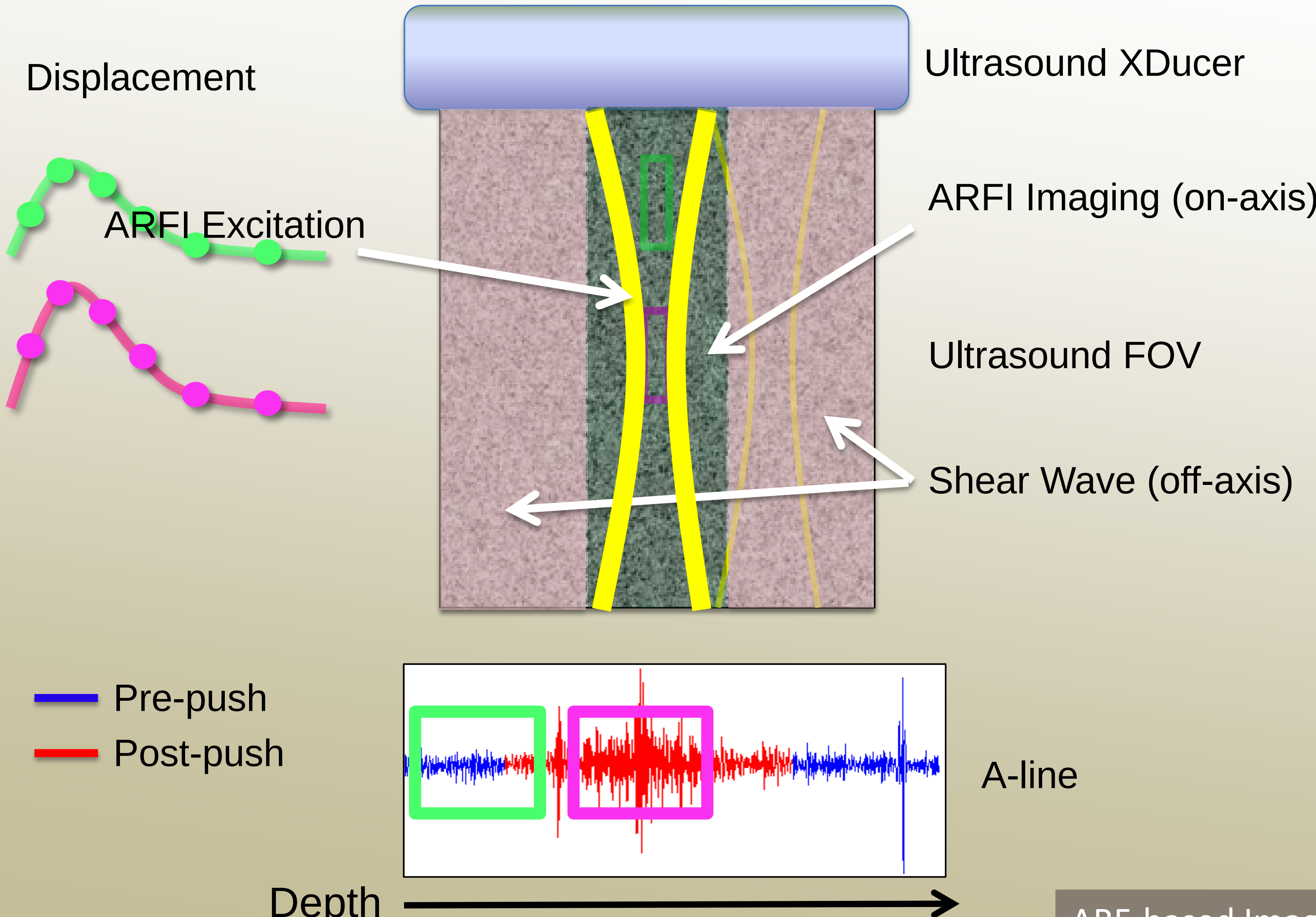
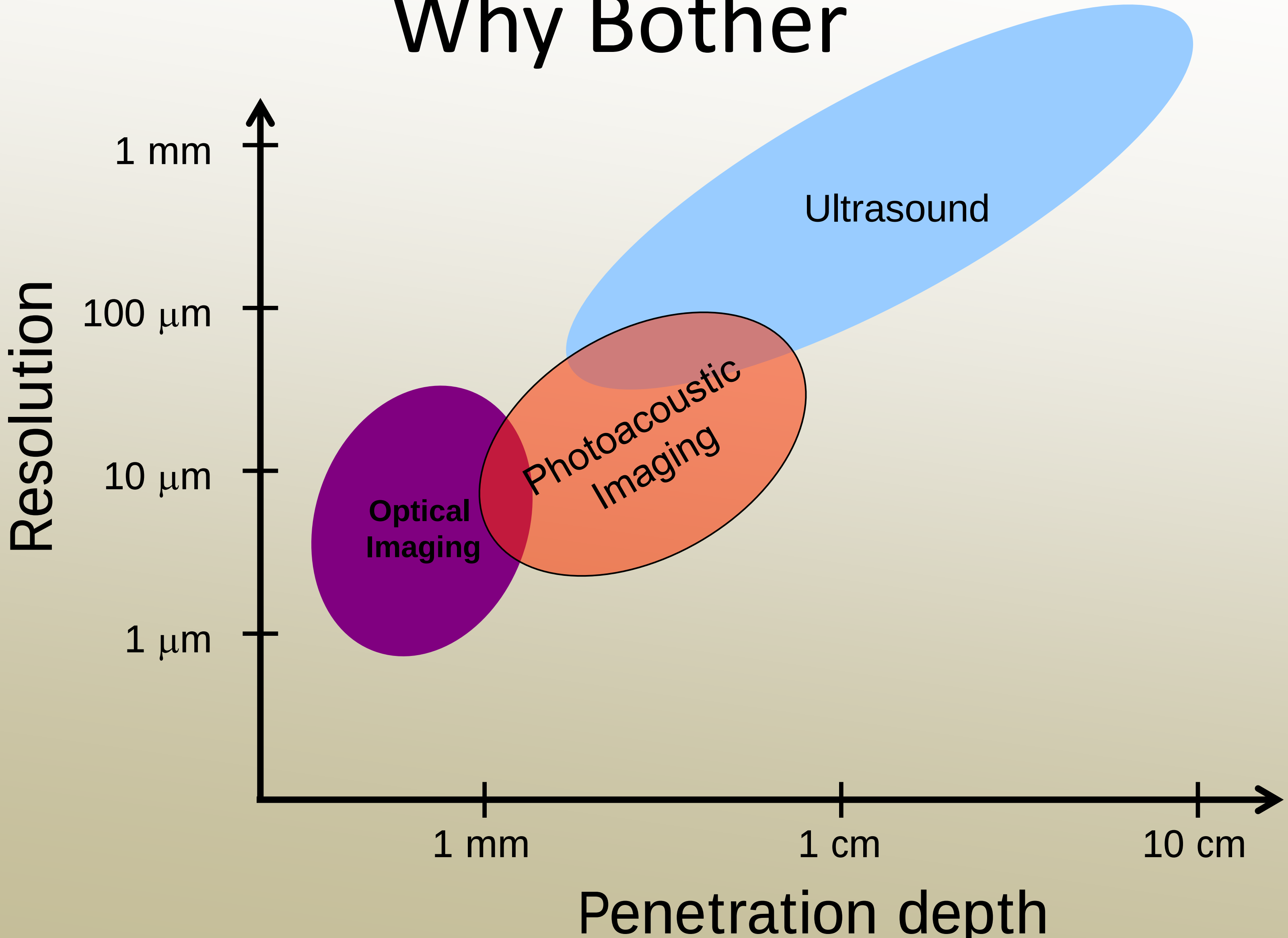
Displacement Tracking



Photoacoustic Imaging: Why Bother

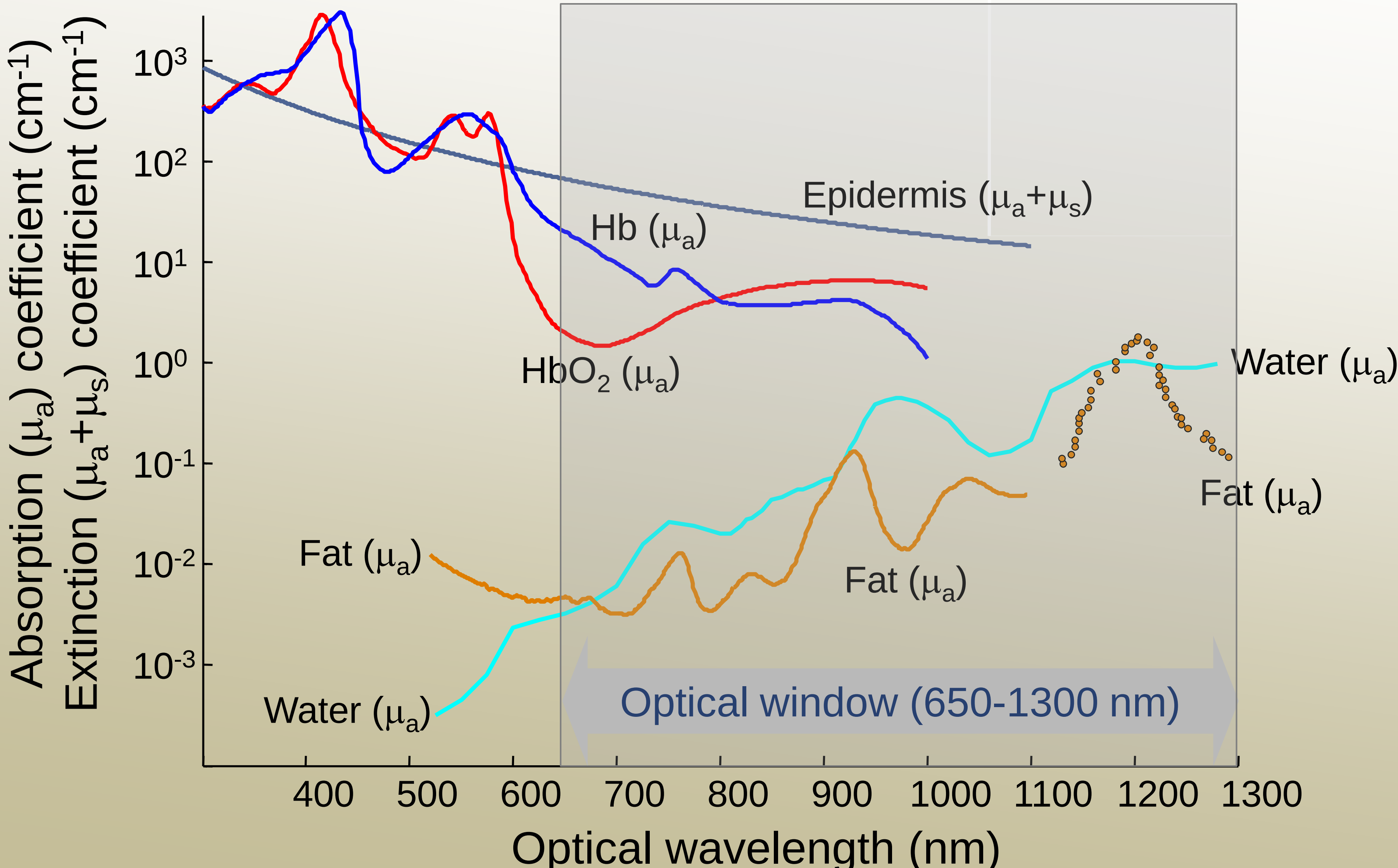


Light Scatters in Tissue and Turbid Media

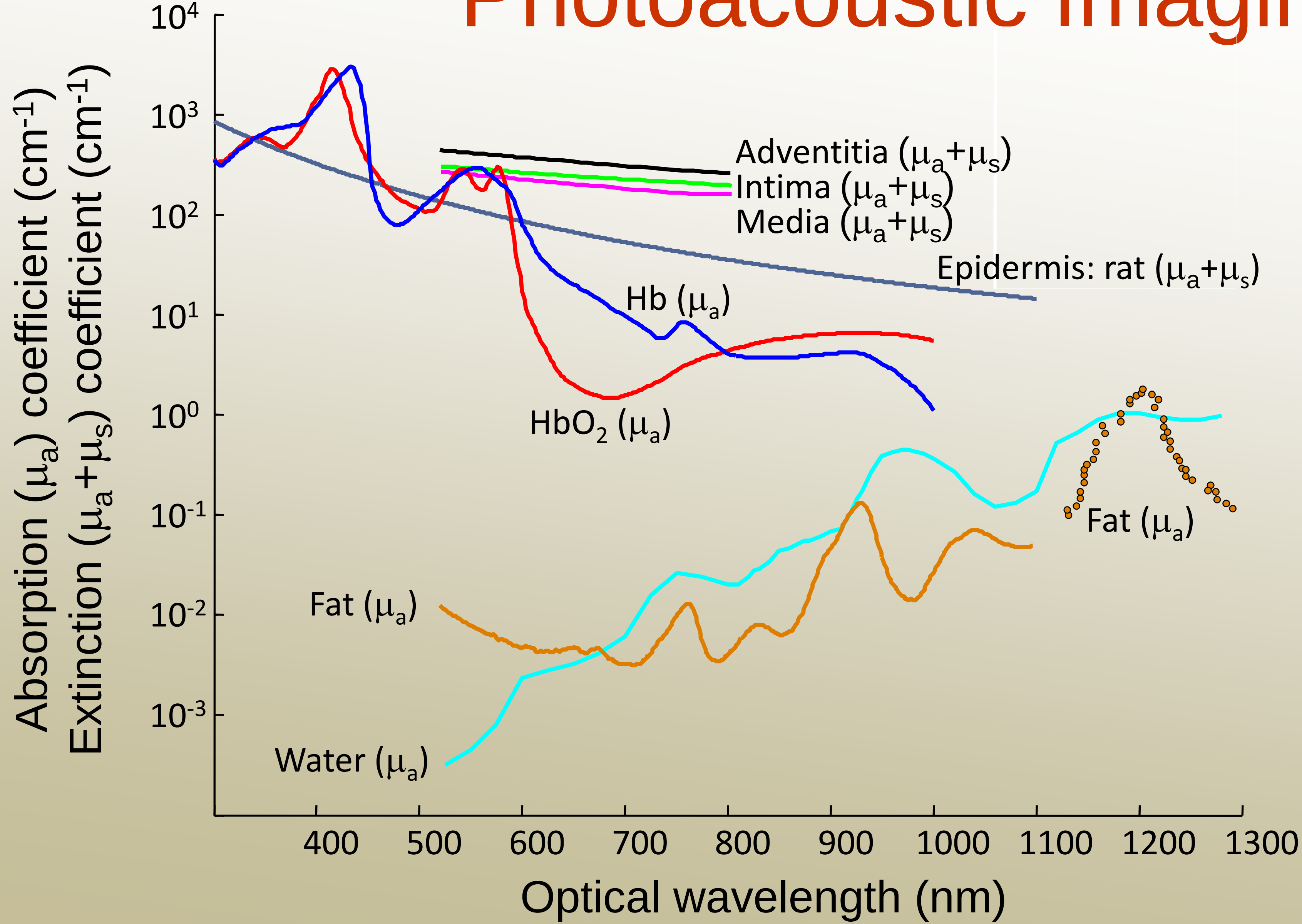
Laser through transparent medium on left and turbid medium on right.

Unlike ultrasound, scattering – and not absorption – tends to predominate in tissue.
A consequence of this is that focusing of light in turbid media is generally not possible.

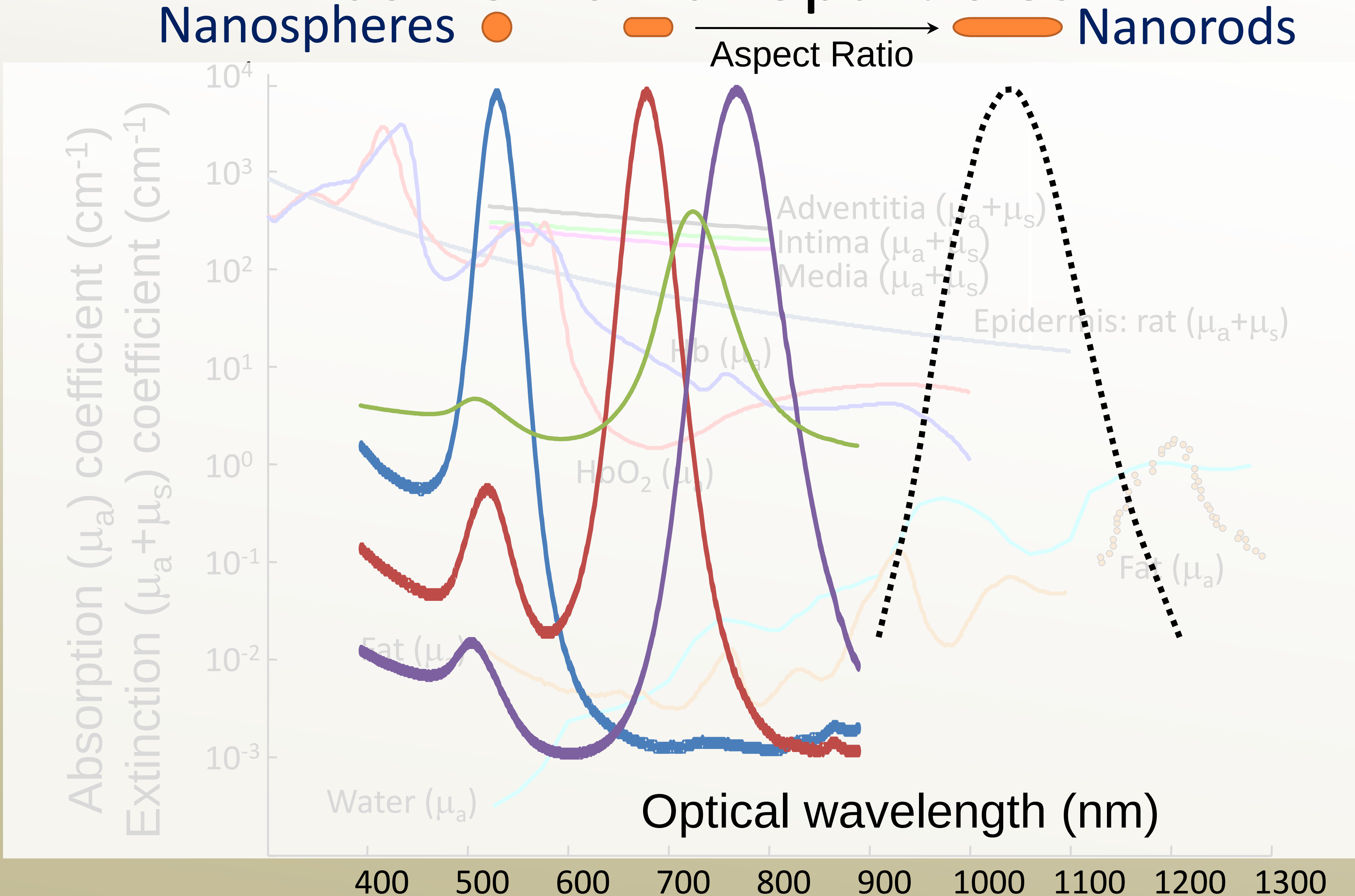
Photoacoustic Imaging: Optical (Imaging/Therapeutic) Window



Contrast and Penetration Depth in Photoacoustic Imaging



Exogenous Contrast: Plasmonic Nanoparticles



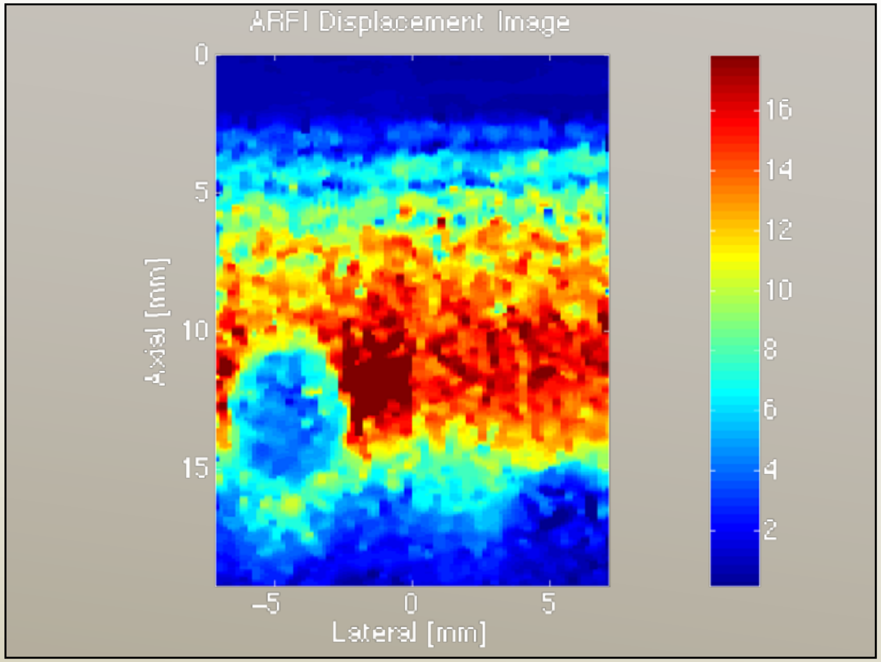
Photoacoustic Imaging: Why Bother

- Optical contrast at ultrasound resolution
- “Compromise” between resolution and penetration
- Tissue characterization and differentiation (i.e., physiological and functional imaging) rather than morphological imaging
- Molecular and functional cellular imaging
- Combined (multi-modality) imaging
- Sensing of biochemical changes in tissue

ARFI Imaging

- Following radiation impulse, tissue achieves max displacement and then recovers
- Typical Tx Frequency: 2-7 MHz
- Pulse Length: 10s-100s of μsec
- Stiff: < Displacement

  Compliant : > Displacement



- Dynamic response metrics (e.g. peak displacement, TTP displacement, etc.) related to elastic modulus of tissue
- **Plus:** Faster sampling **Minus:** Not quantitative

Bouchard RR, Hsu SJ, Dahl JJ, Palmeri ML, Trahey GE. "Image quality, tissue heating, and frame-rate trade-offs in acoustic radiation force impulse imaging," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* 56(1): 63-76, 2009.

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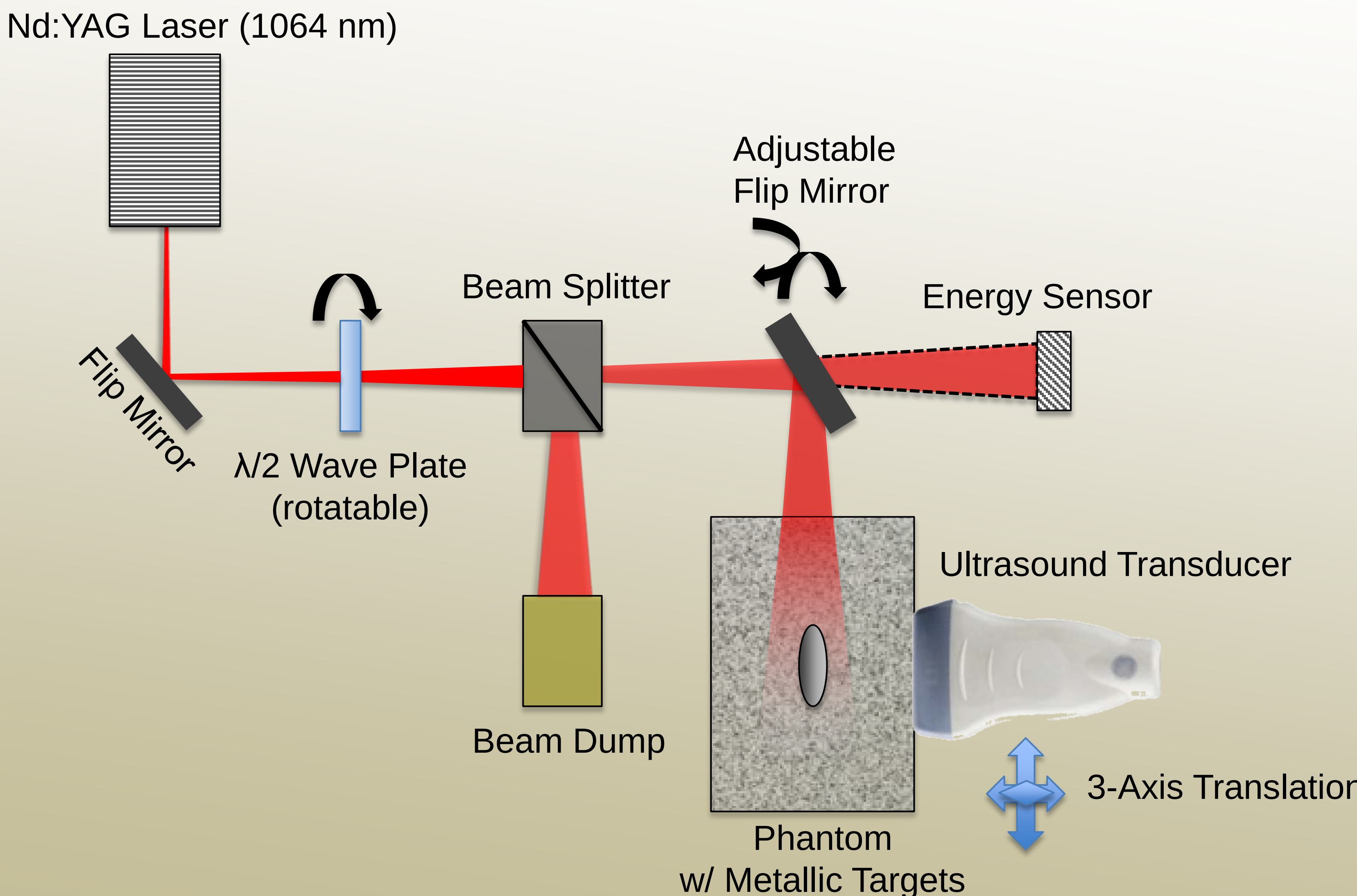
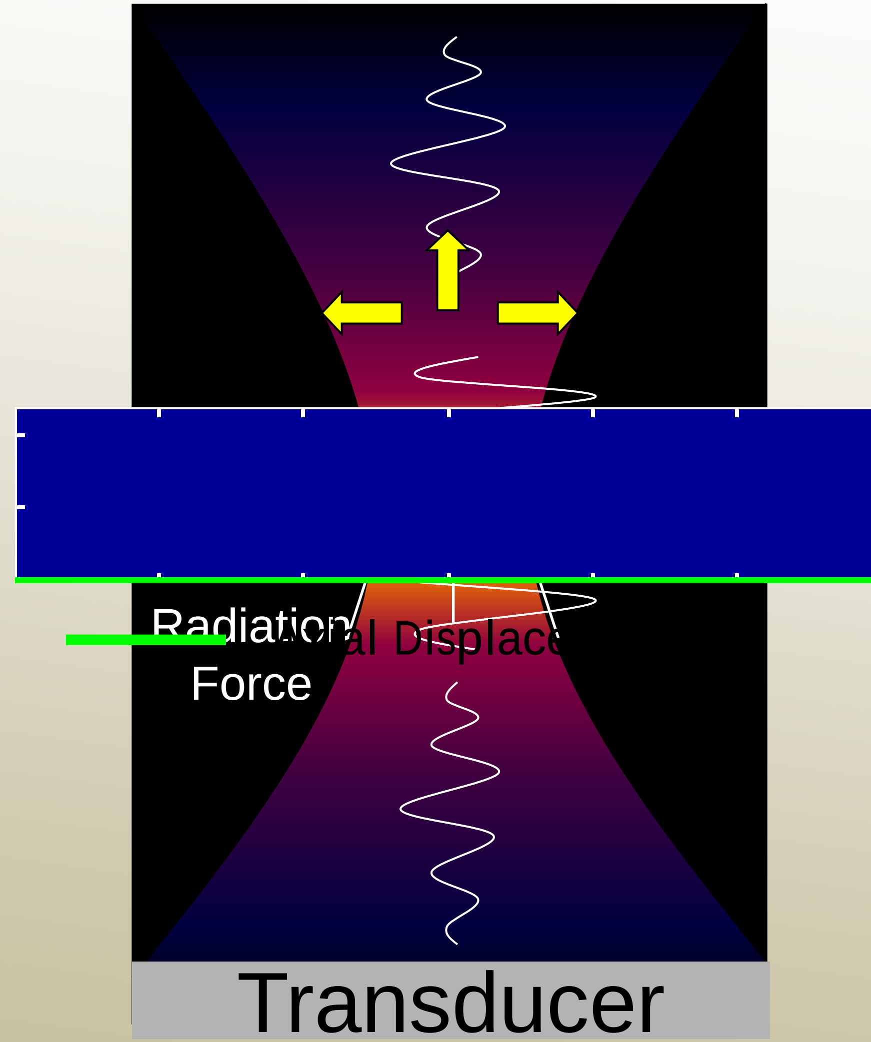
1064-nm Delivery



ARF-Based Elasticity Imaging

- Diseases often manifest as changes in tissue stiffness
  - e.g., self-breast exam
- Assess tissue stiffness non-invasively
- Acoustic radiation force
- Short duration («1 ms) – ARF impulse or “ARFI”
- Track on-axis or off-axis
- ARFI imaging
  - Measure on-axis displacement profile
- Shear wave velocimetry
  - Measure speed of shear wave



Experimental Protocol

- Fresh section of an excised porcine LVFW imaged
- THERMOCOOL Ablation System used to ablate for 45 sec at 40 W
- Modified Vevo 2100 with a synchronized pulsed laser/OPO system used for PA imaging
- Matched histology of ablation site attempted
- Ablation system located at St. David’s Medical Center
  - Logistics are difficult

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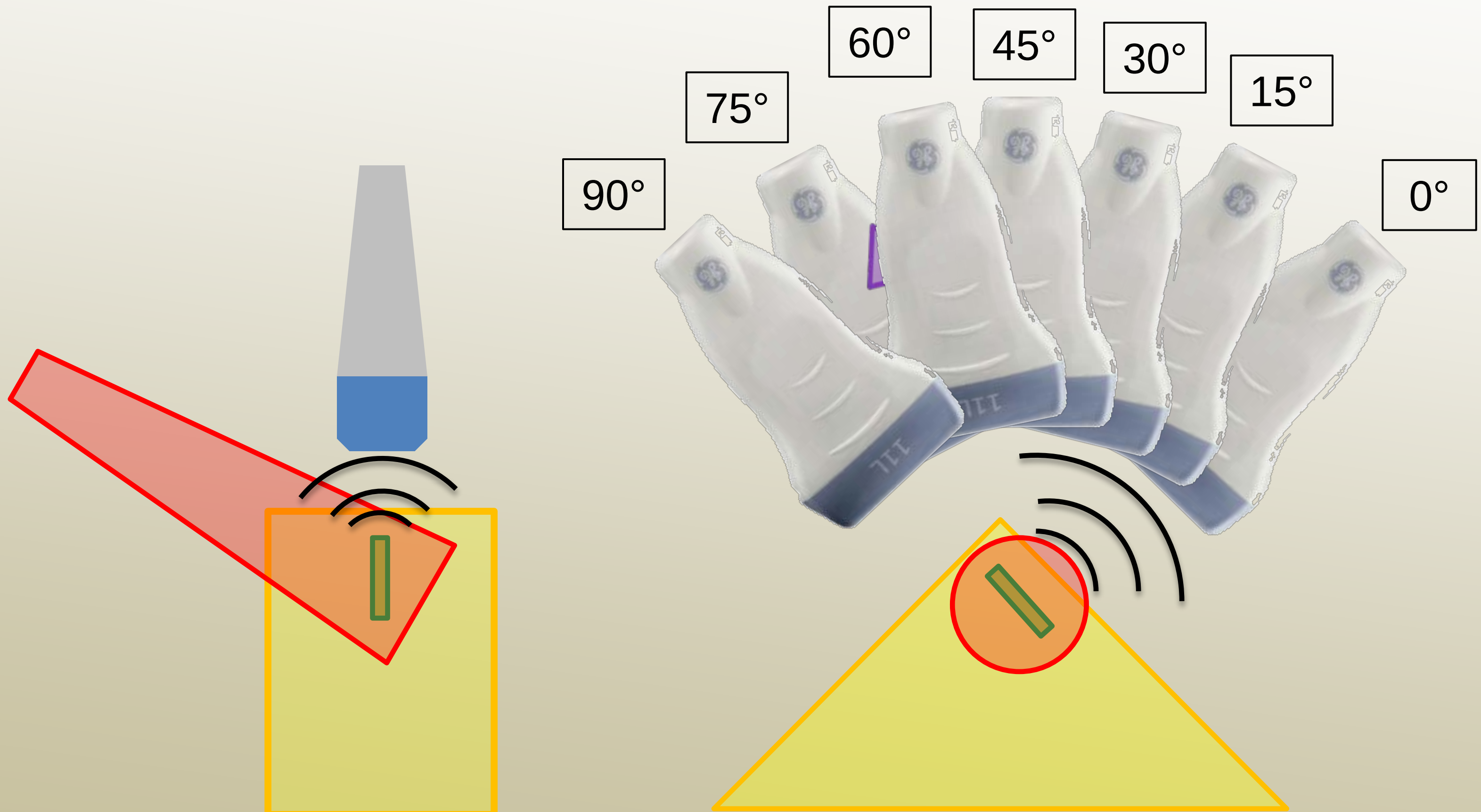
Seed Angle Effect



Front View

Side View

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Seed Angle Effect Result

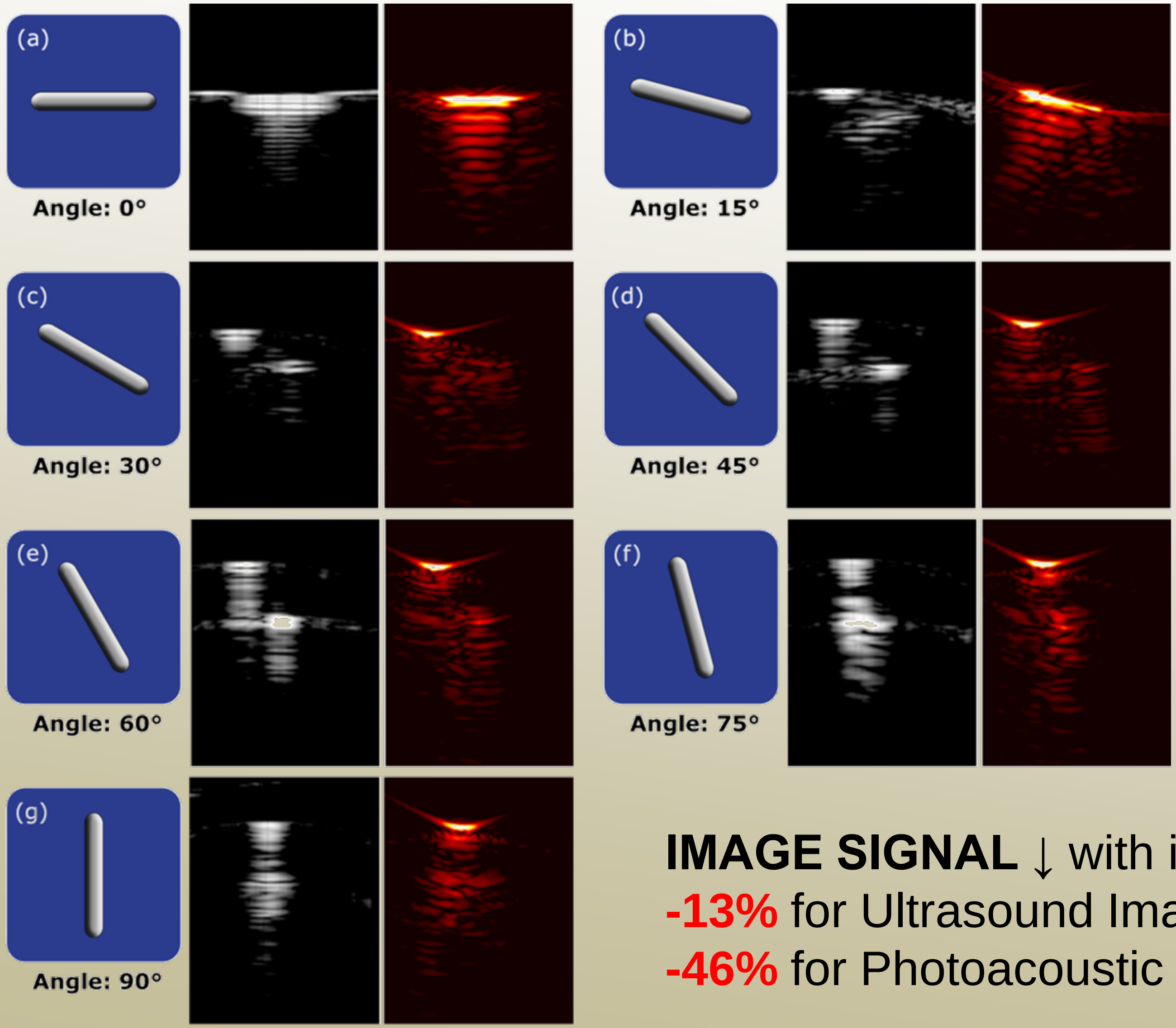

IMAGE SIGNAL ↓ with increasing angle
-13% for Ultrasound Imaging
-46% for Photoacoustic Imaging

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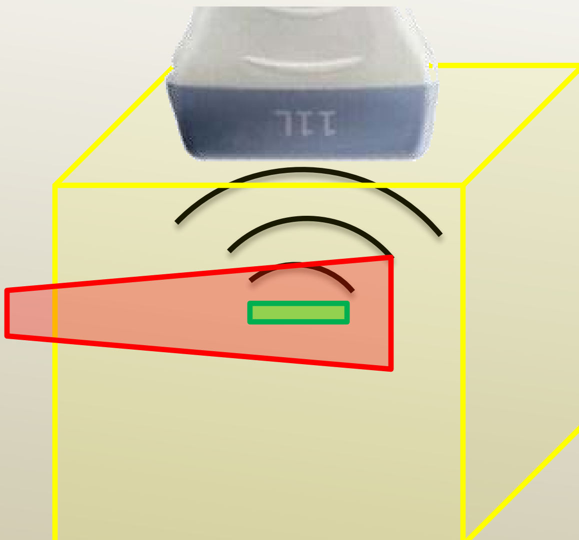
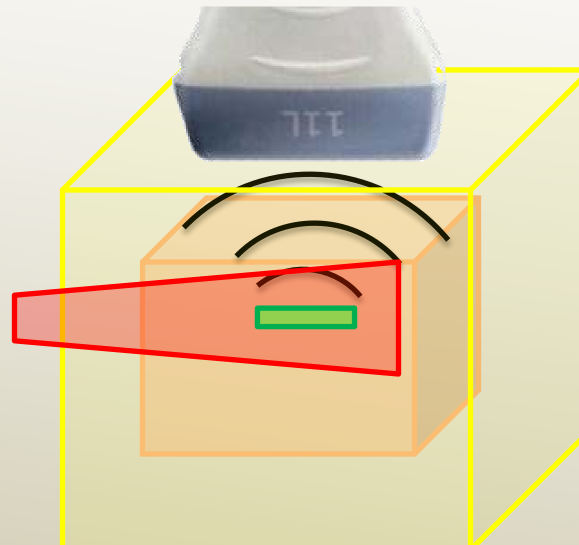
Wavelength Dependence



Seed in Gelatin



Seed in Prostate Tissue

- Laser wavelength swept from 750 to 1090 nm in 20-nm steps
- Gelatin induces negligible optical scattering/absorption

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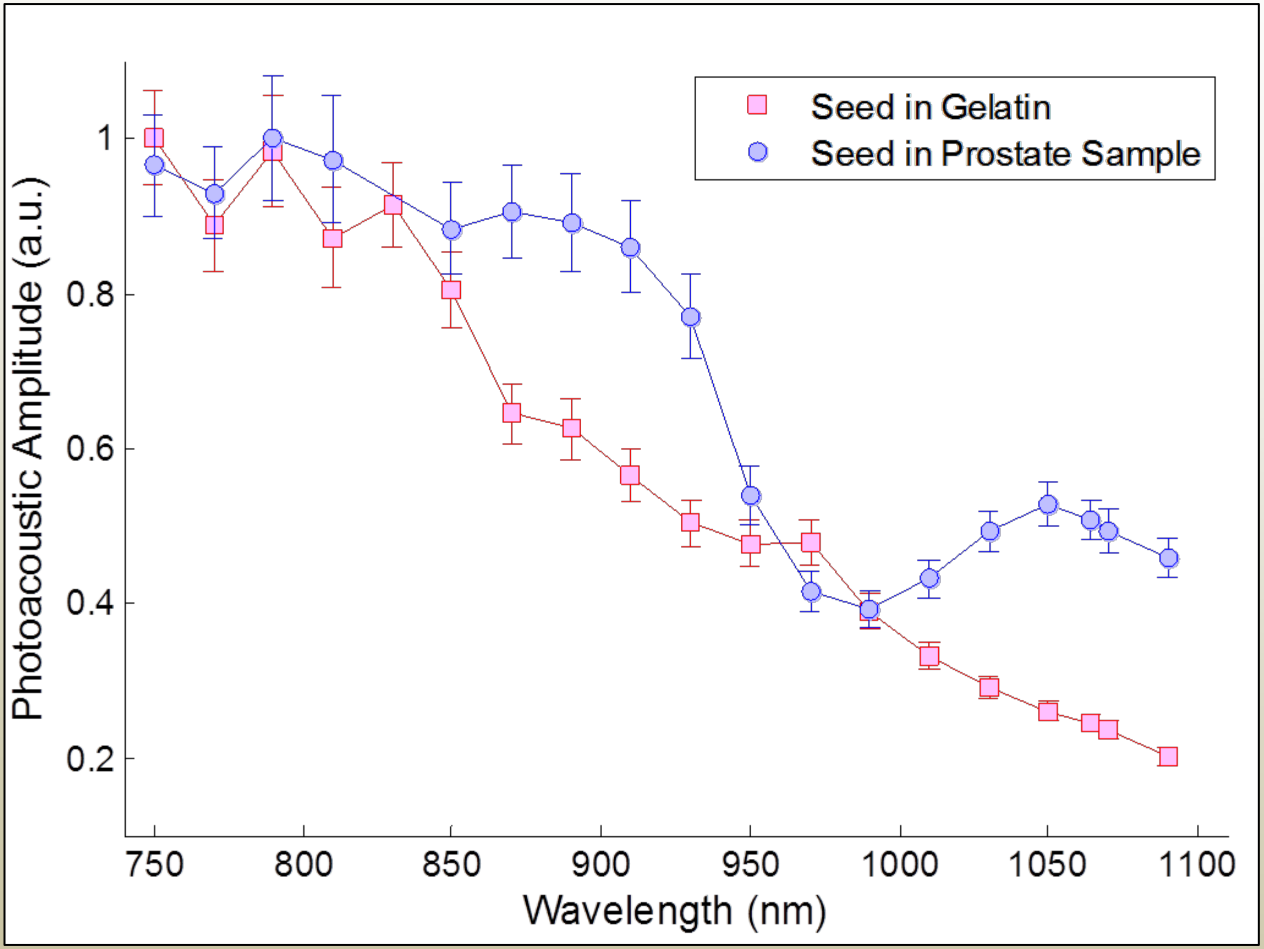
Wavelength Dependence Results



Spectra difference due to optical attenuation and environmental effects

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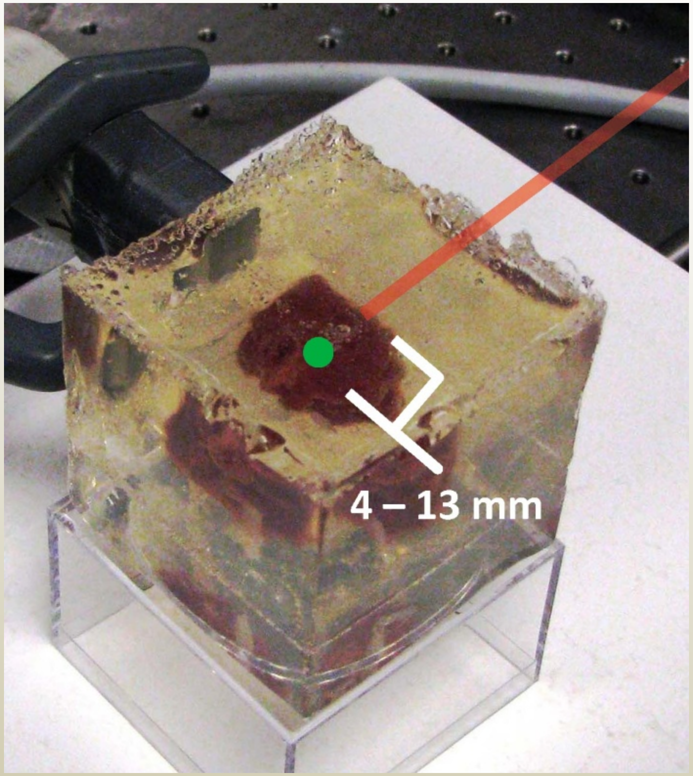
Depth Dependence

- Seed embedded in freshly excised bovine prostate tissue
- Seed imaged at 4, 10, and 13 mm depths from tissue surface
- Tissue sample encased in transparent gelatin block



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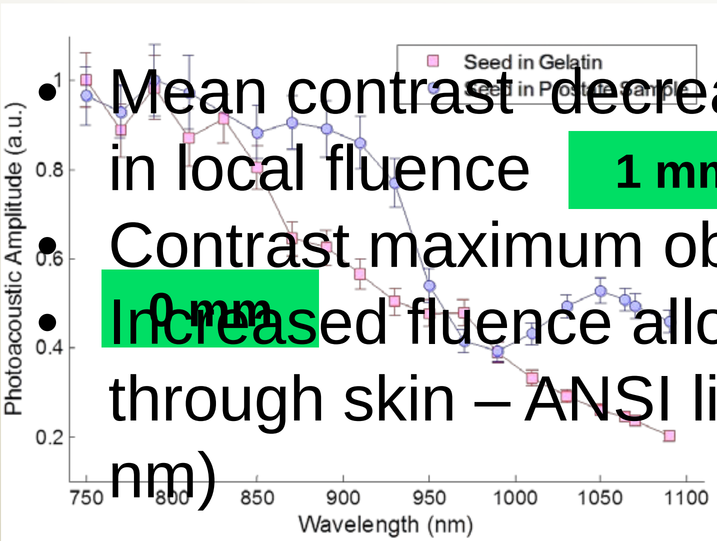
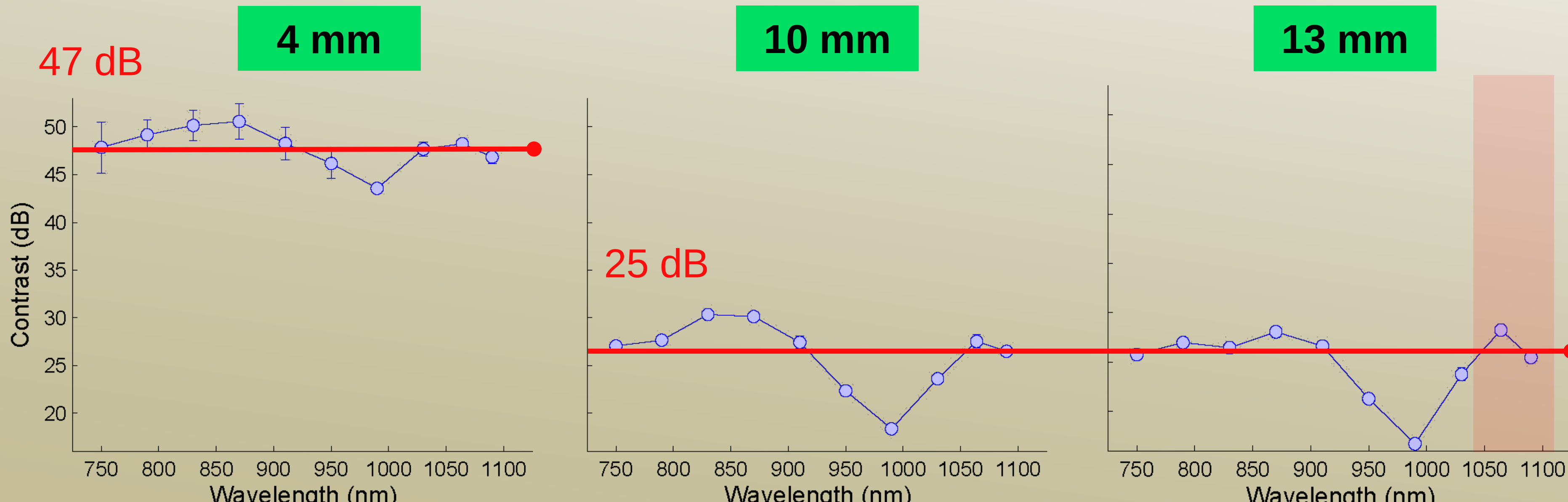
Depth Dependence Results

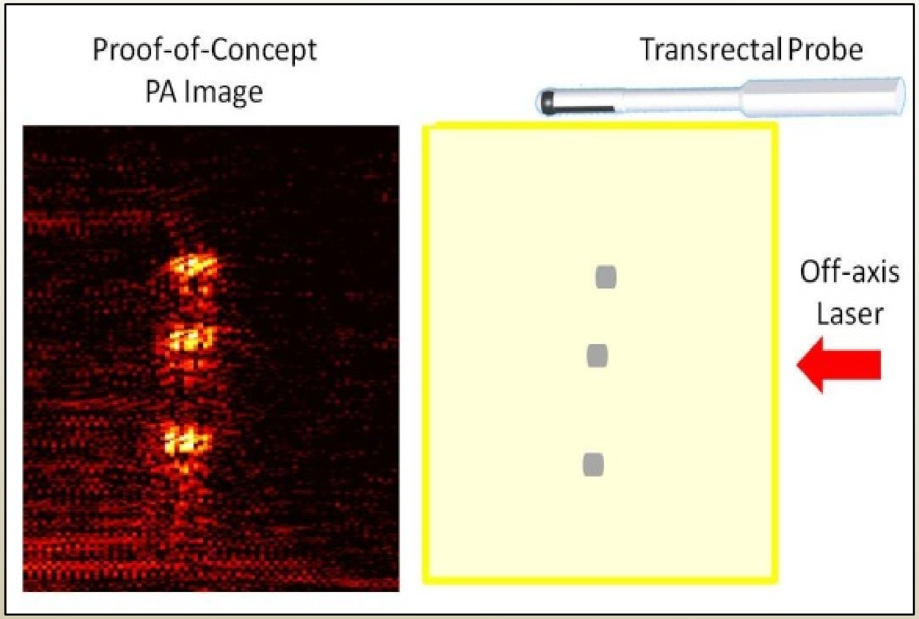
- Mean contrast decreases with increasing depth – reduction in local fluence
- Contrast maximum observed at 1064 nm
- Increased fluence allowed at 1064 nm when imaging through skin – ANSI limit 100 mJ/cm² vs. 20 mJ/cm² (≤700 nm)





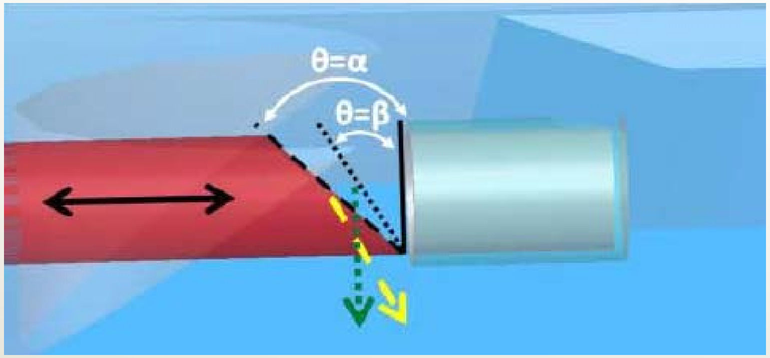
Off-axis Irradiation

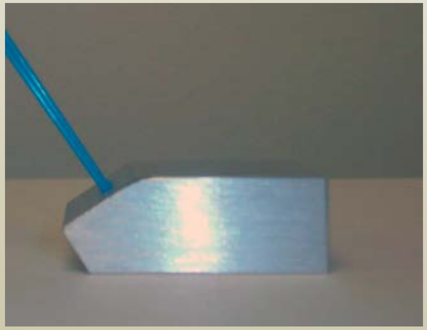
- Transition to transrectal array
- BPL9-5/55 array
- Ultrasonix Sonix RP
- Proof-of-concept imaging with off-axis laser
- Start with clinical ultrasound transrectal probe
- Modify to equip with 7 optical fibers
- Cumulative energy from all 7 fibers > 100 mJ/pulse

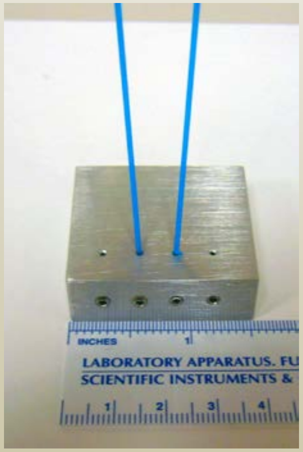


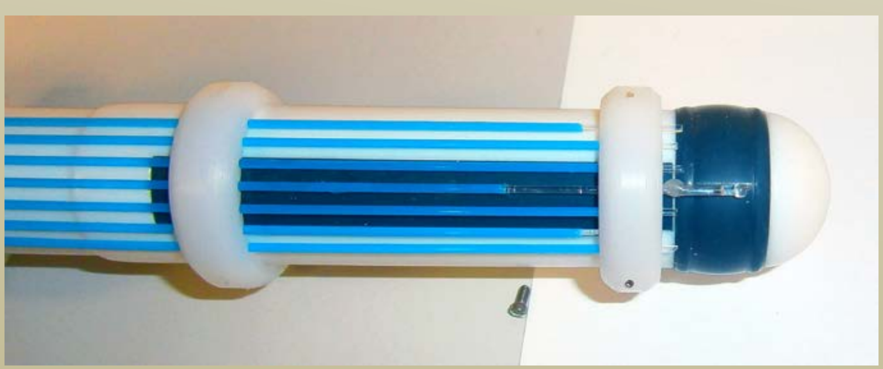
Fiber Preparation

- 800-micrometer multimode fibers
- Fibers must be angled to achieve light redirection
- Angle of approximately 33% to achieve total internal reflection
- Quartz cap installed to ensure air-backed
- Polishing essential for maximum efficiency









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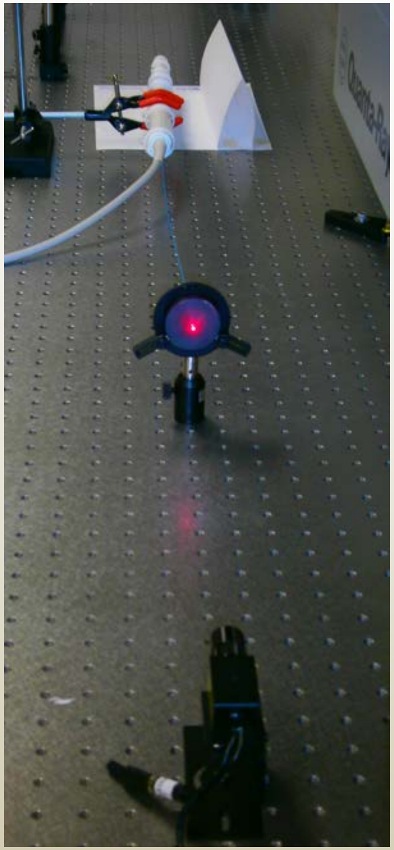
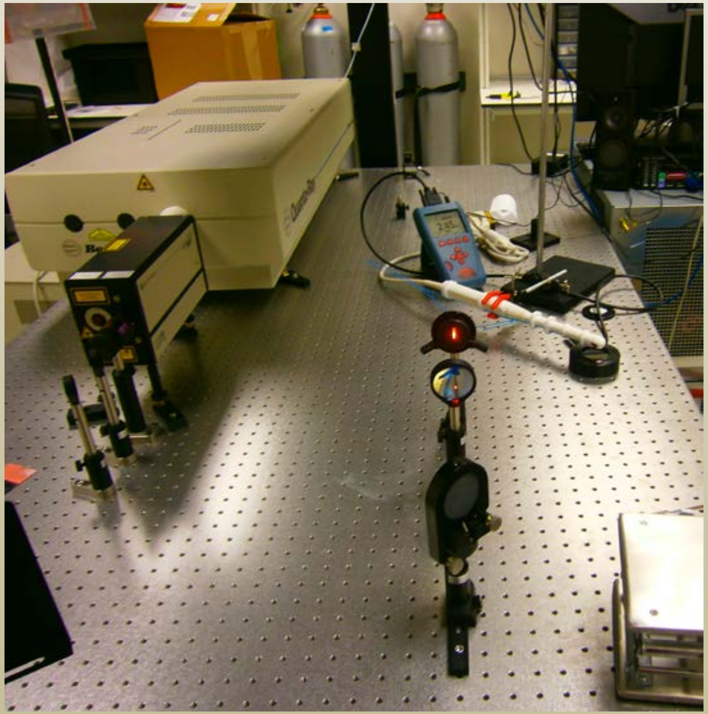
Beam Profile/Energy Assessment

- CW red laser allows for continuous visualization of beam (right)
- Pulsed laser allows for energy measurements (below)
- 9 mJ @ 750 nm through one fiber





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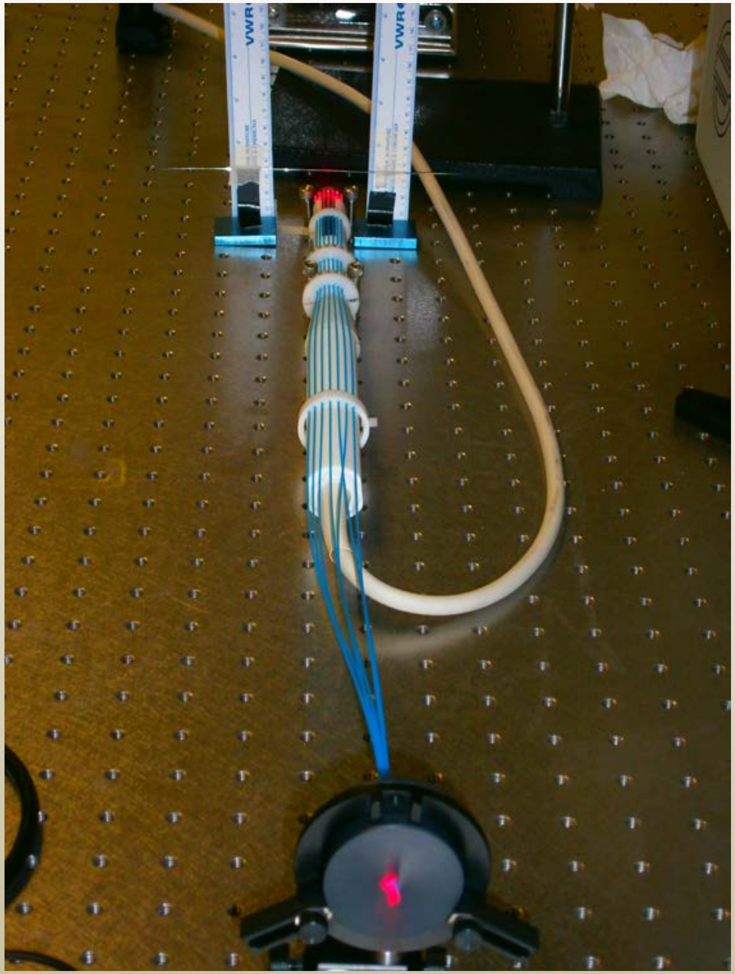
Beam Alignment

- Align beam with ultrasound imaging plane
- Maximize fluence in insonification volume
- Ensure robust enough for eventual large-animal trial



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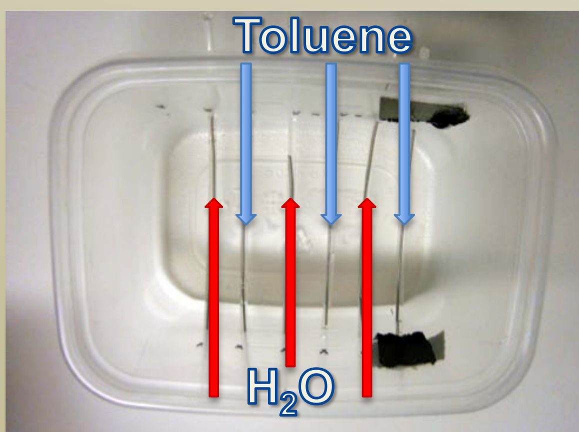
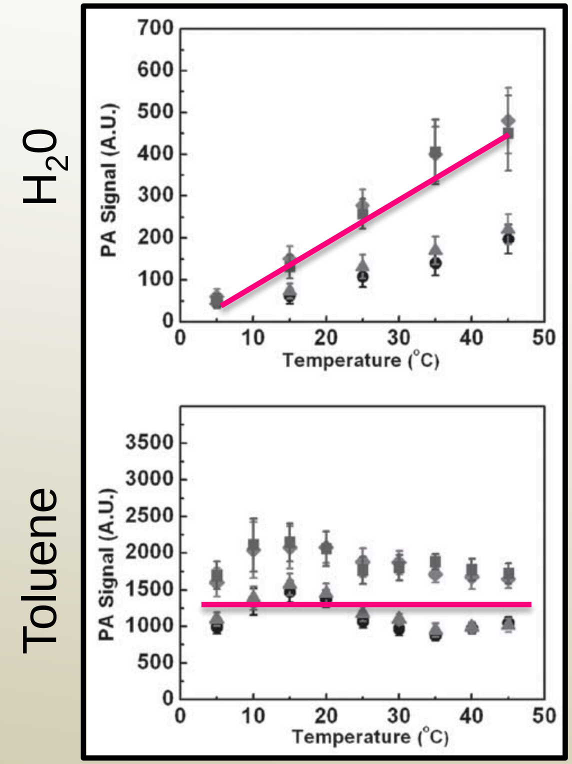
Thermal Mechanism

- Silica coating increases PA signal in nanoparticles due to decrease of interfacial resistance.
- PA signal actually come from environment with nanoparticles.
- *No increase in PA signal with silica coating in Ti seeds*
- Does signal come from Ti or H_2O?



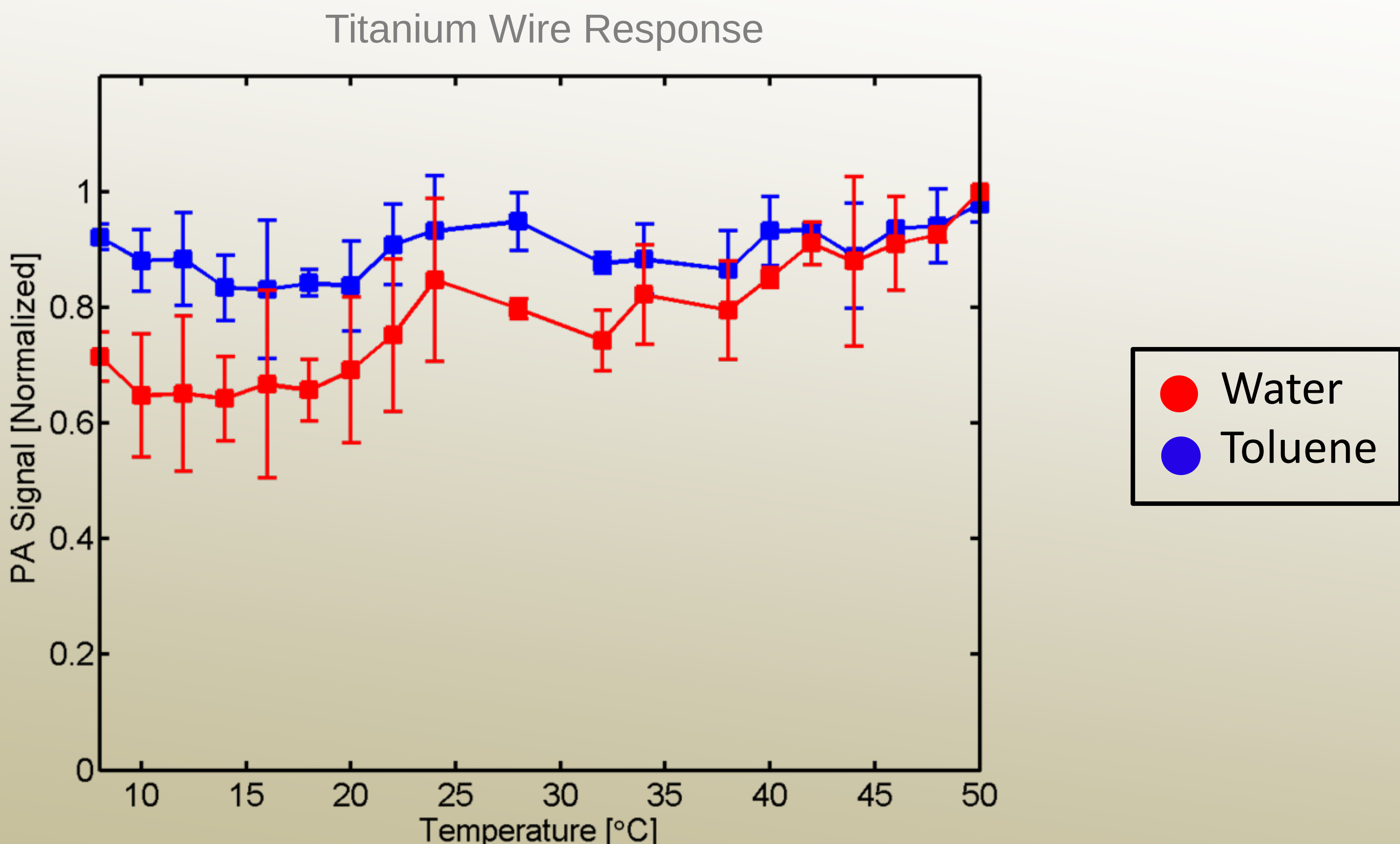
Nanoparticle Response



Follows Grüneisen parameter of liquid…

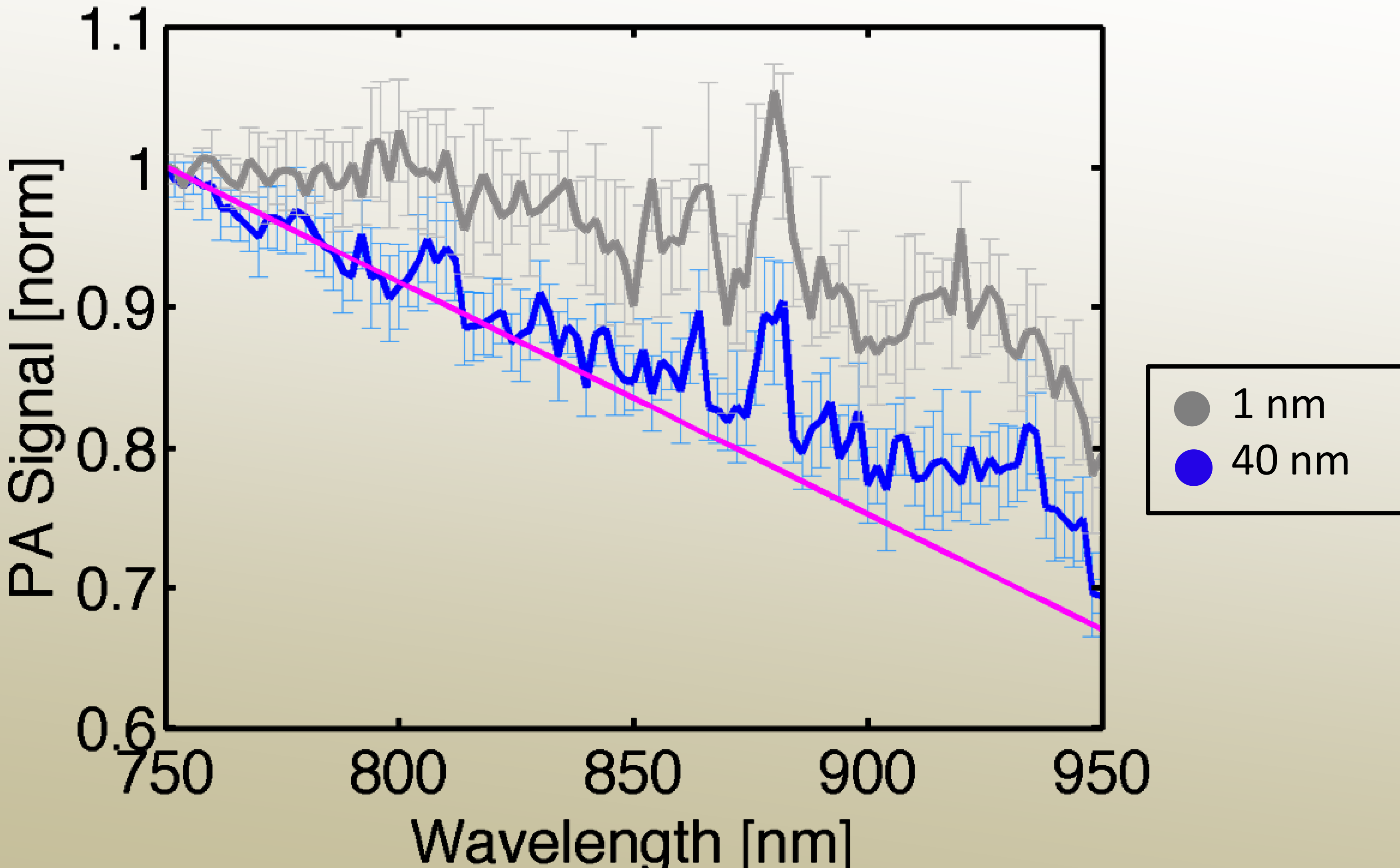
Chen, Y.-S., Frey, W., Aglyamov, S. and Emelianov, S. (2012), Environment-Dependent Generation of Photoacoustic Waves from Plasmonic Nanoparticles. Small, 8: 47–52.

Temperature Dependence



Follows Grüneisen parameter of titanium ⟶ Ti thermally conductive and semi-infinite.

Anodization



Change in PA signal due to simulated change in R ⟶ spectroscopic tuning?

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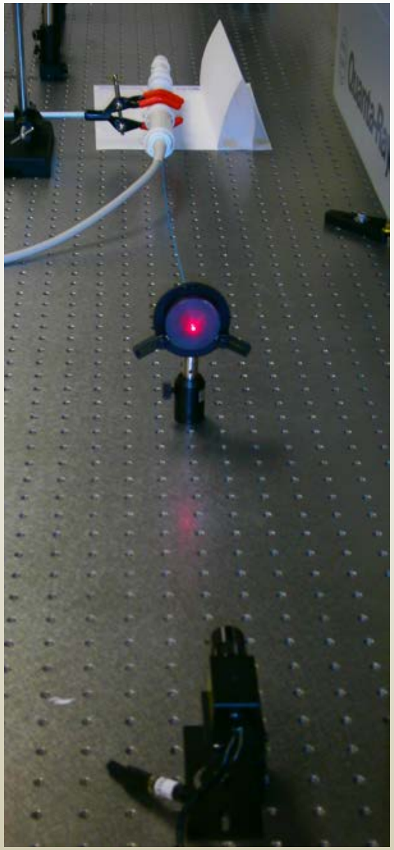

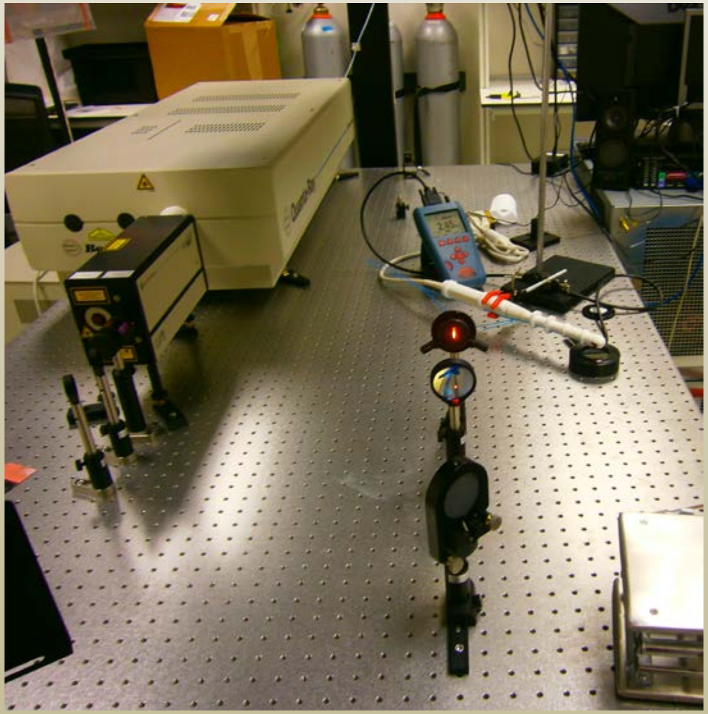

Beam Alignment

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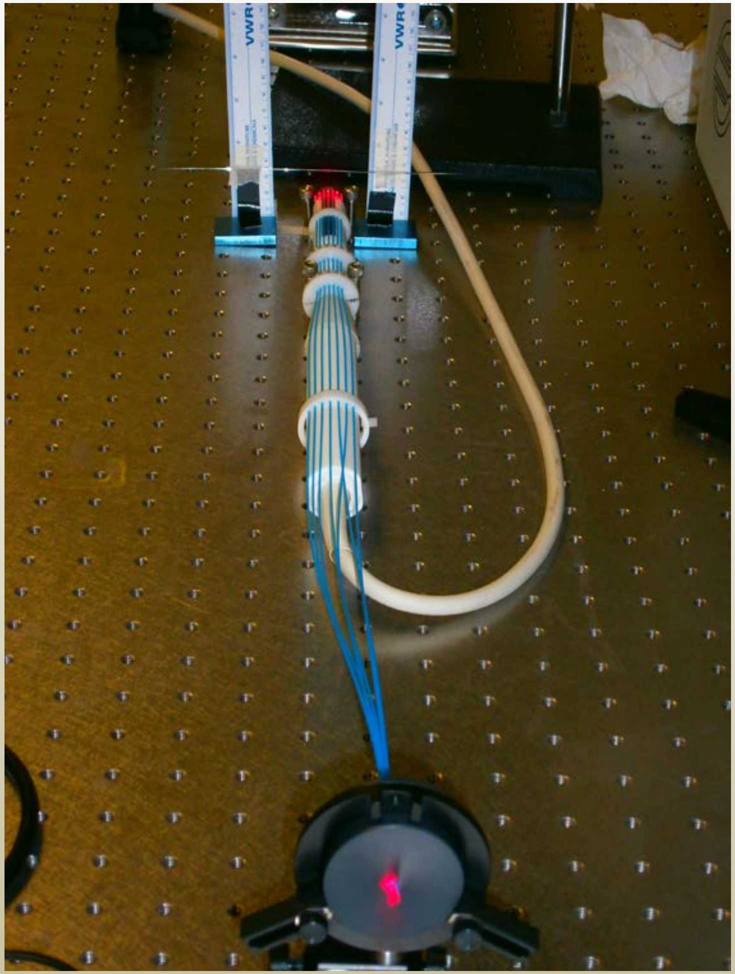

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PAUS Imaging of Brachtherapy Seeds

Hypothesis: A clinically compatible transrectal PAUS probe can be constructed and integrated into a PAUS imaging system to provide high quality combined PAUS images in a clinical setting.

"Development and Optimization of a Photoacoustic-Ultrasonic Transrectal Imaging System for the Improved Visualization of Prostate Brachytherapy Seeds," National Institutes of Health Prostate SPORE Development Research Program Award; Total Cost: $68,900; Role: PI.

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Clinical Introduction

- **Prostate cancer** is the second most common cancer among men in the US (after skin cancer)†
- Second leading cause of cancer deaths in the US (after lung cancer)†
- Primarily develops in men over age 50

Treatment options include:

- Active surveillance
- Radical prostatectomy
- Androgen deprivation therapy
- Radiation therapy

†American Cancer Society Facts and Figures 2012

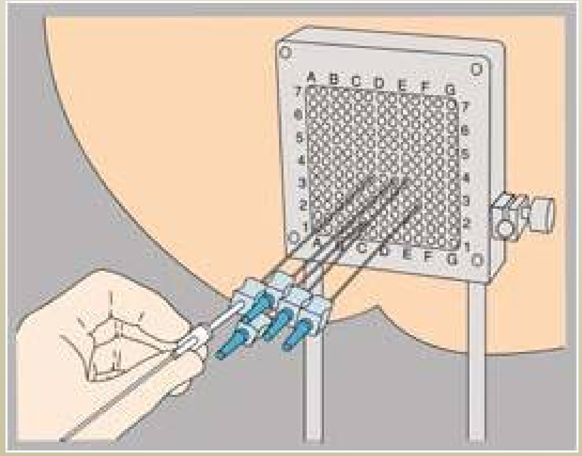
Standard of Care

The use of **brachytherapy seeds** is a common treatment option for low-to-intermediate risk patients.

- Seeds are placed according to a pre-established treatment plan.
- Image-guidance and monitoring is conducted using ultrasound and x-ray.

Use of transrectal ultrasound (TRUS) is the c**urrent standard of care** during the procedure.

- Allows for determination of prostate boundary (CT imaging does not provide).
- Monitoring of seed insertion procedure in real-time.



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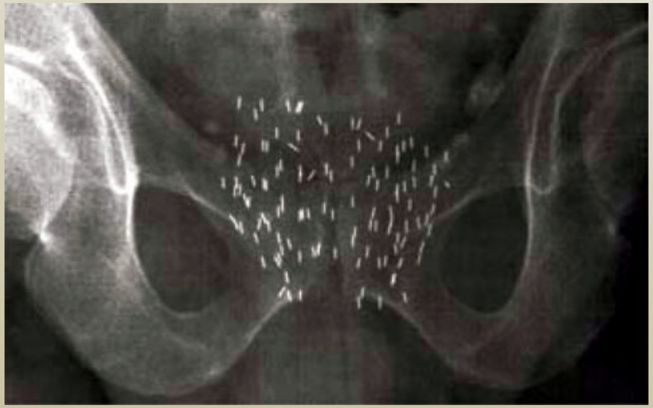
Limitations of Current Technology

- TRUS has many visualization issues
- Seeds can be too small for detection - location often achieved indirectly by visualization of insertion needles
- Echogenicity of tissue can be similar to seeds (poor contrast)
- Acoustic signal of seed is dependent on orientation
- Fluoroscopy provides excellent contrast but cannot used for real-time guidance because of ionizing radiation



Fluoroscopy Image

Clinical Need

- Seed misplacements require post-op dose corrections with external beam radiation or a revision implantation
- Needle deflections of 5° can reduce dose by 10% and increase tumor-cell survival by 200x[†]
- Overdosing can lead to multiple complications, including urinary retention (14.5%) and/or rectal bleeding (13.7%)[††]

†S. Nath, Z. Chen, N. Yue, S. Trumpore, and R. Peschel, “Dosimetric effects of needle divergence in prostate seed implant using 125I and 103Pd radioactive seeds,” Med. Phys. 27, 1058–1066 (2000).

††R. Benoit, M. Naslund, J. Cohen, “A comparison of complications between ultrasound-guided prostate brachytherapy and open prostate brachytherap,” International Journal of Radiation*Biology*Physics 47, 909-913 (2000).

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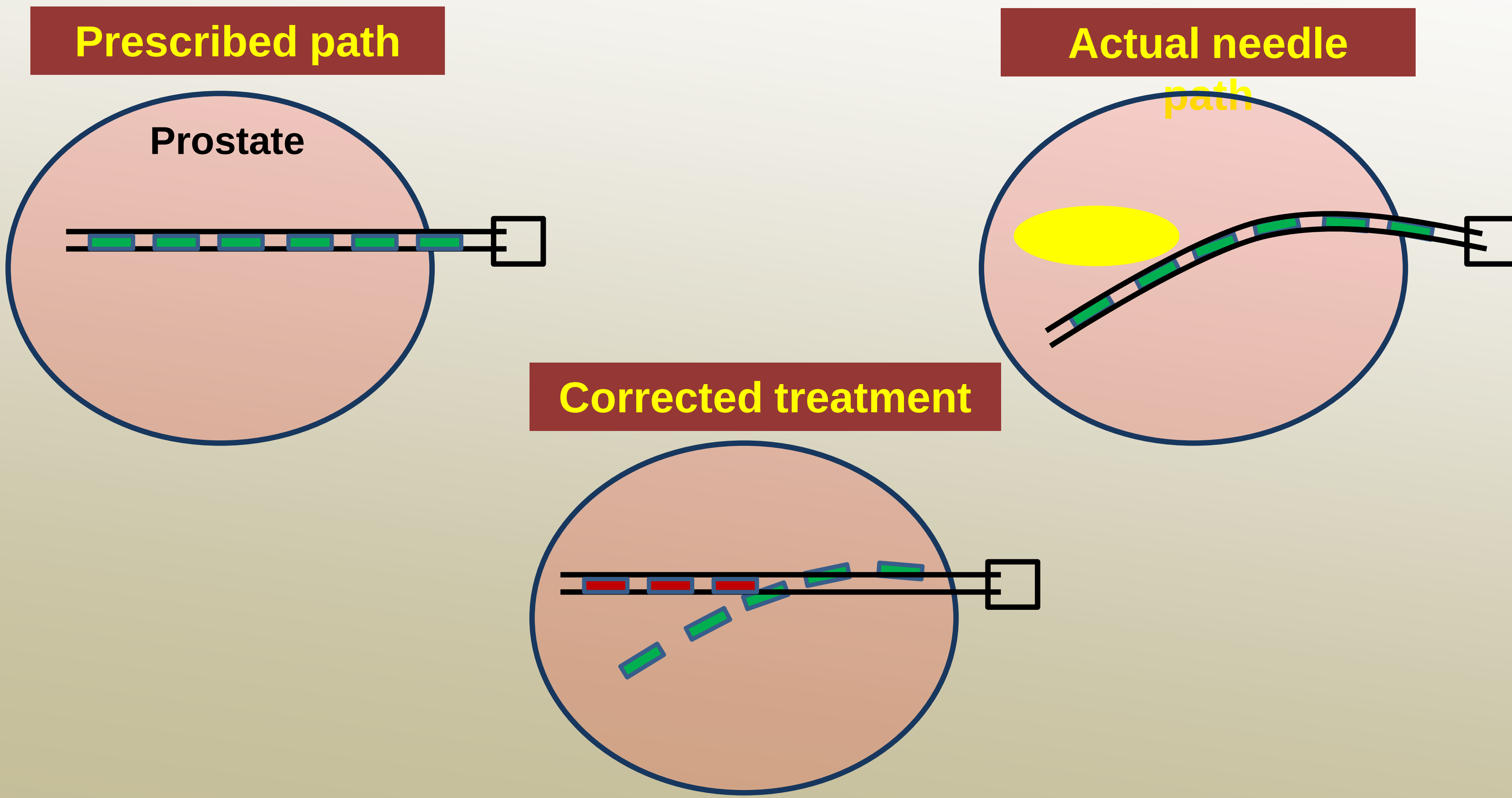
Addressing the Clinical Need

What is needed: An ADAPTIVE treatment plan during the procedure

Requires real-time visualization of seeds AND anatomy!!



Figures: Fichtinger, G. "Research Issues in Robot-Assisted Needle Interventions" 2003.
http://miccai.irisa.fr/Program/description/G-Fichtinger.pdf

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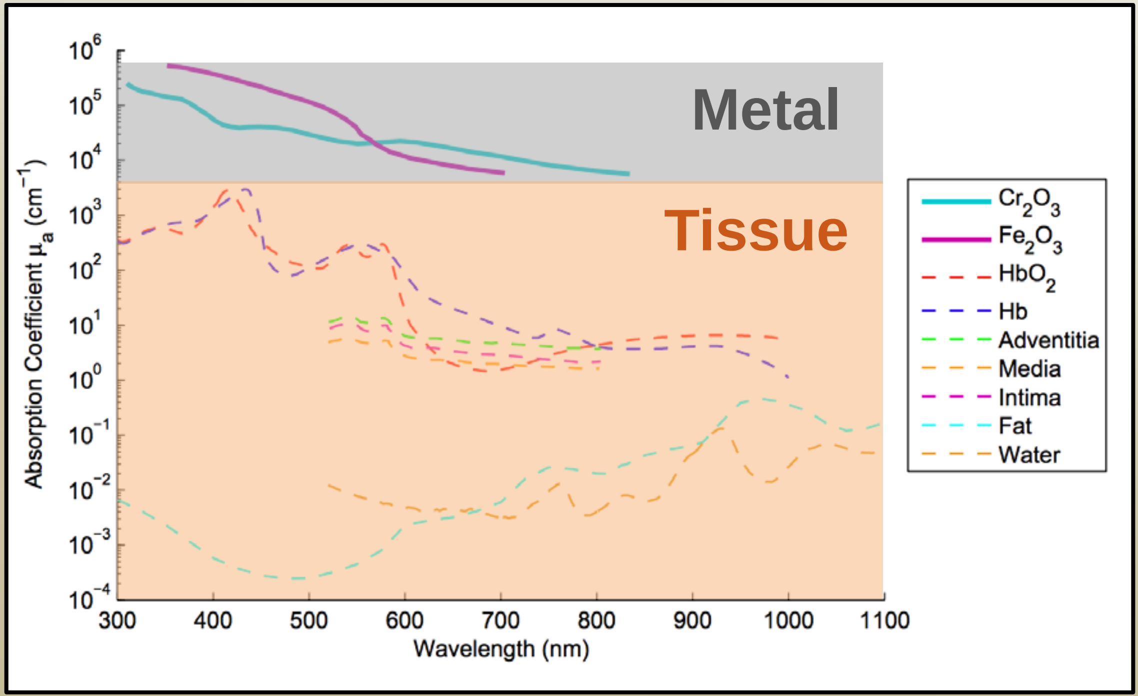
Photoacoustic Imaging

- Photoacoustic imaging uses laser pulses to generate acoustic sources in tissue through absorption and thermoelastic expansion.
- Provides contrast (optical absorption) and spectroscopic capabilities of optical technique with depth penetration of acoustic technique.
- Combined with ultrasound (PAUS) to achieve real-time imaging of absorbers (e.g., hemoglobin or plasmonic nanoparticles) and anatomy.



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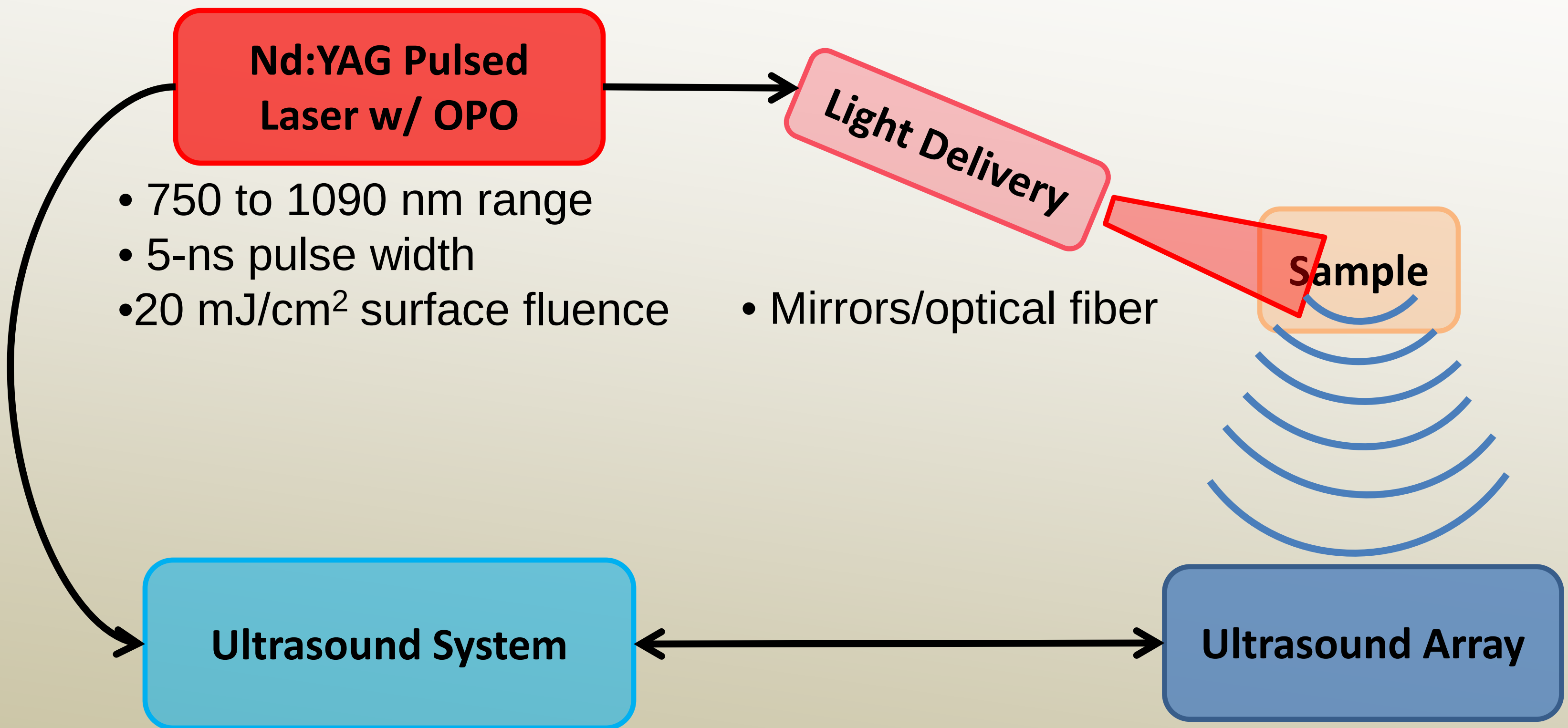
PAUS Prototype System



- 750 to 1090 nm range
- 5-ns pulse width
- 20 mJ/cm^2 surface fluence

- Mirrors/optical fiber

- Winprobe Corp. customizable platform
- Capable of PA and US beamforming

- 128-element linear array
- 7-MHz Center Frequency
- Rx (PA imaging) and Tx/Rx (US imaging) modes

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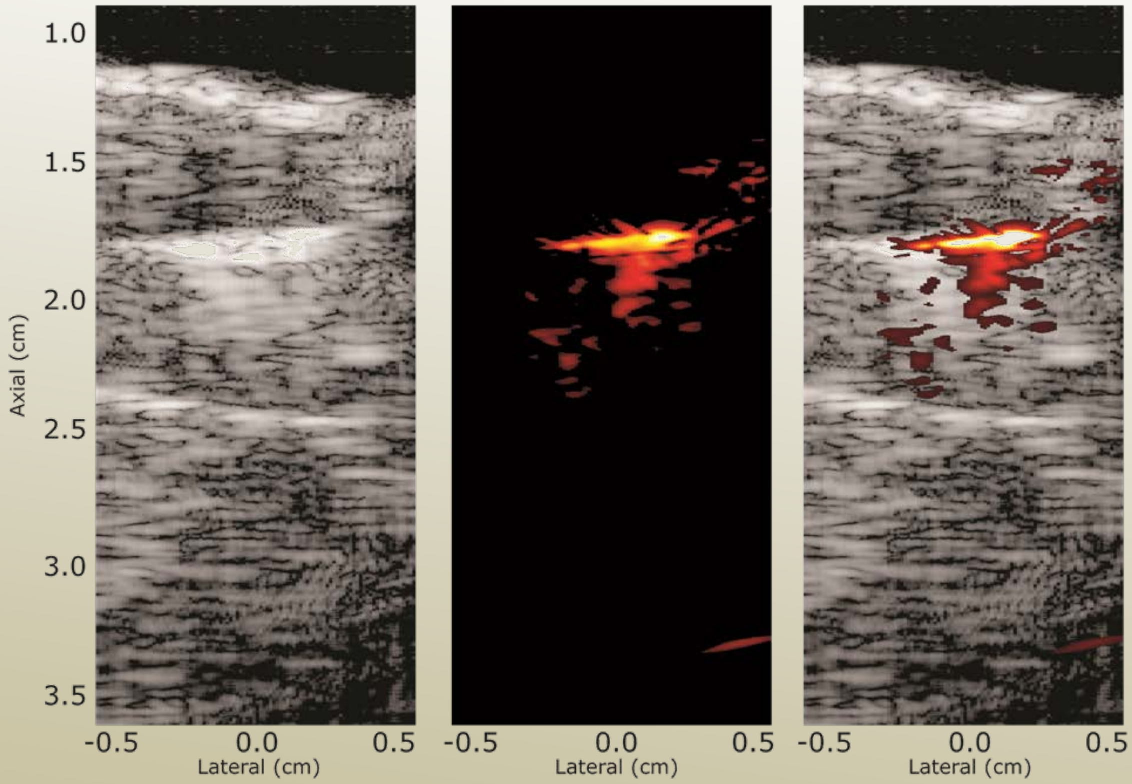
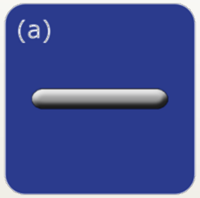
Contrast Improvement Result

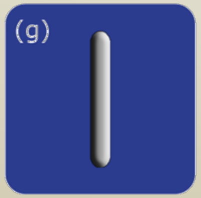
Seed shallowly embedded in prostate tissue





Angle: 0°

28-dB contrast improvement
Photoacoustic over Ultrasound

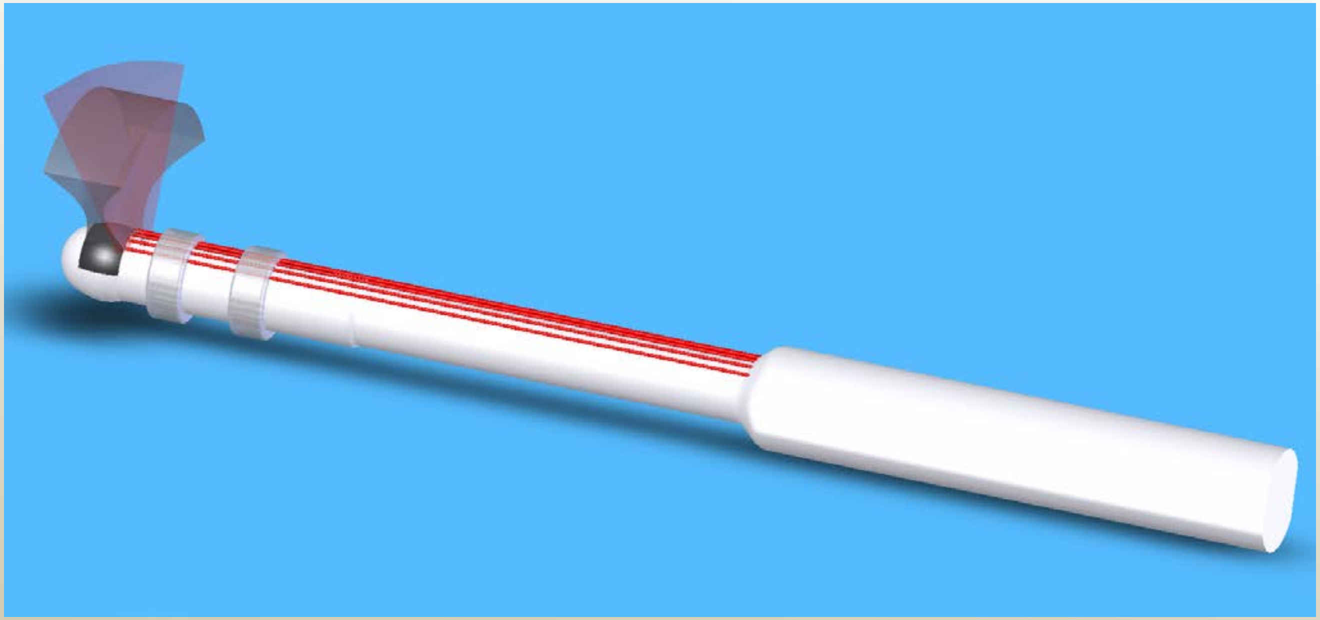


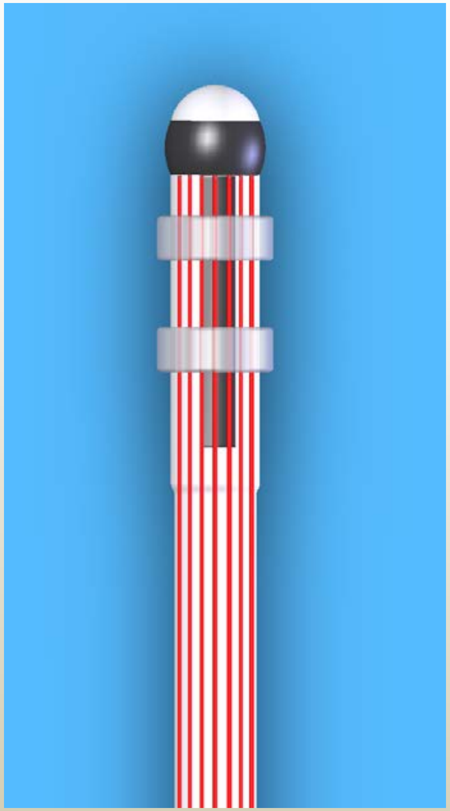
Angle: 90°

24-dB contrast improvement

Su JL*, **Bouchard RR***, Karpiouk AB, Hazle JD, Emelianov SY. “Photoacoustic imaging of prostate brachytherapy seeds,” Biomedical Optics Express, 2(8): 2243-2254, 2011. (*authors contributed equally)

SolidWorks Design





Start with axial array – develop light delivery for sagittal array later.

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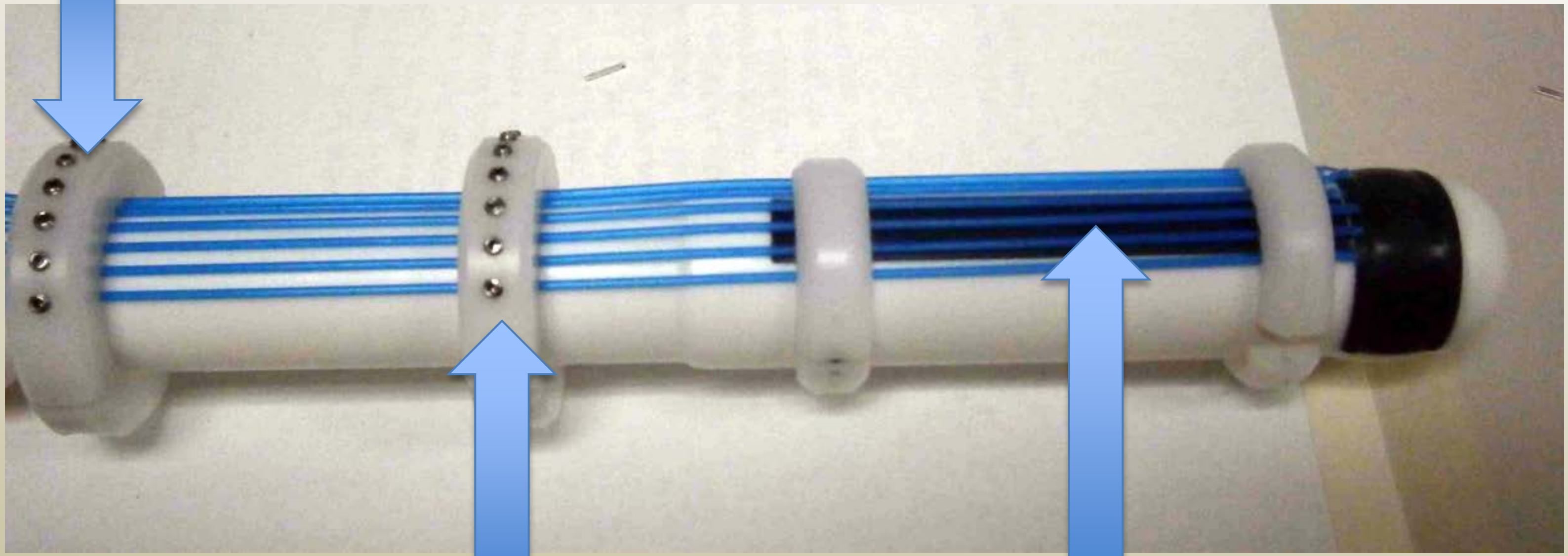
Machined Realization

Biocompatible Delrin and stainless steel bolts



Set screws allow for rotation/translation of individual fibers

7 total fibers

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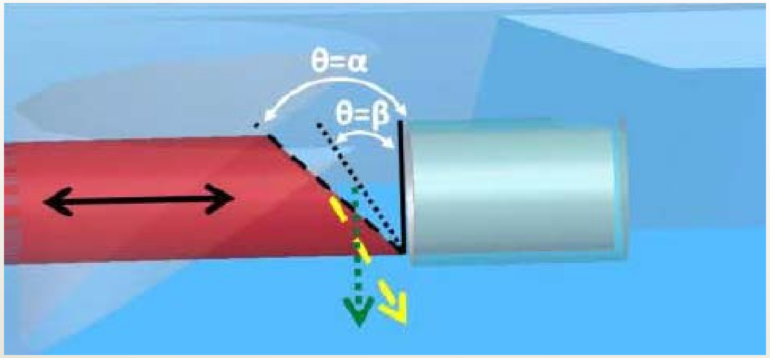
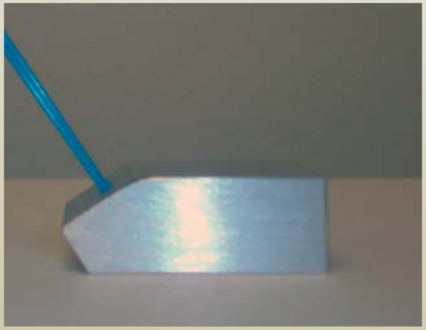
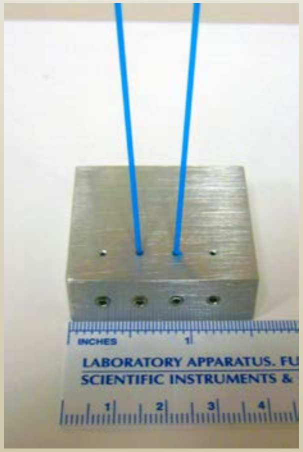
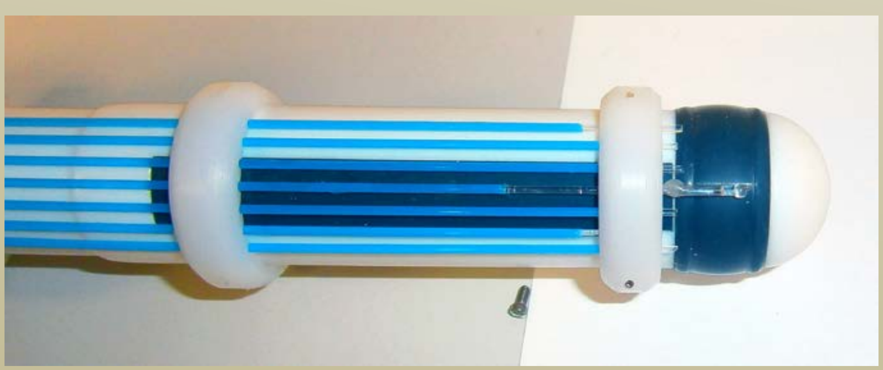
Fiber Preparation

- 800-micrometer multimode fibers
- Fibers must be angled to achieve light redirection
- Angle of approximately 33% to achieve total internal reflection
- Quartz cap installed to ensure air-backed
- Polishing essential for maximum efficiency









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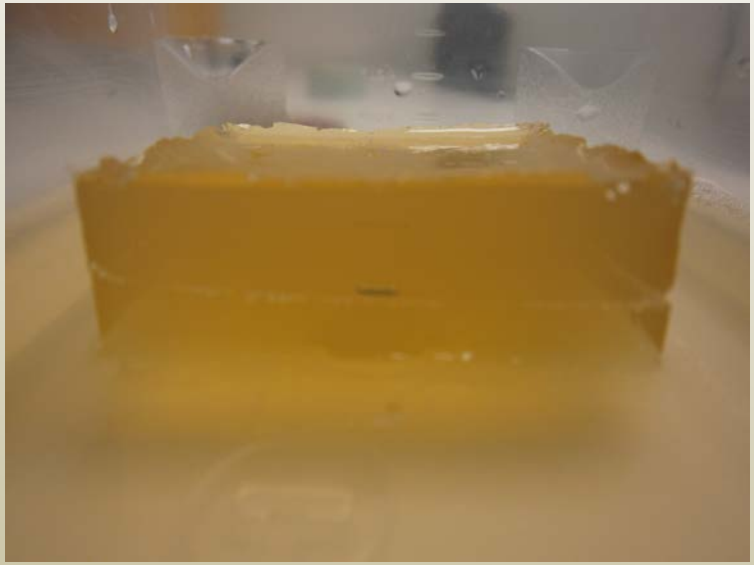
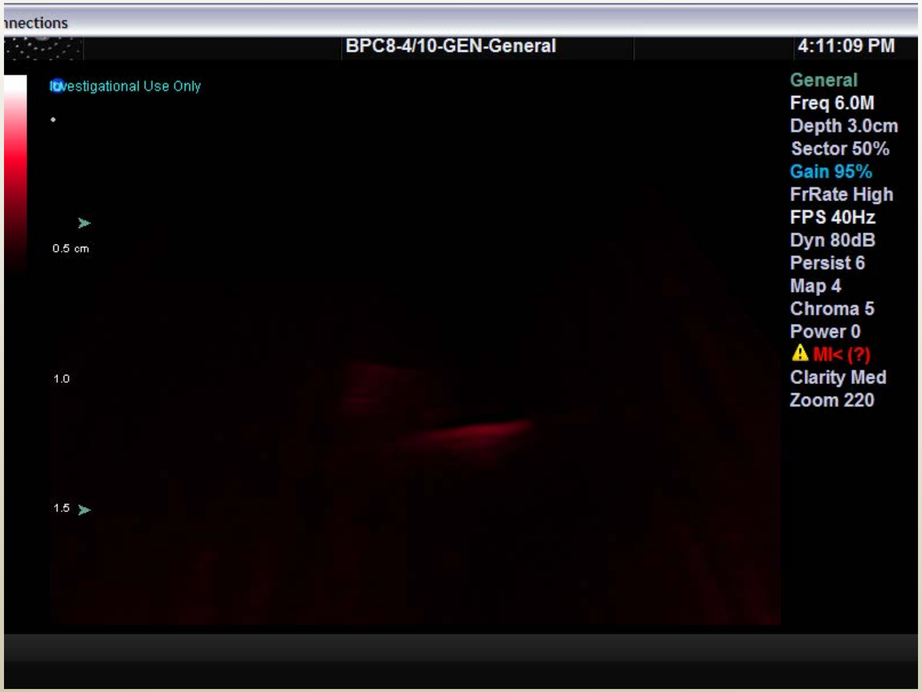
First Images!

Phantom w/ Seed



Photoacoustic Image



Obtained with clinical transrectal probe on clinical imaging system using integrated light delivery system @ 1064 nm.

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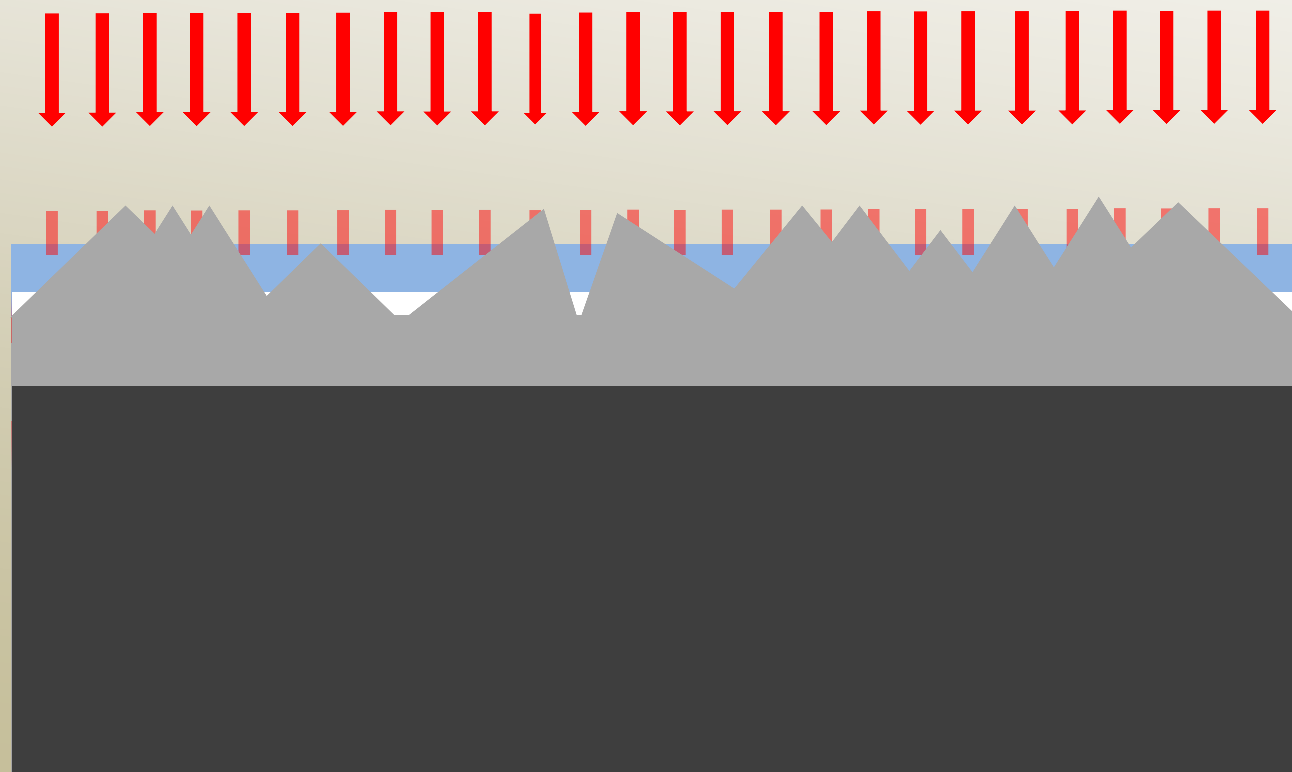
Enhancement Possibilities

Remember: $p_0 = (\frac{\beta c^2}{C_p})\mu_a F$

1. Incident Light
2. Reflection (> 50%) & Transmission
3. Absorption
4. Heating & Thermal Conduction
5. Thermal Expansion → Sound



Surface Modifications

- Thermal
  - ~10s nm silica coating (enhances particles)
- Material
  - PVD Coatings (~1-4 µm – “biocompatible”)
    - TiN*** - reflectivity lower than Ti
    - TiAlN**, AlTiN** - α_{Al} > 2x Ti
    - MoS_2* - graphite-like coating
  - Metals (biocompatible)
    - Ti (control), 316L SS, & Nitinol (NiTi)
- Surface
  - Roughness
    - Polished vs. Sanded (600 grit)
  - Oxidation Layer
    - ~40 nm thickness (dark blue)

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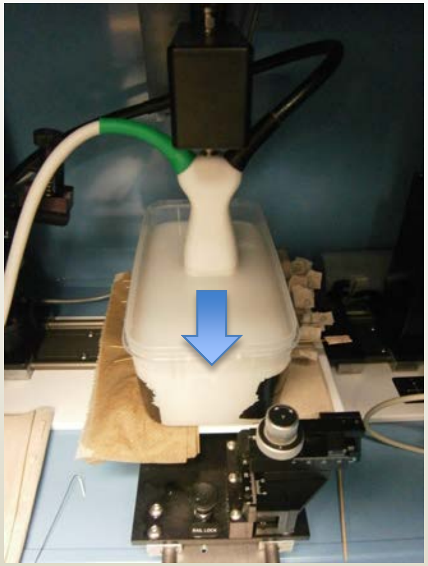
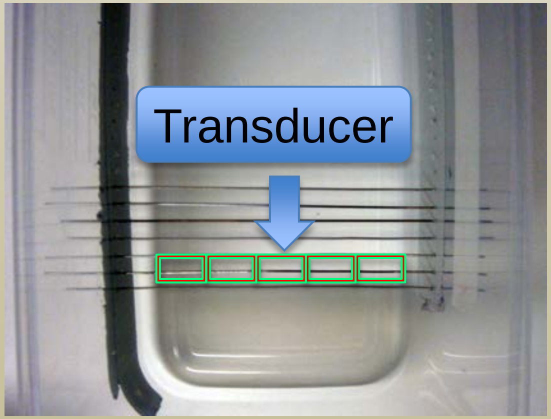
Experimental Methods

- VisualSonics Vevo LAZR system
- 21-MHz linear array
- 970 nm @ ~7 mJ pulse energy
- Wire phantom (diameter of brachytherapy seed)
- Filled with DI water and 3% milk (scattering)
- 3D scan performed
- Average PA signal for 10 segments
- All enhancements shown relative to bare Ti

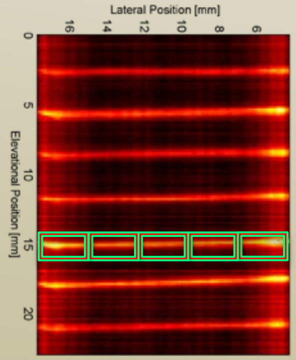
LAZR Phantom Setup



Overhead Phantom View



PA C-Scan



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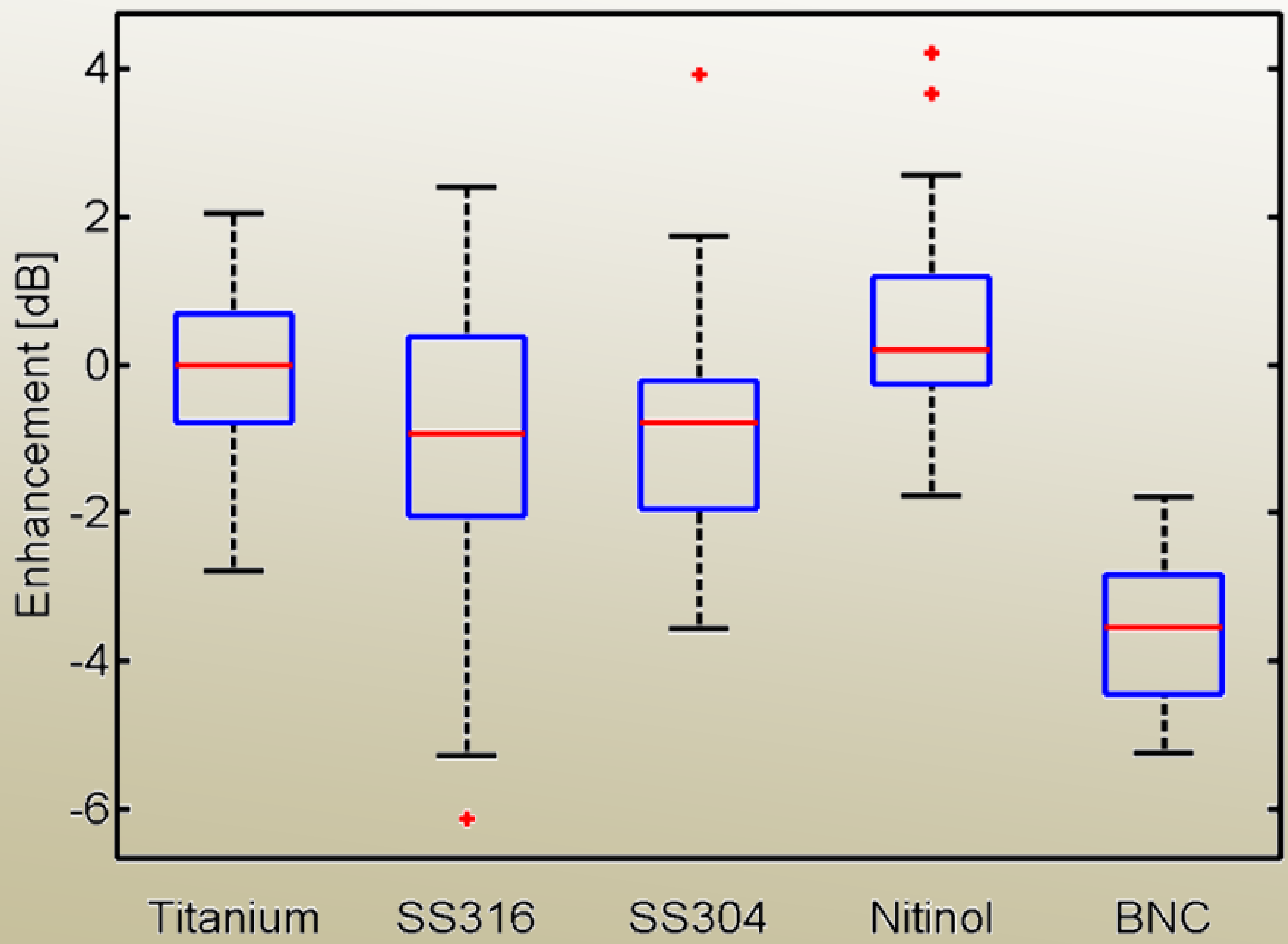
Raw Material



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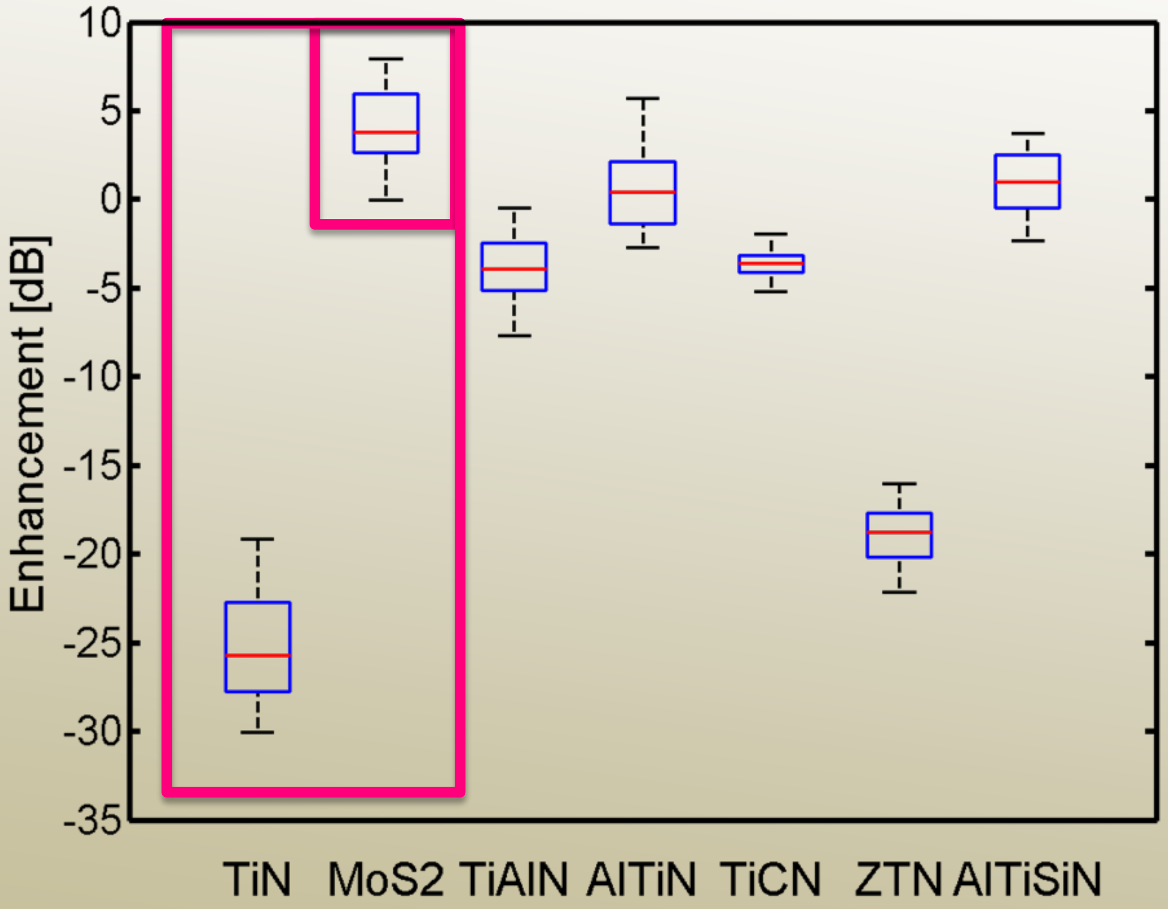
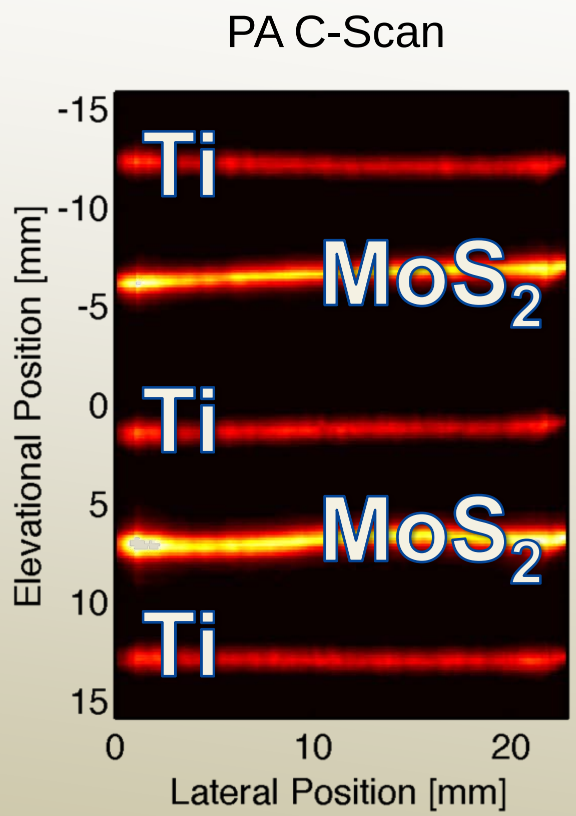
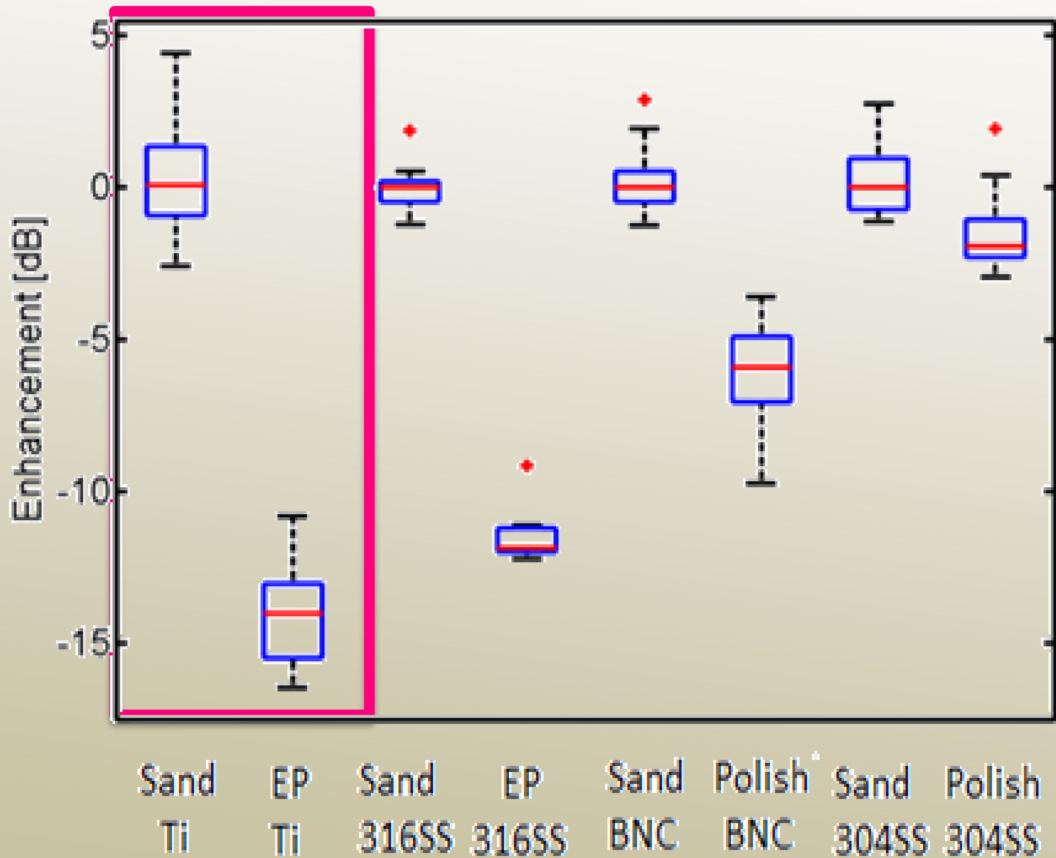
Coating Enhancement

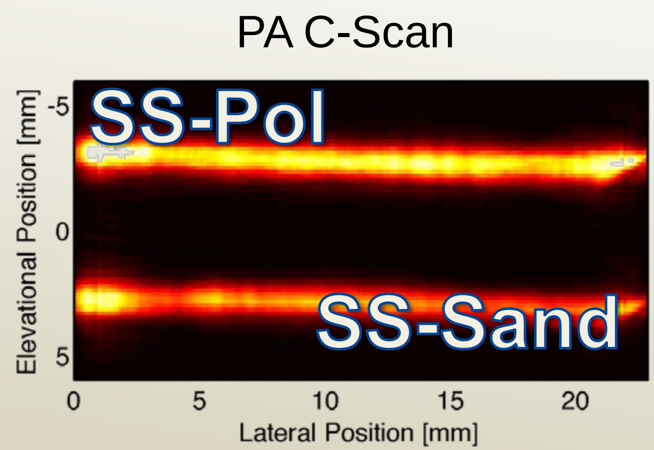




4-dB increase over bare Ti And 30-dB difference between TiN and MoS_2.

Surface Roughness





14-dB difference between polished and sanded 316L SS.

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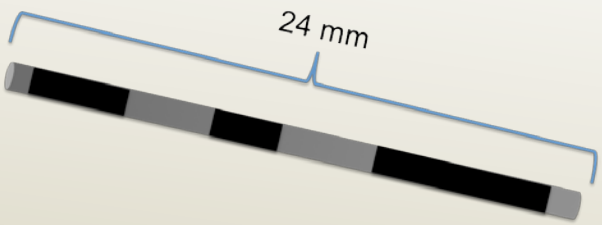
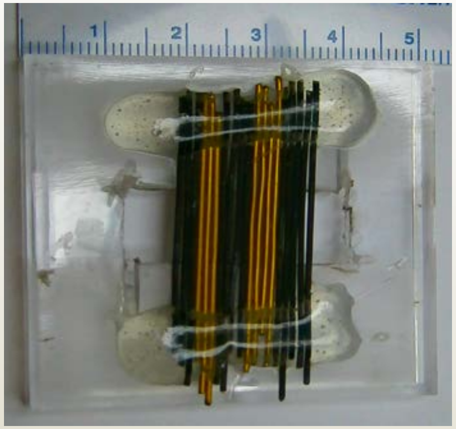
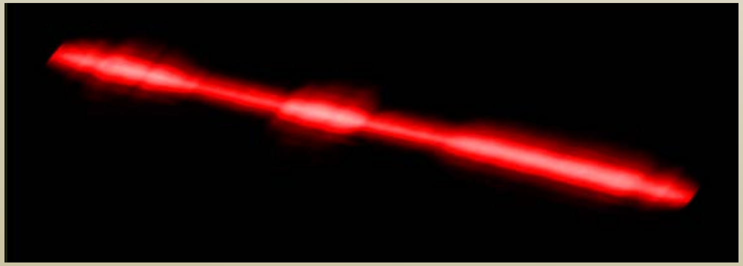
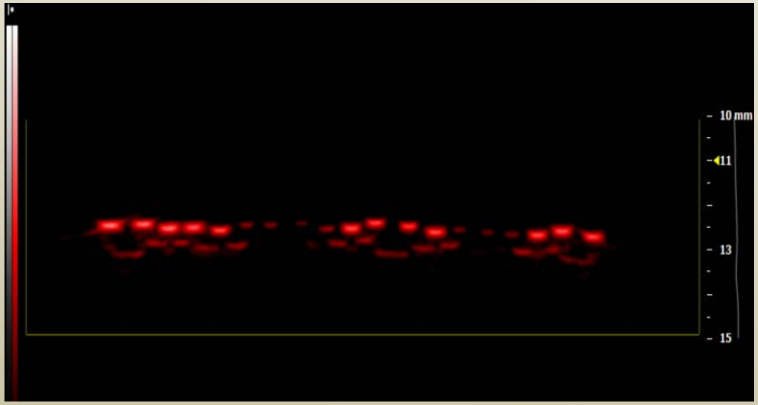
Patterning of Implants









Surface Roughness

PVD Coating

Photoacoustic Imaging Research Lab

- 3 rooms in SCRB 3 in the Center for Advanced Biomedical Imaging Research (CABIR)
- Pulsed, tunable Nd:YAG laser synchronized with an Ultrasonix clinical, customizable ultrasound imaging platform and a pnuematic optical table

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Generated Pressure Amplitude

- Based on the photoacoustic wave equation for thermal expansion (assuming thermal and stress confinement conditions are met):

$$p_o(r,T,\lambda)=\frac{\beta(r,T)c(r,T)^2}{C_p(r,T)}\mu_a(r,\lambda)F(r,\lambda)$$

- Spatial dependence of absorption allows for imaging
- Wavelength dependence allows for spectroscopic imaging
- Temperature dependence allows for thermography
- Local fluence is always unknown -> big problem