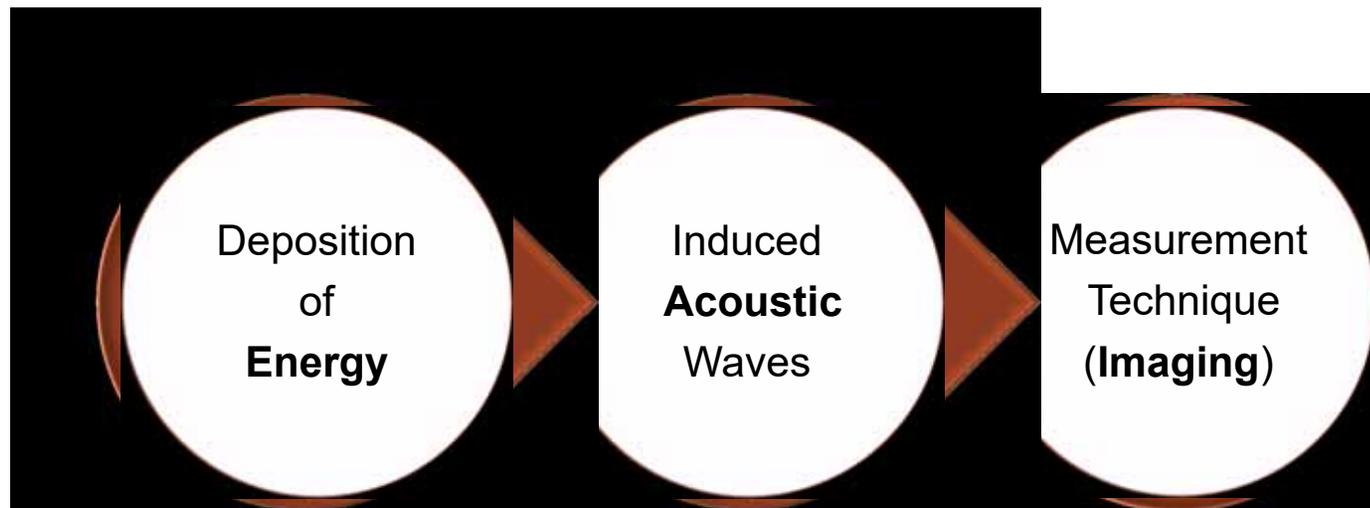


Radiation-Induced Acoustic Imaging

Siavash Yousefi

October 20th, 2016

Acoustic/Ultrasonic Imaging



- High-energy acoustic

- Shockwaves

- Pulsed echo detection
- Motion detection
- High-frame rate imaging

Most Common Ultrasound Modalities

Ultrasound Imaging



**Pulse-Echo
Echo Detection**

Acoustic Impedance Mismatch
between Tissue Structures

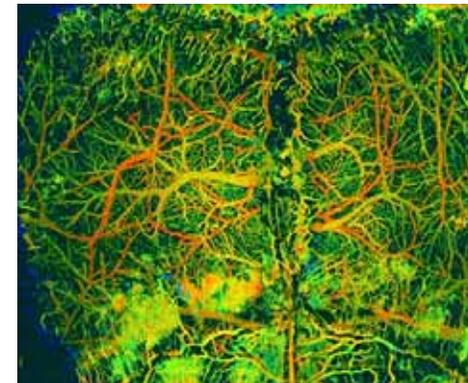
ARFI Elastography



**High-Energy Acoustic
Echo Detection**

Speed of Sound Variation in
Soft/Hard Tissue

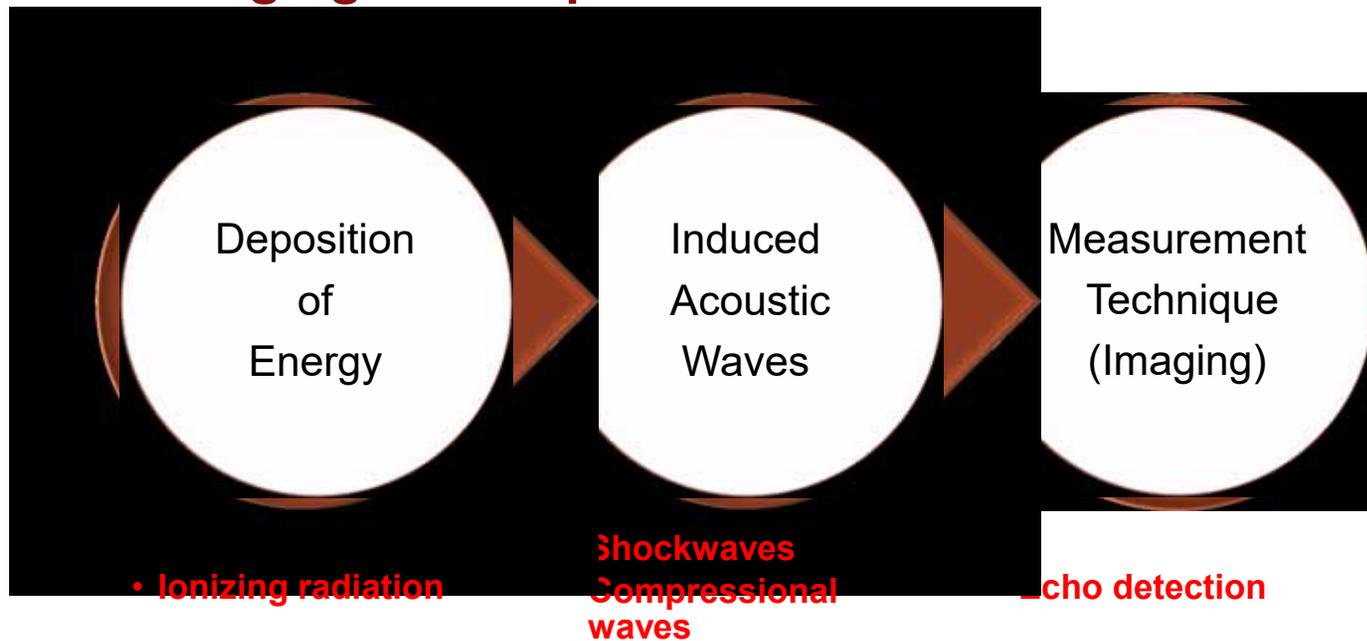
Photoacoustic Microscopy



**Pulsed Laser
Echo Detection**

Endogenous Differential Light
Absorption Contrast

Novel Imaging Technique



Radiation-Induced Acoustic Imaging

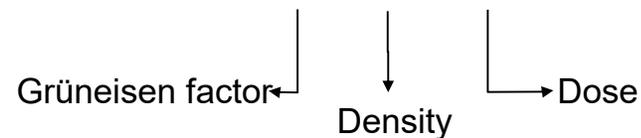
Theory: Thermoacoustics

Wave equations

$$\left(\nabla^2 - \frac{1}{v_s^2} \frac{\partial^2}{\partial t^2}\right) p(r, t) = -\frac{\beta}{\kappa v_s^2} \frac{\partial^2 T(r, t)}{\partial t^2}$$

Initial pressure

$$P_0(r) = \Gamma(r) * \rho * D(r)$$



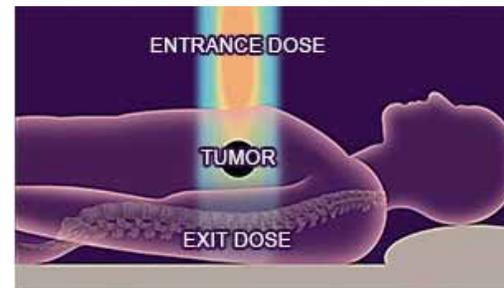
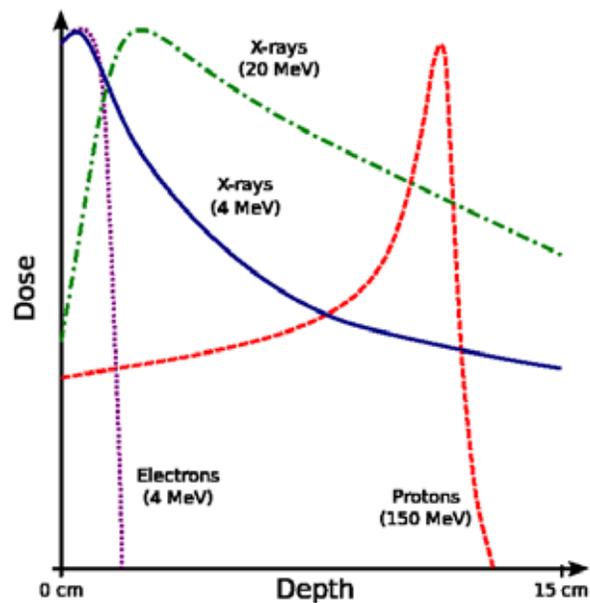
Pulse requirements

$$t_L < \frac{d_c}{v_s} < \frac{d_c^2}{4\alpha_{th}}$$

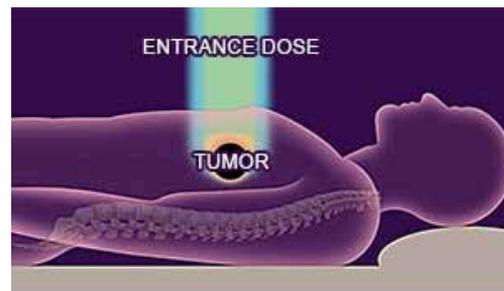


Radiotherapy: Protons vs. X-rays

Superior Dose Distribution



CONVENTIONAL RADIATION THERAPY:
Deposits most energy before target



TARGETED PROTON THERAPY:
Deposits most energy on target

Photo: UF Health

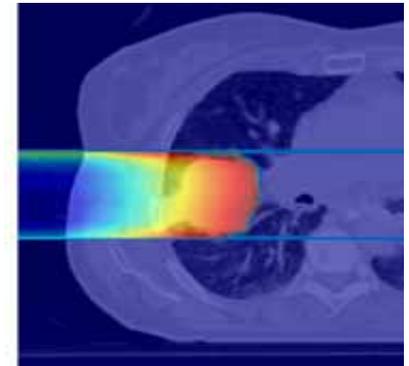
Uncertainties in Proton Therapy

Sources of uncertainties

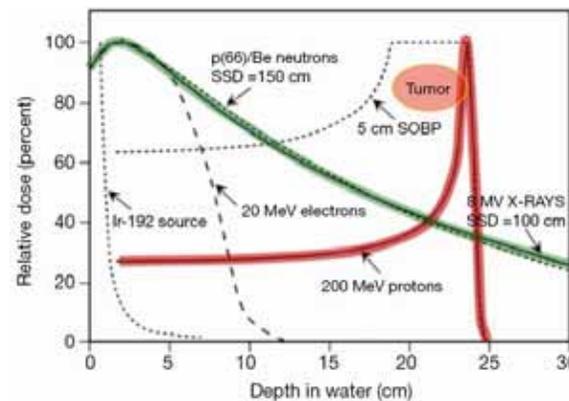
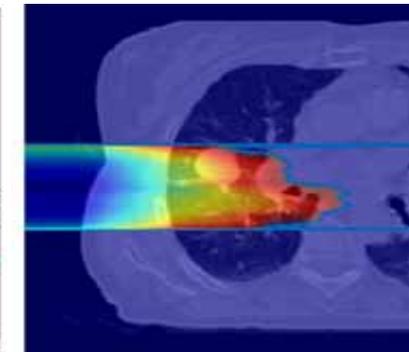
- Stochastic error (CT noise)
- CT artifacts, CT resolution (partial volume effect)
- Hounsfield unit (HU) conversion method error
- Anatomical changes:
- Tumor shrinkage
- Patient weight variations
- Organ motion

Can damage healthy tissue!

Beam stops at distal edge

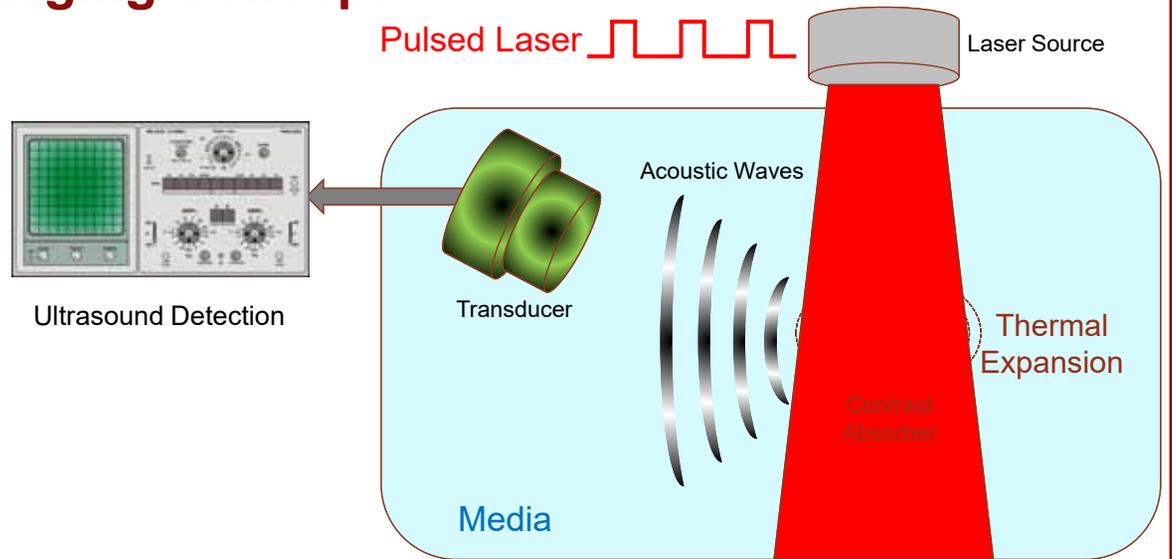
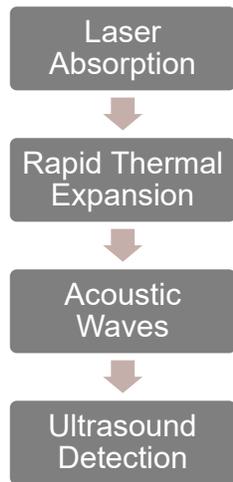


Beam overshoot



S. Mori, G. Chen, MGH

Thermoacoustic Imaging Concept

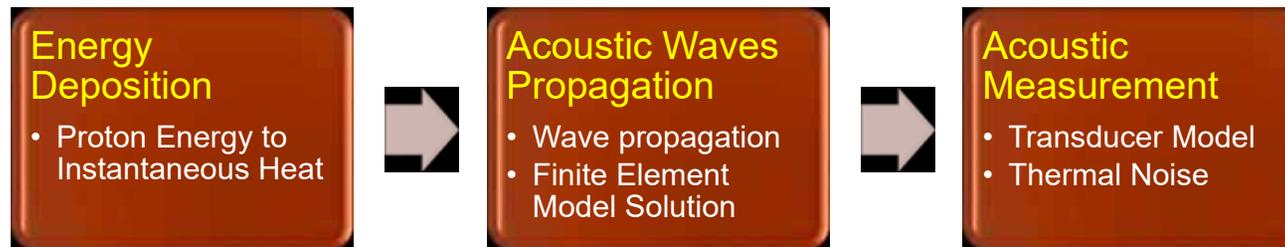


$$t_L < \frac{d_c}{v_s} < \frac{d_c^2}{4\alpha_{th}}$$

→ Thermal confinement
→ Stress confinement

$$\left(\nabla^2 - \frac{1}{v_s^2} \frac{\partial^2}{\partial t^2}\right) p(r, t) = -\frac{\beta}{\kappa v_s^2} \frac{\partial^2 T(r, t)}{\partial t^2}$$

Proton-Acoustics Simulations

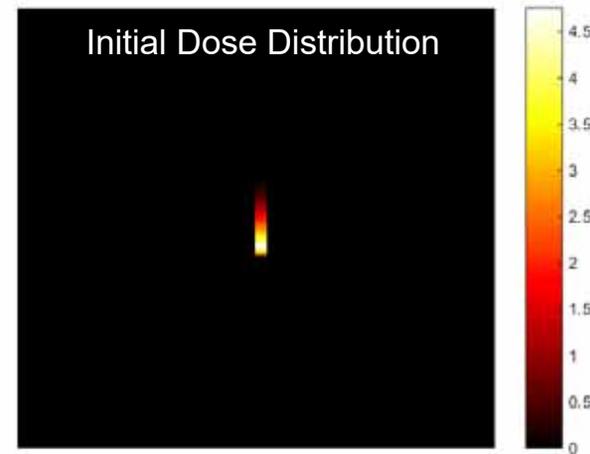
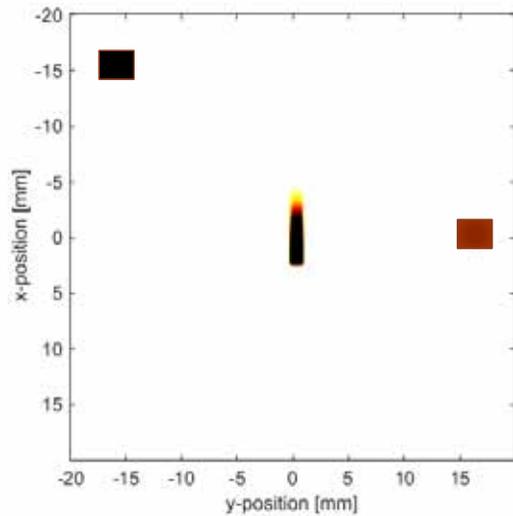


$$\underbrace{\left(\nabla^2 - \frac{1}{v_s^2} \frac{\partial^2}{\partial t^2}\right)}_{\text{Wave Propagation}} p(r, t) = \underbrace{-\frac{\beta}{\kappa v_s^2} \frac{\partial^2 T(r, t)}{\partial t^2}}_{\text{Initial Pressure}} = P_0 = \Gamma \rho D$$

Γ : Gruneisen factor
 D : Dose Delivered
 ρ : Density

Finite Element Model

Simulation Studies



$$\left(\nabla^2 - \frac{1}{v_s^2} \frac{\partial^2}{\partial t^2} \right) p(r, t)$$

Wave propagation

=

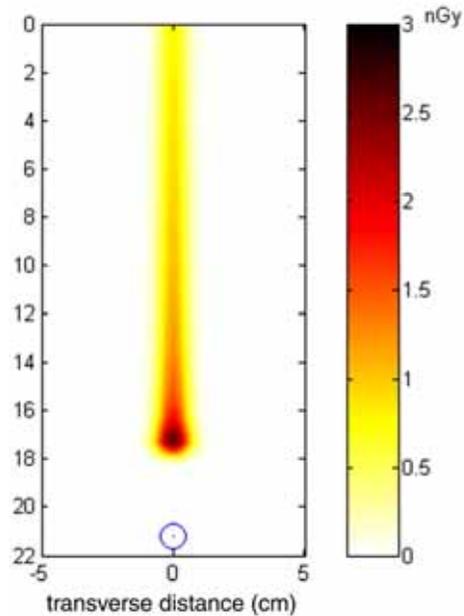
$$- \frac{\beta}{\kappa v_s^2} \frac{\partial^2 T(r, t)}{\partial t^2}$$

Initial pressure

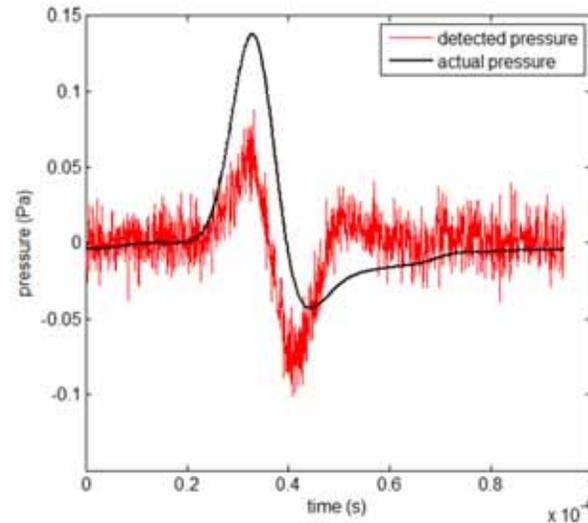


Simulation Results

Dose distribution
160 MeV, 10- μ s, 647 mGy/pulse



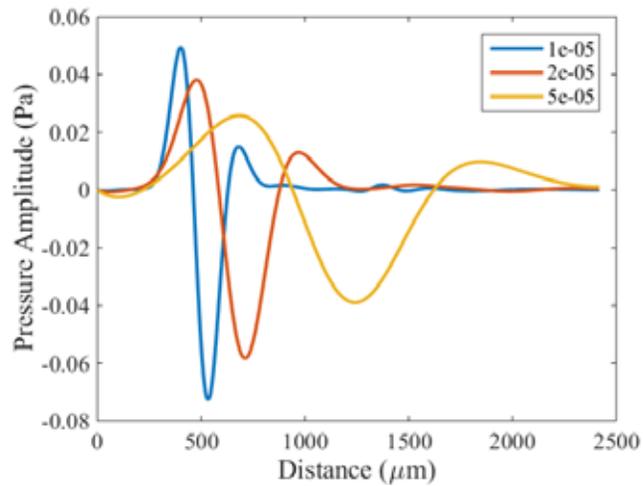
Simulated acoustic waveforms
Detector at 4 cm from the Bragg peak



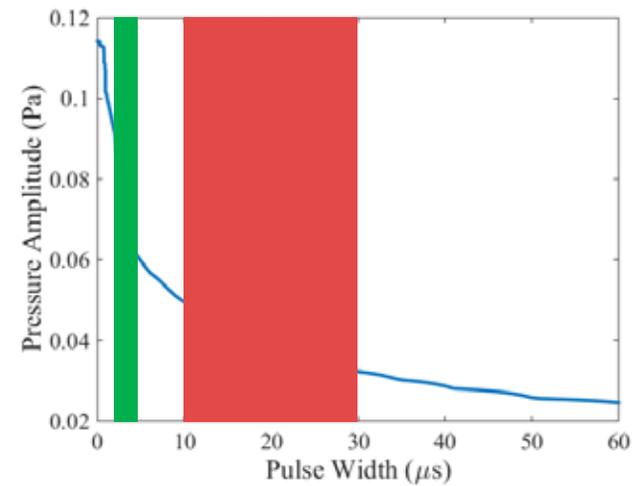
Ahmad et al., (2015). Theoretical detection threshold of the proton-acoustic range verification technique. *Medical physics*, 42(10), 5735-5744.

Proton Pulse Width Parameter

Acoustic Pulse Shape



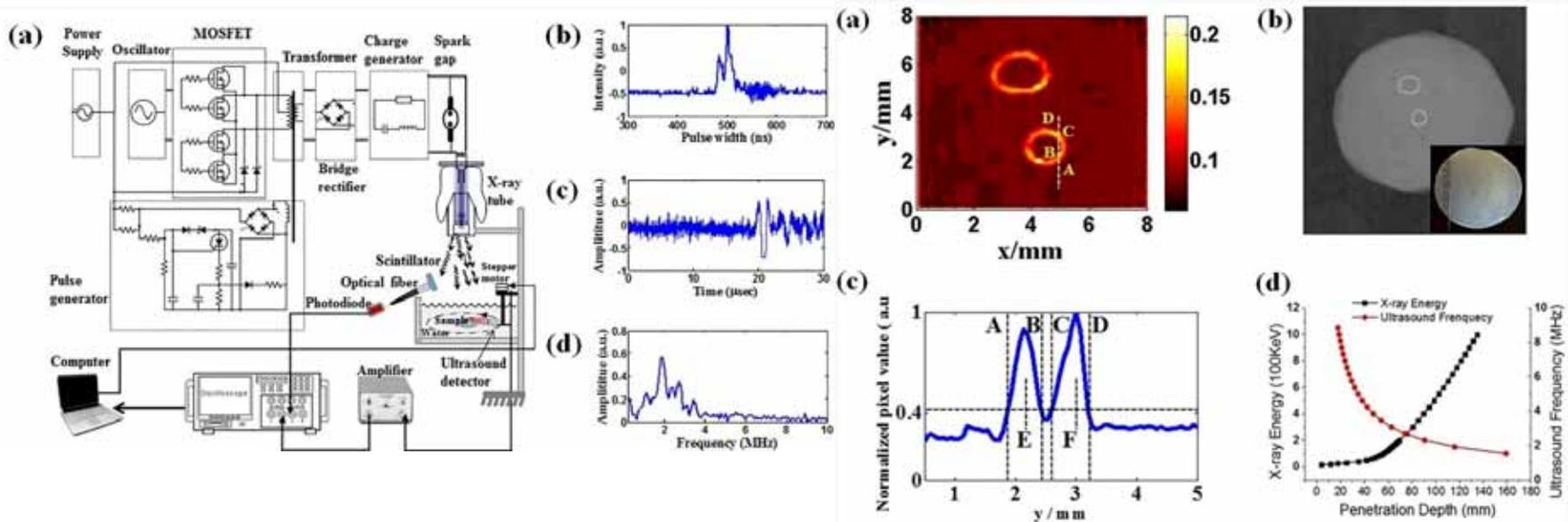
Acoustic Pulse Amplitude



$$(\text{Stress Confinement}) \tau_s = \frac{\text{Characteristic Length}}{\text{Speed of sound in tissue}} \approx \frac{1 \text{ mm}}{1500 \text{ m/s}} \approx 670 \text{ ns}$$

$$\text{Resolution} = \text{Pulse Length} * V_s \approx 20 \mu\text{s} * 1500 \frac{\text{m}}{\text{s}} = 30 \text{ mm}$$

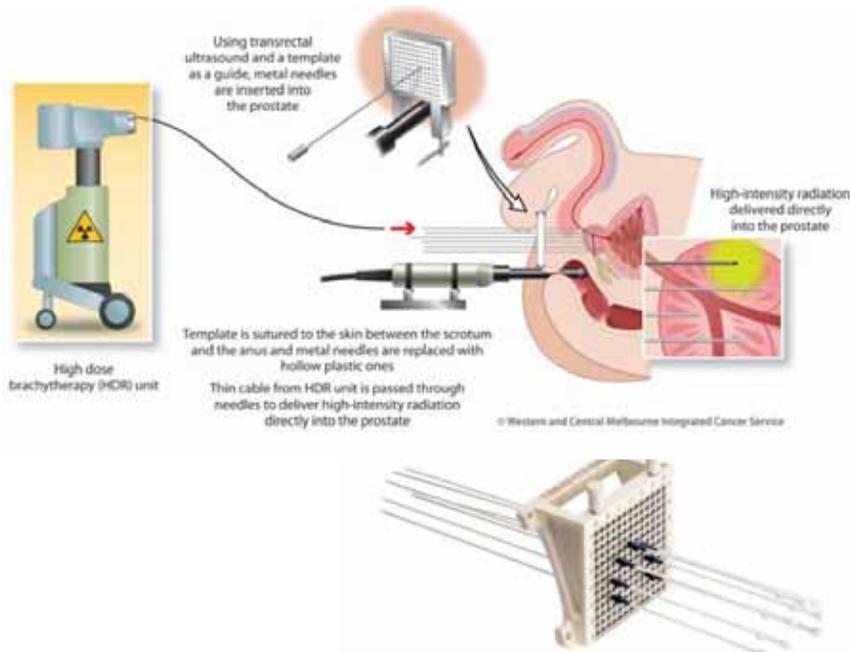
X-ray Induced Acoustics Tomography



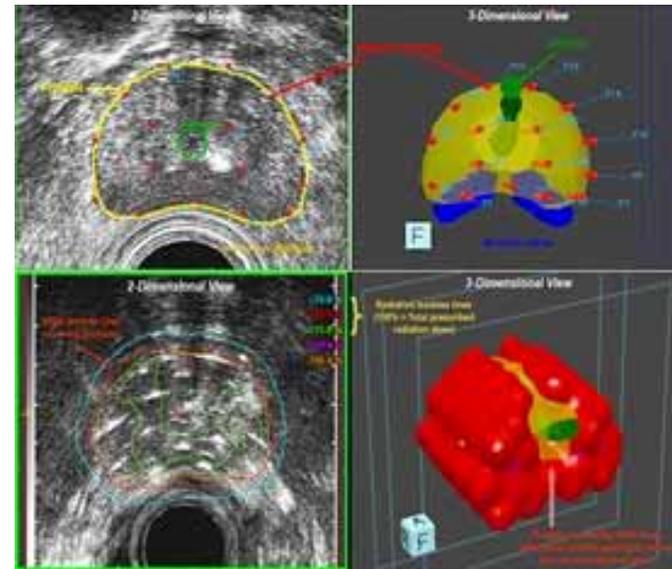
Xiang, et al. "High Resolution X-ray-Induced Acoustic Tomography." Scientific reports 6 (2016).

Localizing HDR Brachy Needles

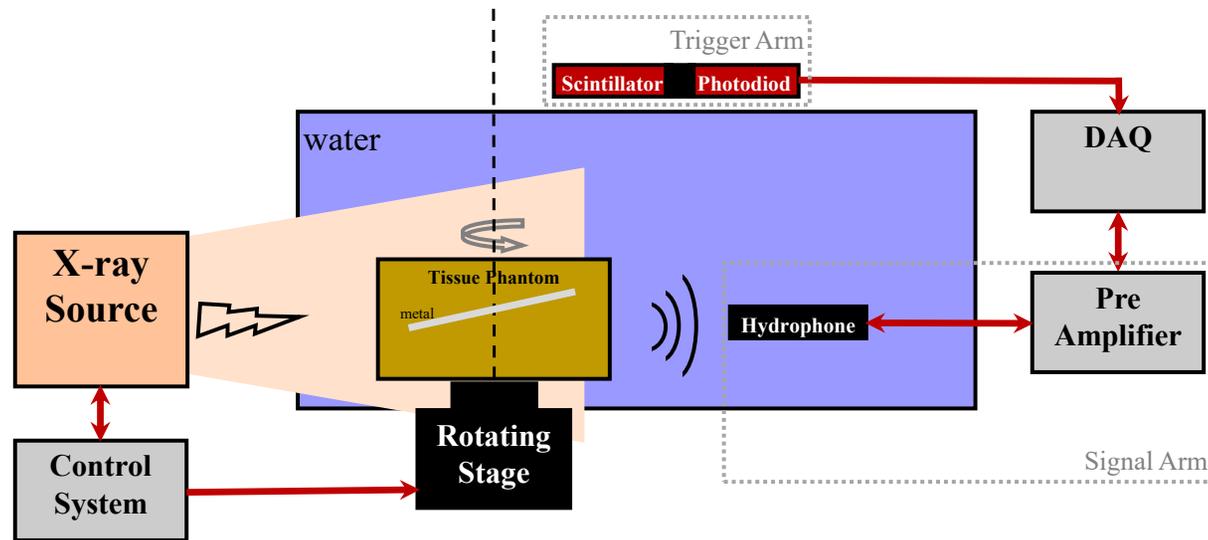
HDR Brachytherapy of Prostate



Prostate/Needle in US



System Setup

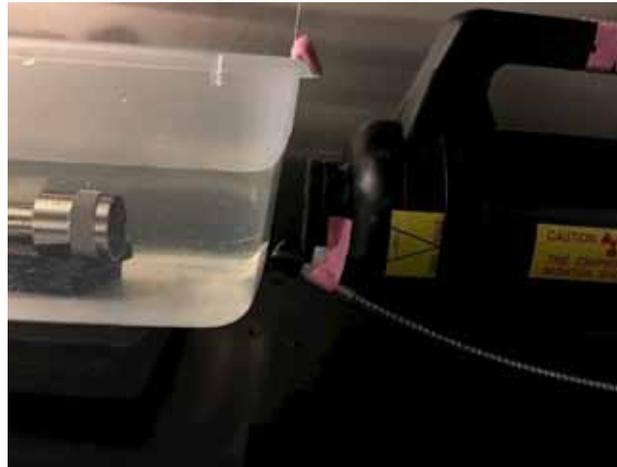


Preliminary Implementation

Shielded Measurements



Hydrophone Placement



Target Placement



Preliminary Results

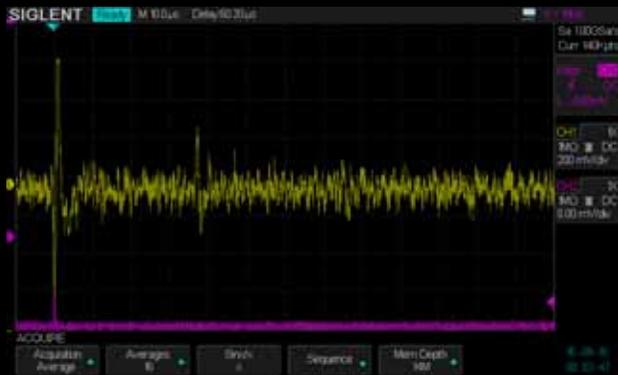
Brachy Needle, 5 cm distance



Zinc Target, 14 cm distance



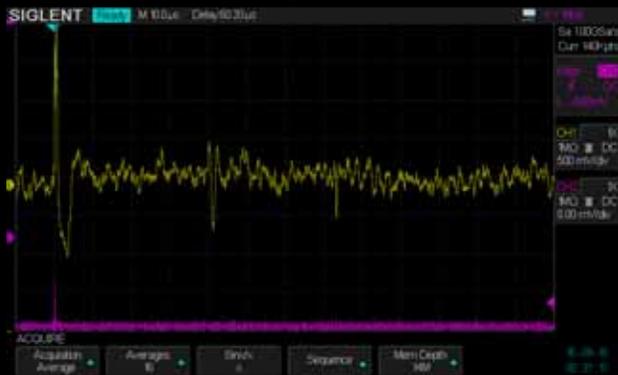
Al



Cu



Fe



Ni



Dose Comparison

3 mSv per year in the U.S.

- Received from naturally occurring radioactive materials and cosmic radiation

0.1 mSv, Chest X-ray

10 mSv, CT-Abdomen and Pelvis

25 mSv, PET/CT

~27 μ Sv per pulse, Pulsed X-ray source

Conclusions

- Radiation-induced acoustic imaging for clinical applications
- Localizing metallic objects such as brachytherapy needles and catheters
- Towards deep tissue molecular imaging

Challenges

- Lack of pulsed radiation sources
- Designing new acoustic measurement systems