Recent Applications of Radiation Acoustics in Photon Therapy: Dosimetry and Guidance

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Joint AAPM COMP Virtual Meeting
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Outline

- Theory of radiation acoustics
- Early studies of radiation acoustics in photon beams
- Water tank dosimetry applications
- *In vivo* dosimetry/guidance applications
- Future outlook and challenges

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p = Pressure
v_s = Speed of sound
β = Isobaric expansion coefficient
C_p = Specific heat capacity
H = Heat energy
Γ = Grüneisen coefficient

Radiation acoustic theory

- Thermoacoustic wave equation:

$$\nabla^2 p(\mathbf{r},t) - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2}p(\mathbf{r},t) = -\frac{\beta}{C_p}\frac{\partial}{\partial t}H(\mathbf{r},t)$$

- Initial pressure distribution:

$$p(\mathbf{r})|_{t=0} = H(\mathbf{r}) \cdot \Gamma(\mathbf{r}) \qquad \text{where} \qquad \Gamma = \frac{v_s^2 \beta}{C_p}$$

- Relating pressure to dose:

$$p\,(\mathbf{r}) = \mathrm{D}\,(\mathbf{r}) \cdot \rho\,(\mathbf{r}) \cdot \Gamma\,(\mathbf{r})$$

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Early applications of radiation acoustics in photon dosimetry

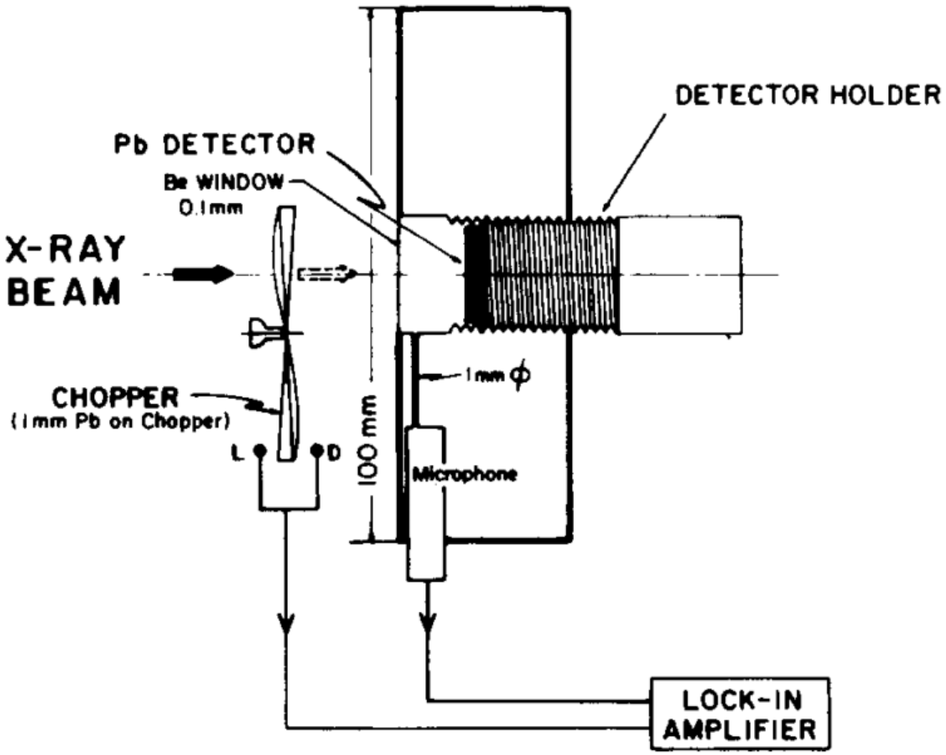

FIG. 1. Schematic diagram of the photoacoustic radiation dosimeter.

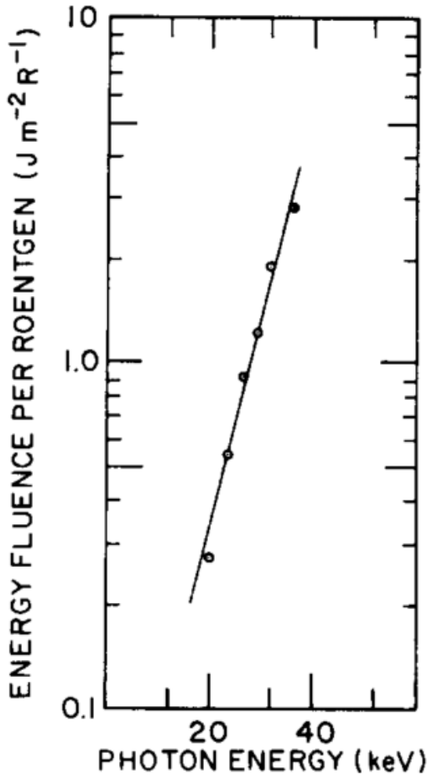

FIG. 2. PARD signal (normalized at 27 keV) for energy fluence per roentgen (dots) compared to the predicted response (solid line) from Fig. 7-14 of Ref. 5 vs equivalent photon energy.

Mascarenhas et al, Med Phys 11 (1), 1984.

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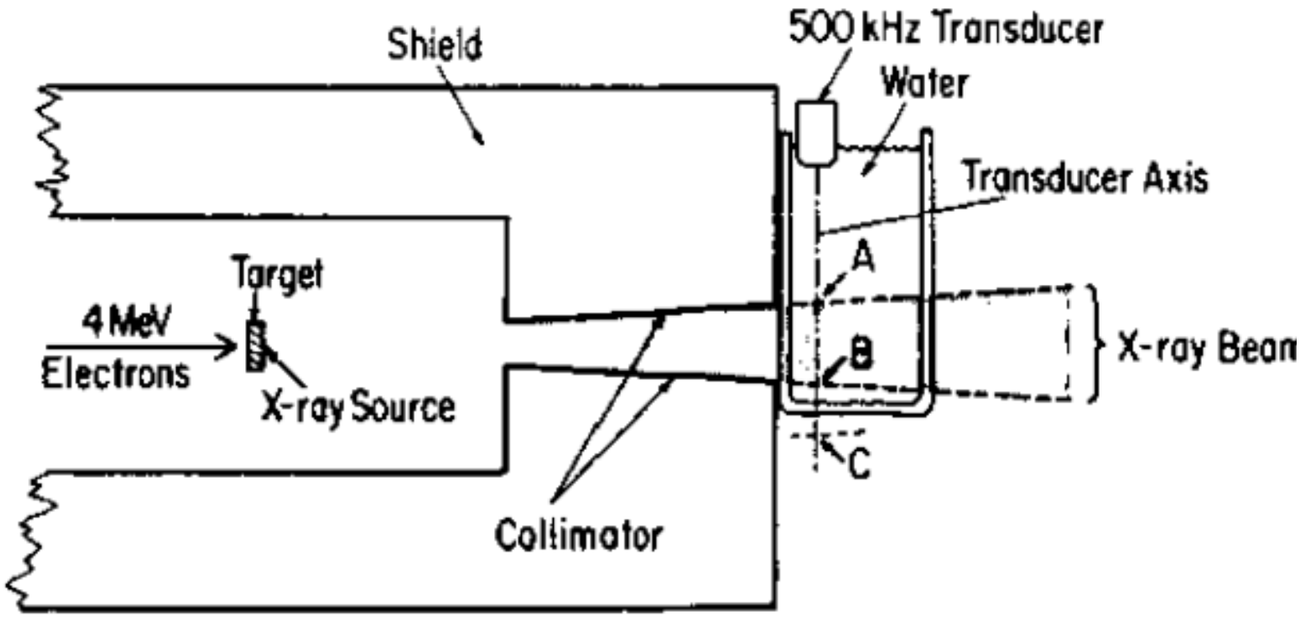
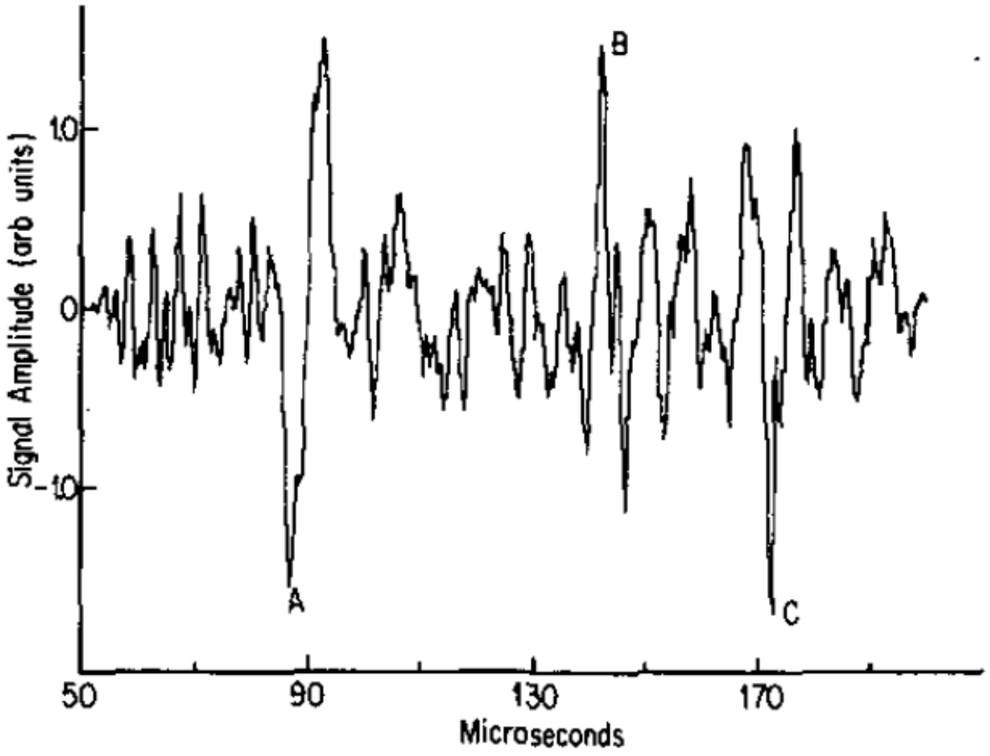
First published detection of acoustic waves induced by clinical linac photon irradiation





Bowen et al., Phys Med Biol 36 (4), 1991

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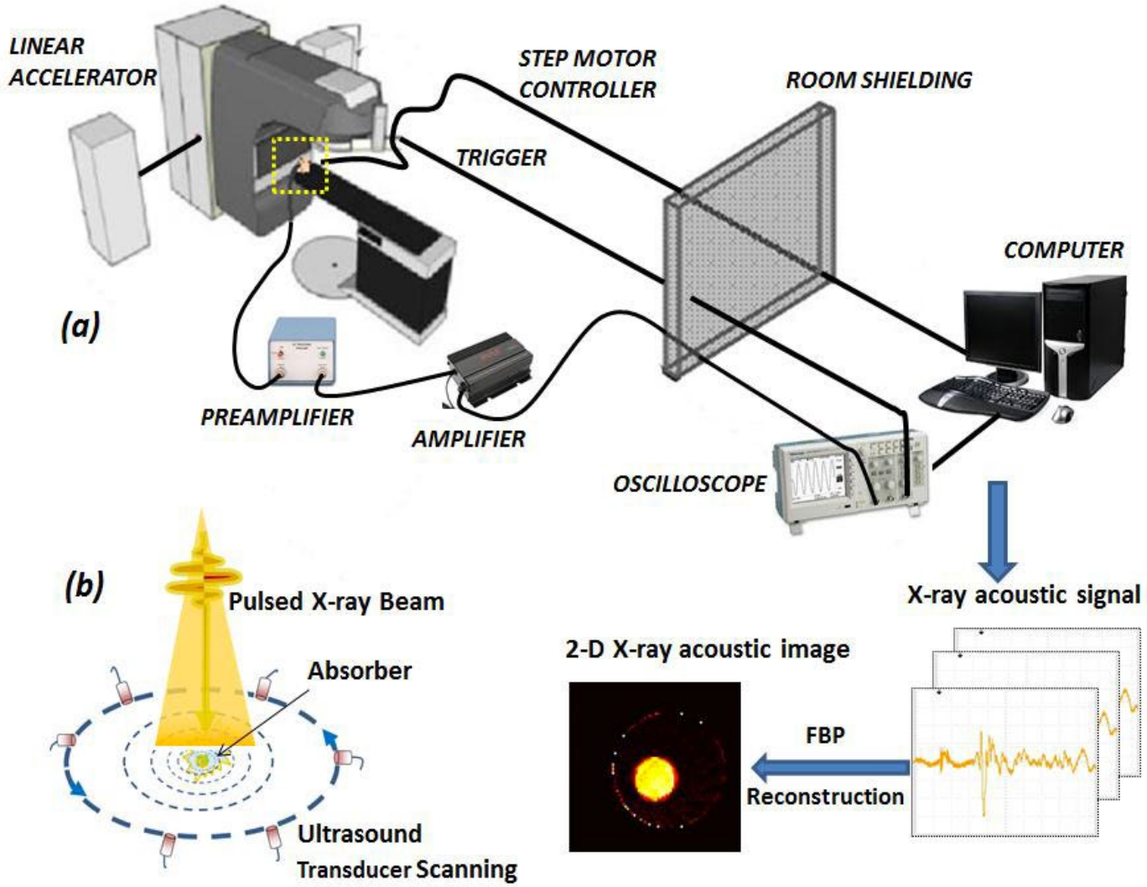
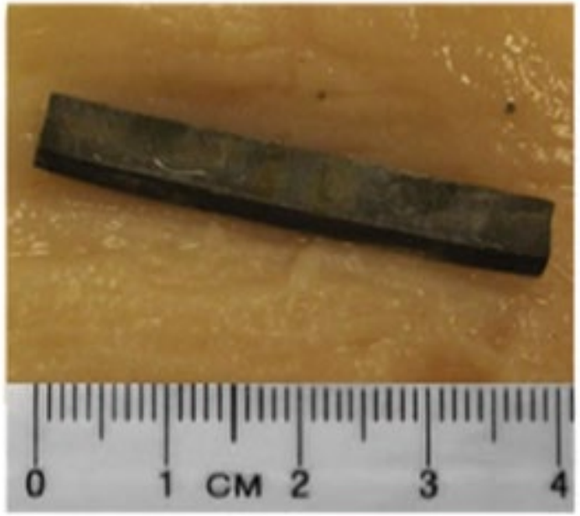
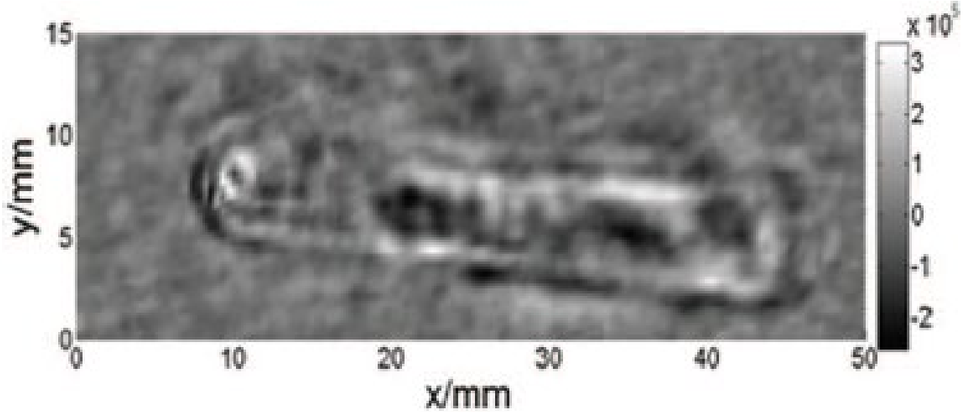
Proposal of x-ray acoustic computed tomography







Xiang et al., Med Phys, 40 (1), 2013

X-ray acoustic computed tomography

Pulsed photon beam from linac deposits energy

↓

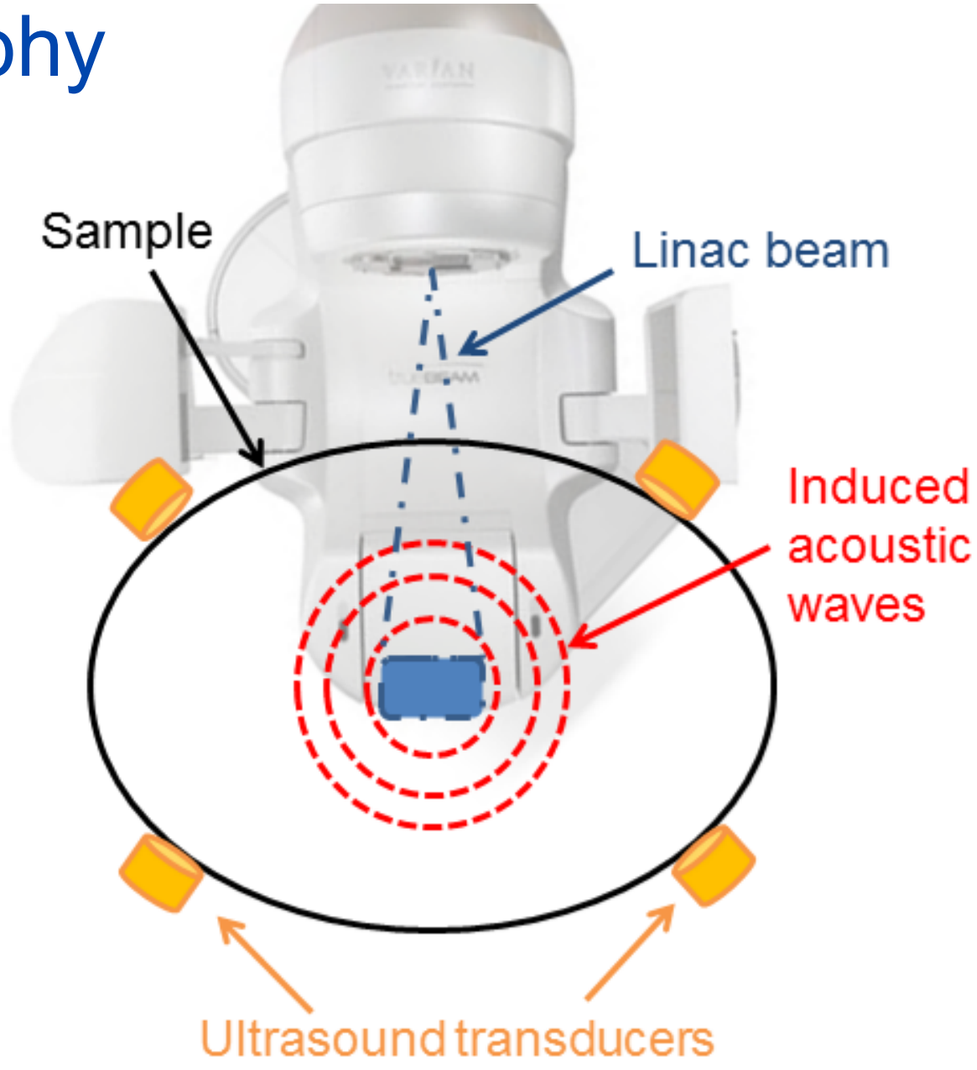
Acoustic waves generated through the thermoacoustic effect

↓

Acoustic waves detected by ultrasound transducers

↓

Image of initial pressure/dose distribution reconstructed



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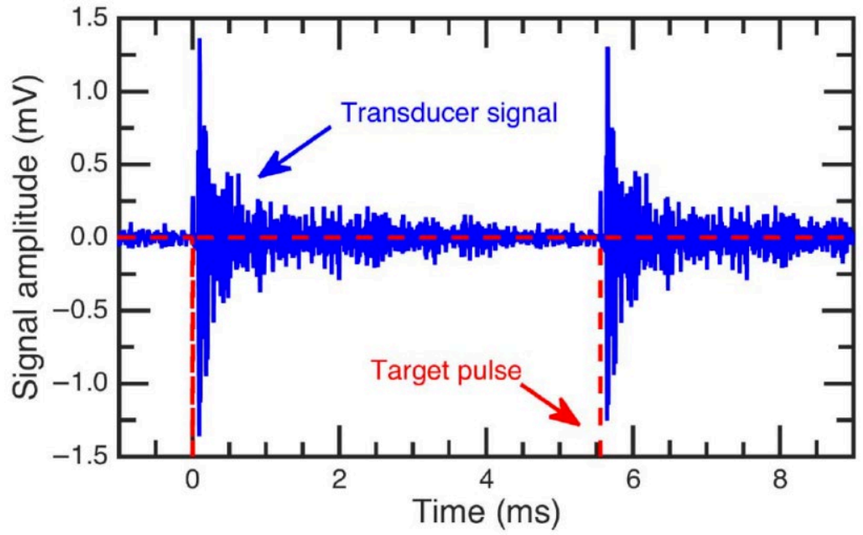
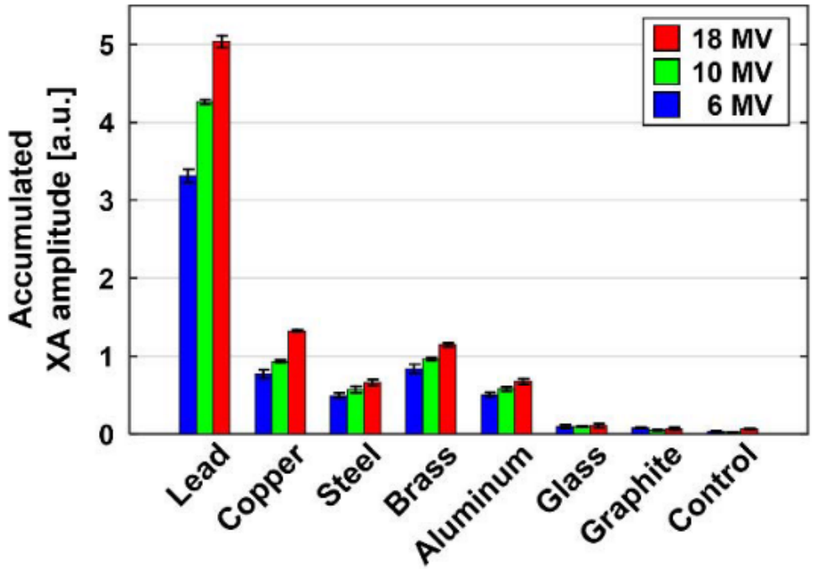
Initial studies with lead

- Lead was used as an absorber in early studies due to its increased Grüneisen coefficient
- Studies looked at characterizing the properties of detected acoustic waves during irradiation
- Simulation workflows combining Monte Carlo dose calculations with acoustic wave transport techniques developed to guide future experiments were validated against initial lead measurements





Hickling et al., IEEE Trans Ultrason Ferroelectr Freq Control, 63 (5), 2016

Kim et al., IEEE Trans Rad Plasma Med Sci, 1 (6), 2017

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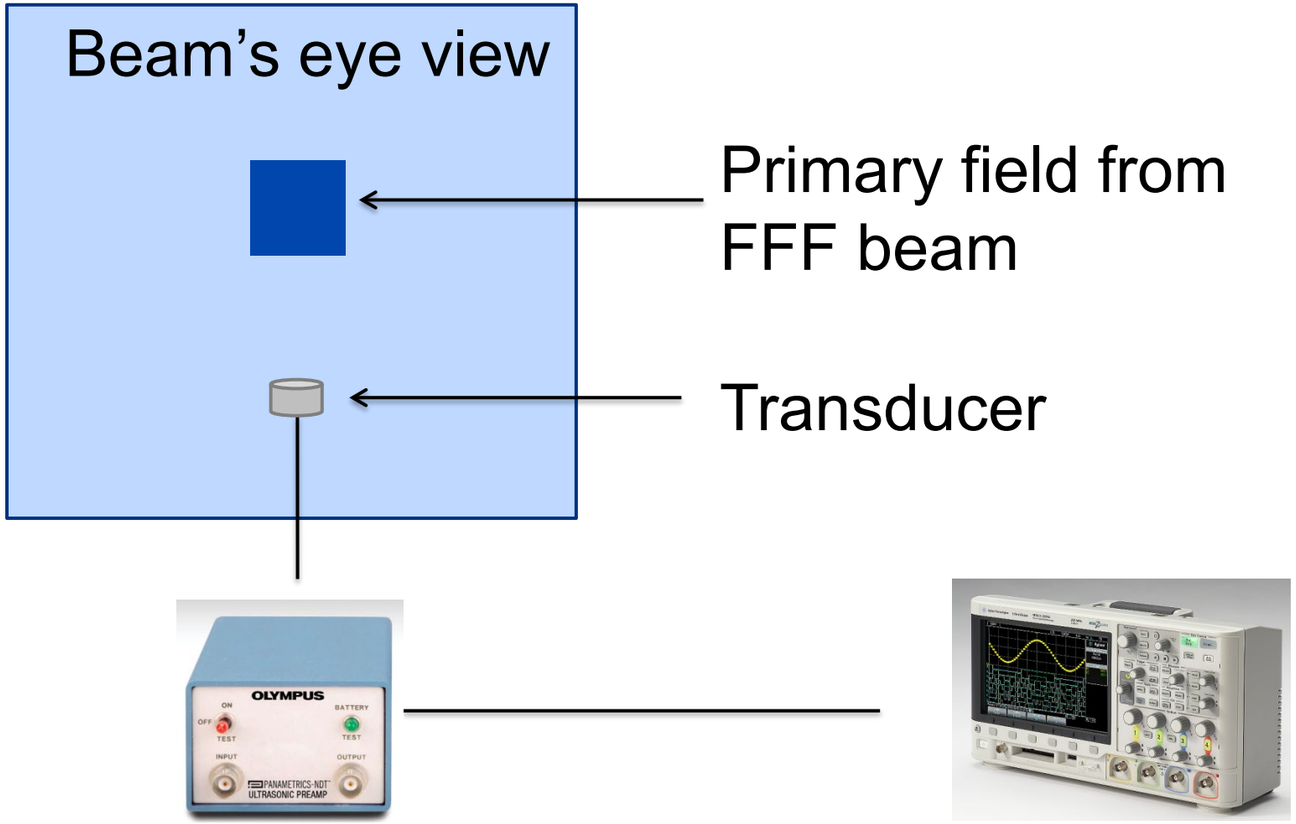
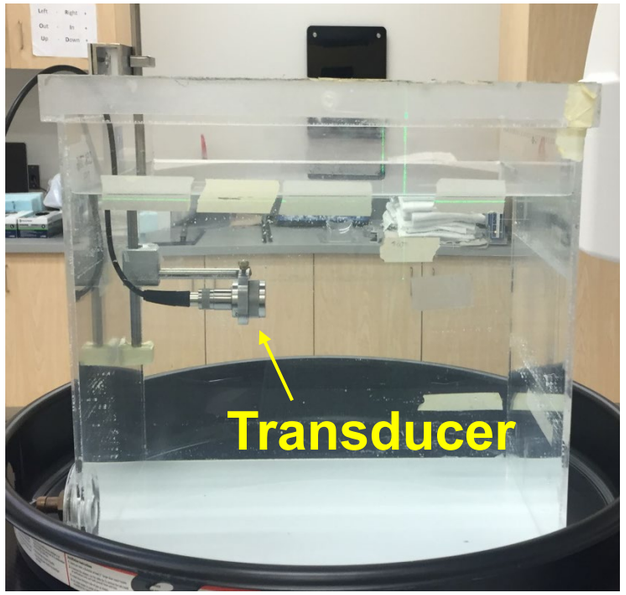
Initial set-up for planar imaging



Preamplifier

Oscilloscope



Hickling et al., Med Phys, 44(2), 2017

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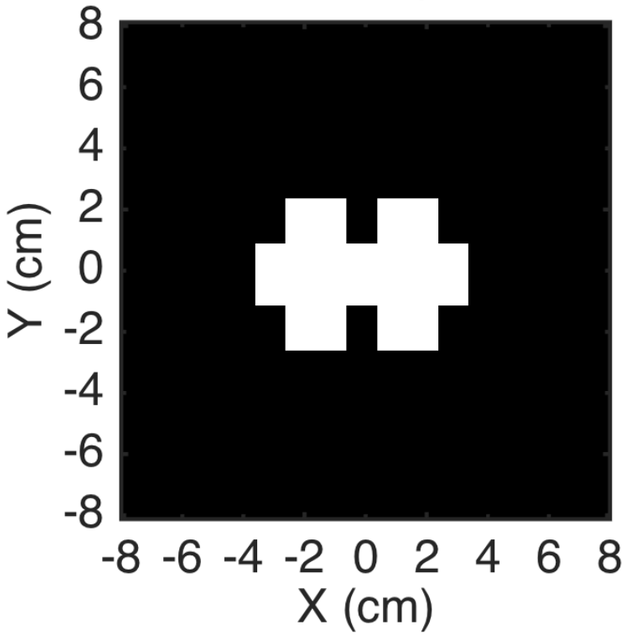
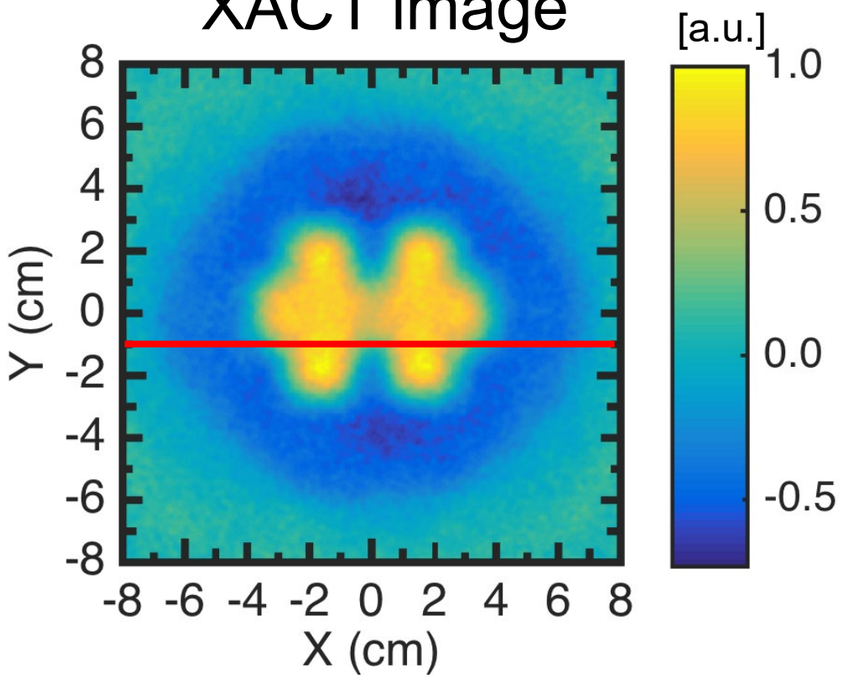
Initial XACT images in water

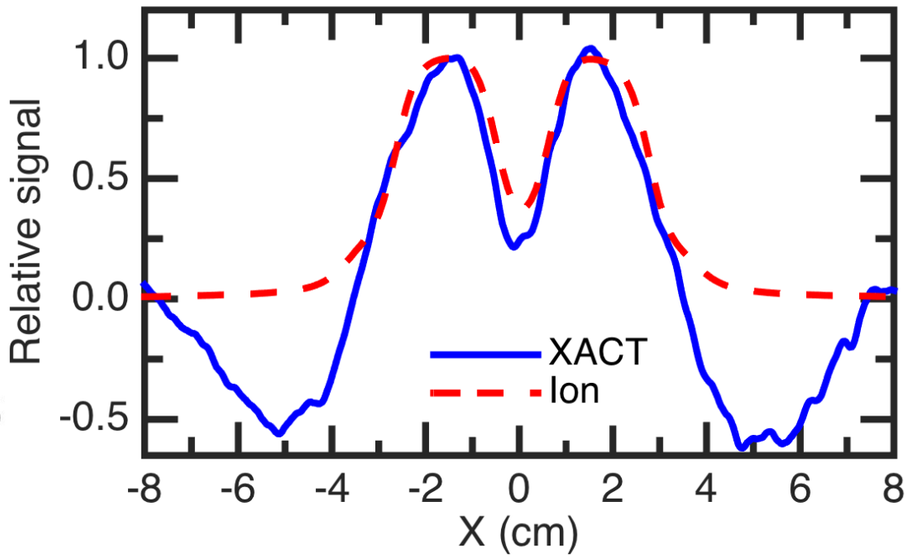
Field diagram



XACT image



XACT and ion chamber profiles



Hickling et al., Med Phys, 44(2), 2017

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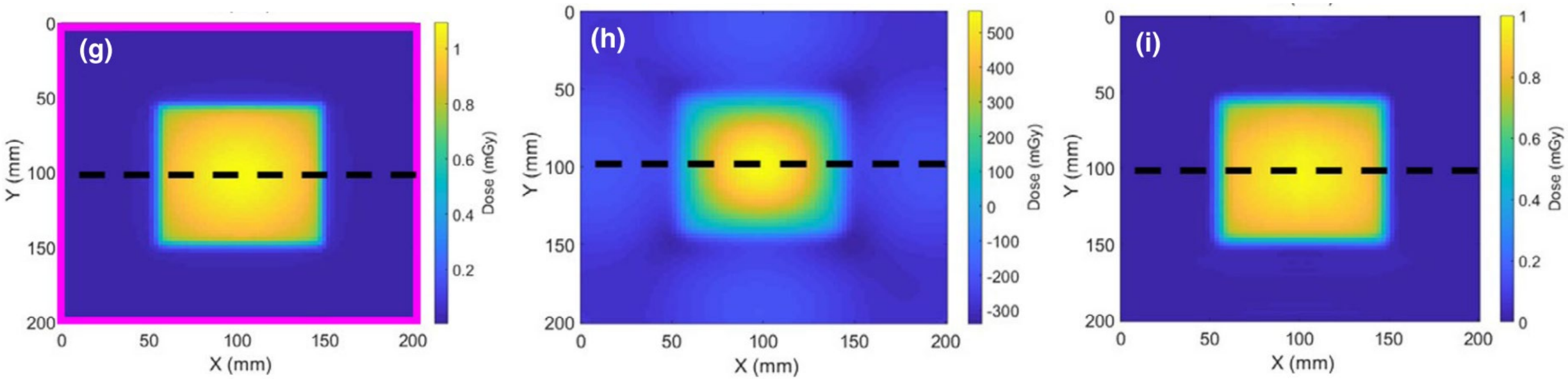
Improving reconstruction of x-ray induced acoustic images for absolute dosimetry

- Simulation study investigating different reconstruction algorithms

Planned dose | Back projection | Iterative time reversal



Forghani et al., Med Phys, 47 (3), 2020

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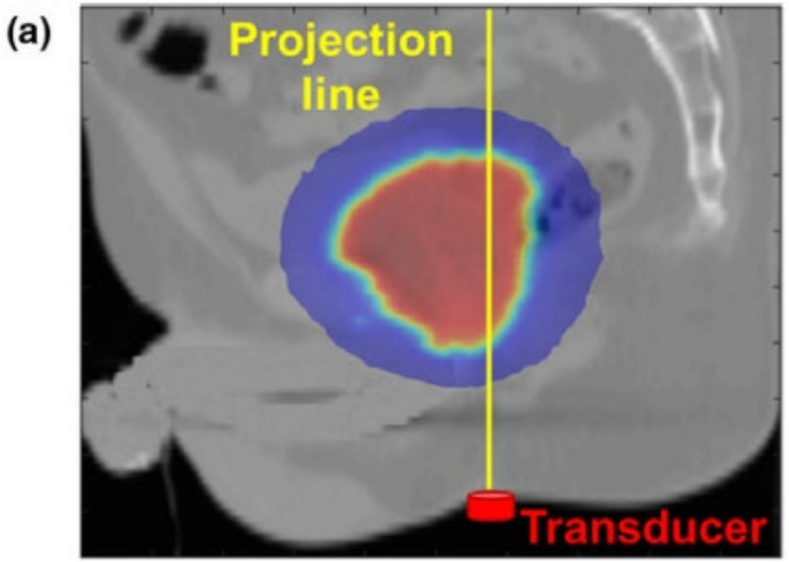
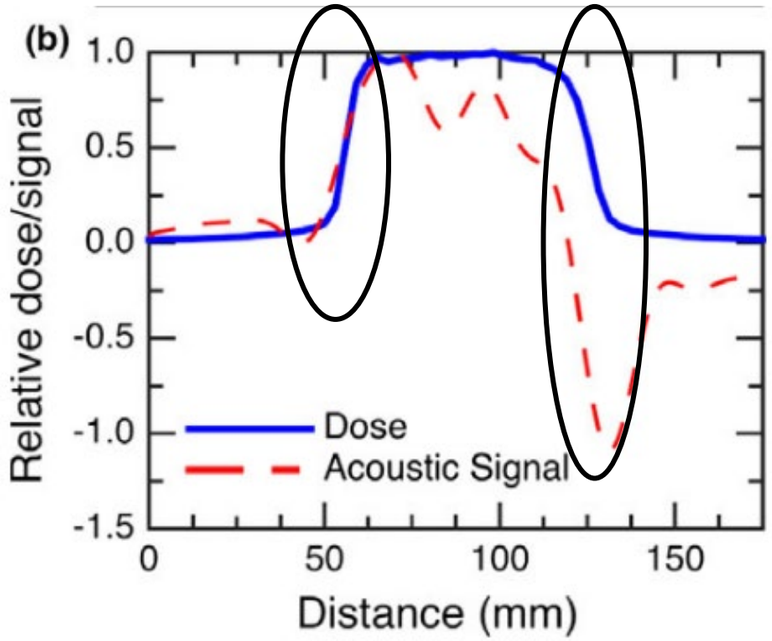
Radiation acoustics for therapy guidance/*in vivo* dosimetry

- Initially investigated through simulation studies
- Dose gradients generate peaks in the acoustic signal
- Potential for combination with anatomical ultrasound imaging





Hickling et al., Med Phys, 45 (7), 2018

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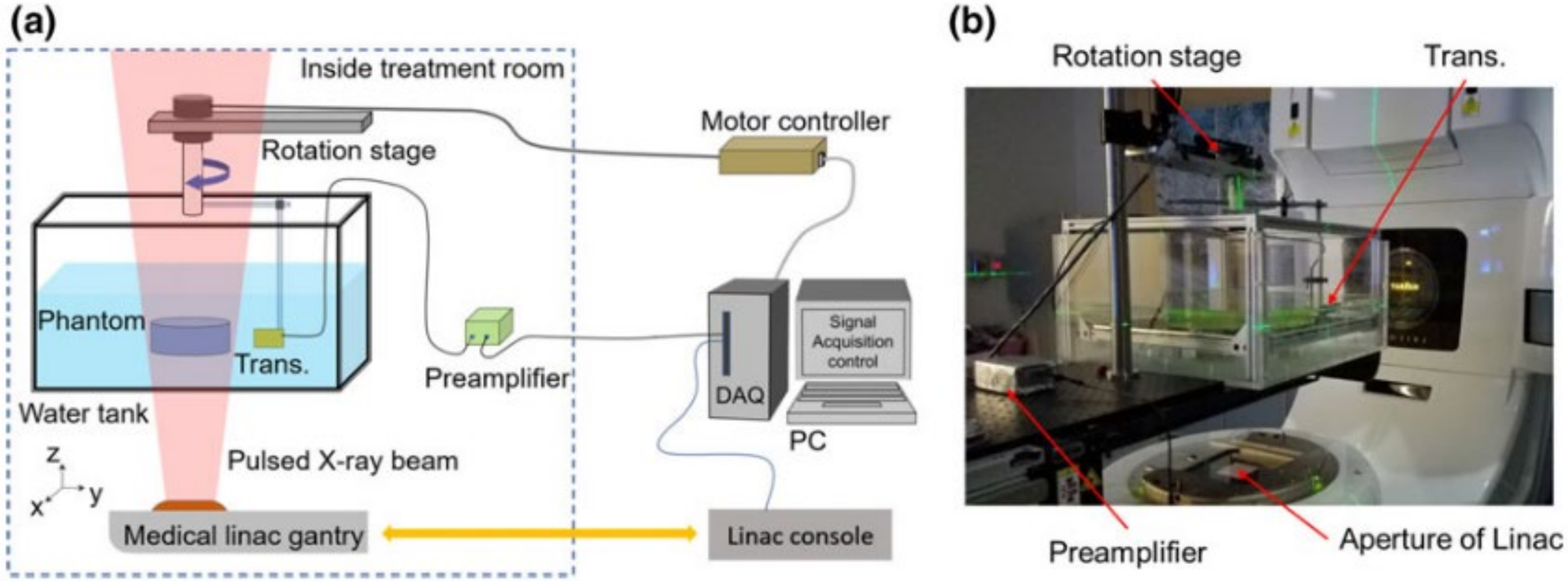
Experiments in soft tissue phantoms

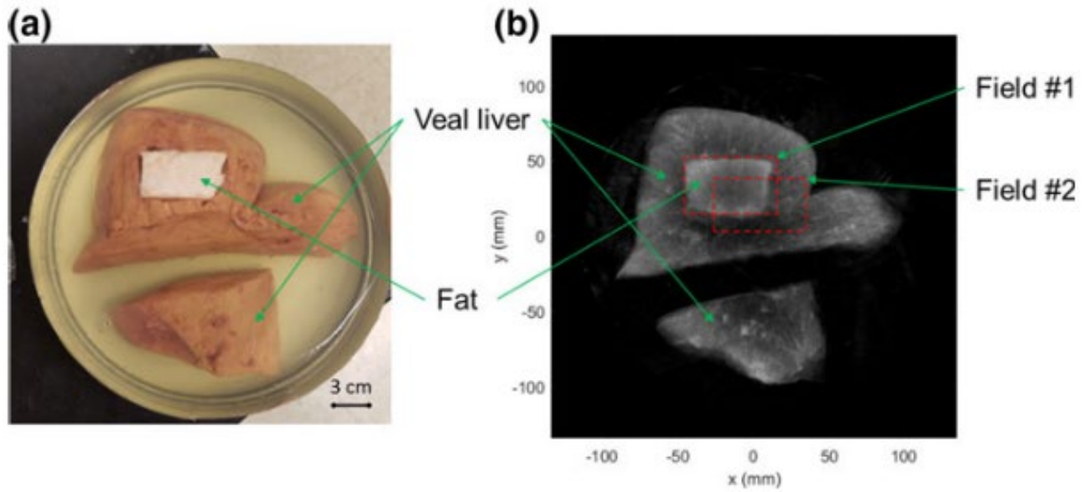
- Radiation induced acoustic signals detected with a single element 0.5 MHz immersion ultrasound transducer
- B-mode images acquired with a commercial ultrasound system



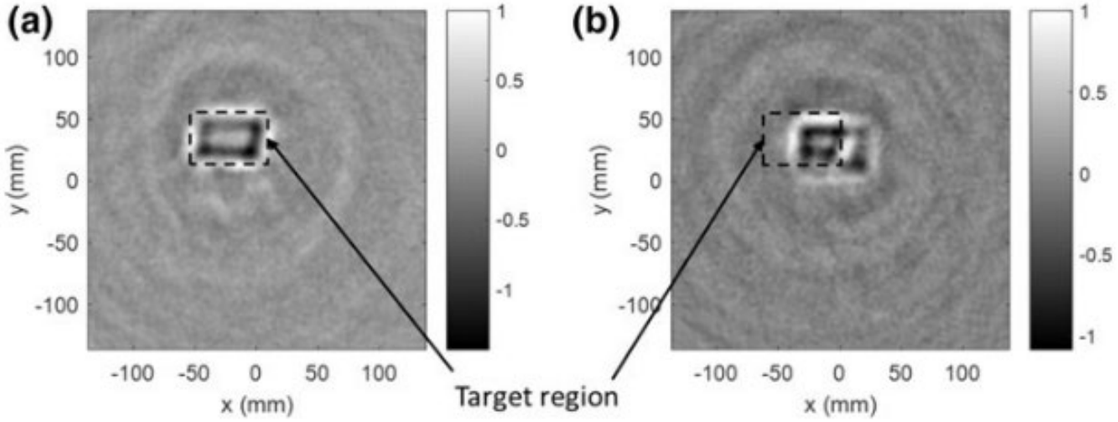
Lei et al., Med Phys, 45 (9), 2018.

Experiments in soft tissue phantoms

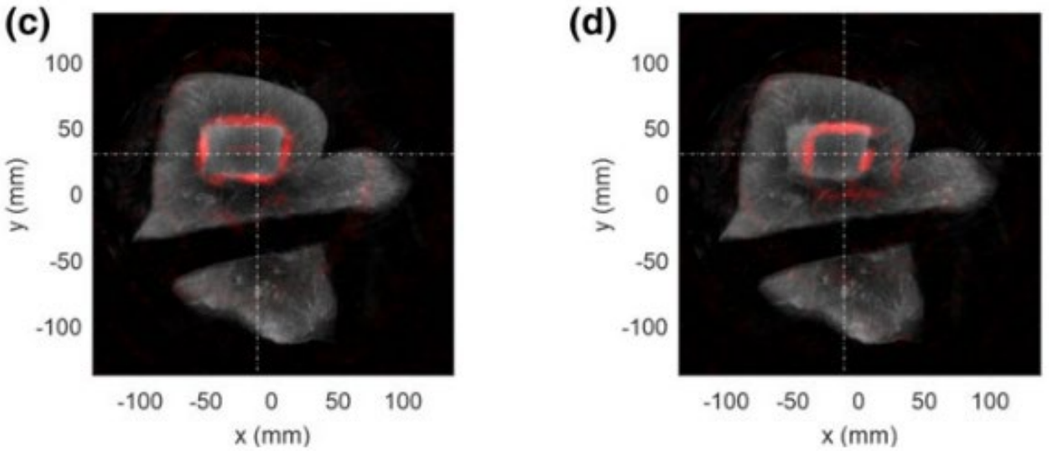
Porcine gel phantom
with veal liver and fat



XACT images of
field 1 and field 2



XACT images overlaid on B-
mode ultrasound



Lei et al., Med Phys, 45 (9), 2018.

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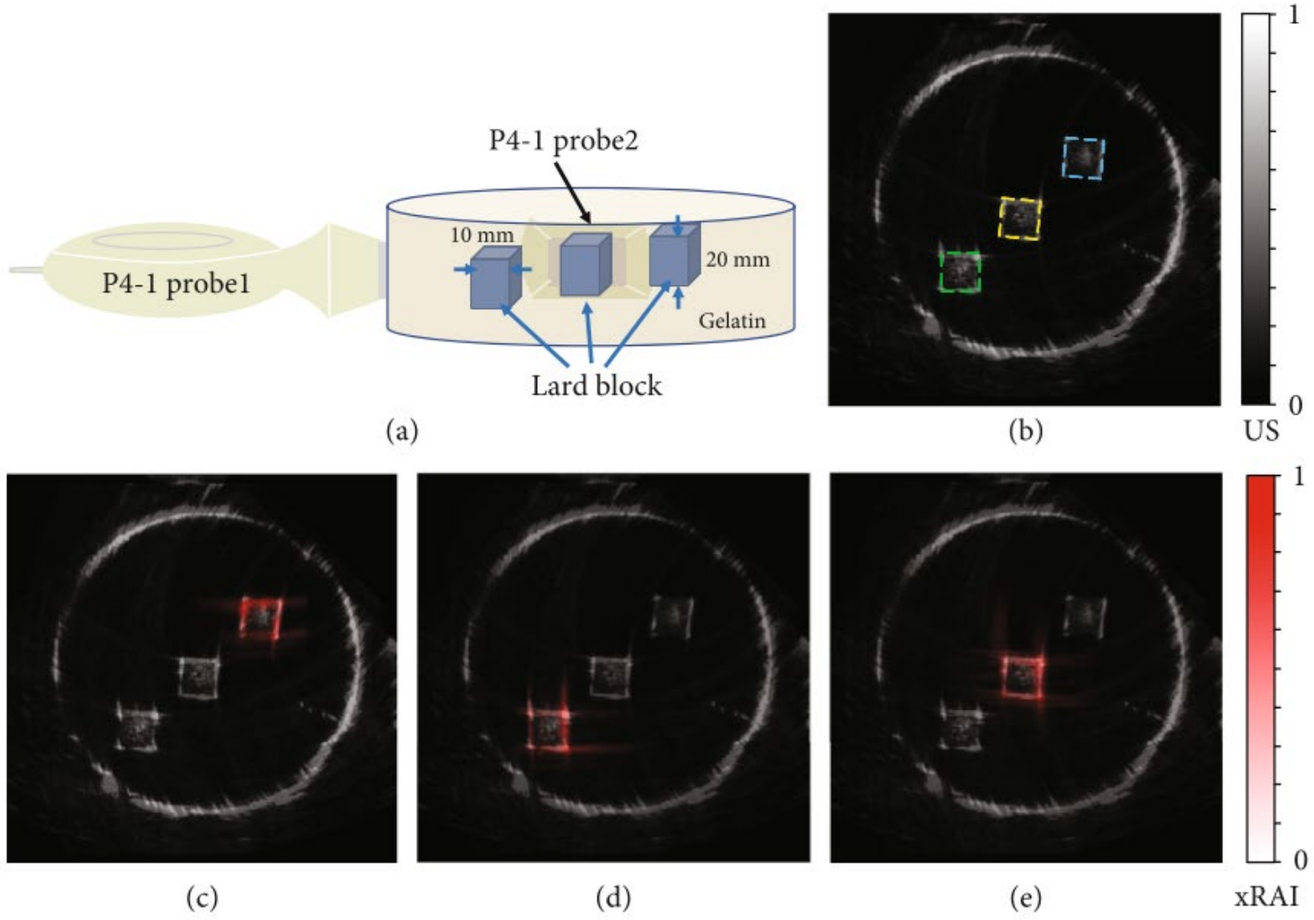
Dual modality x-ray induced radiation acoustic and ultrasound imaging

- Created a dual modality system that can switch between x-ray induced acoustic imaging (xRAI) and B-mode ultrasound imaging using the same transducer probe



Zhang et al., BME Frontiers, 2020.

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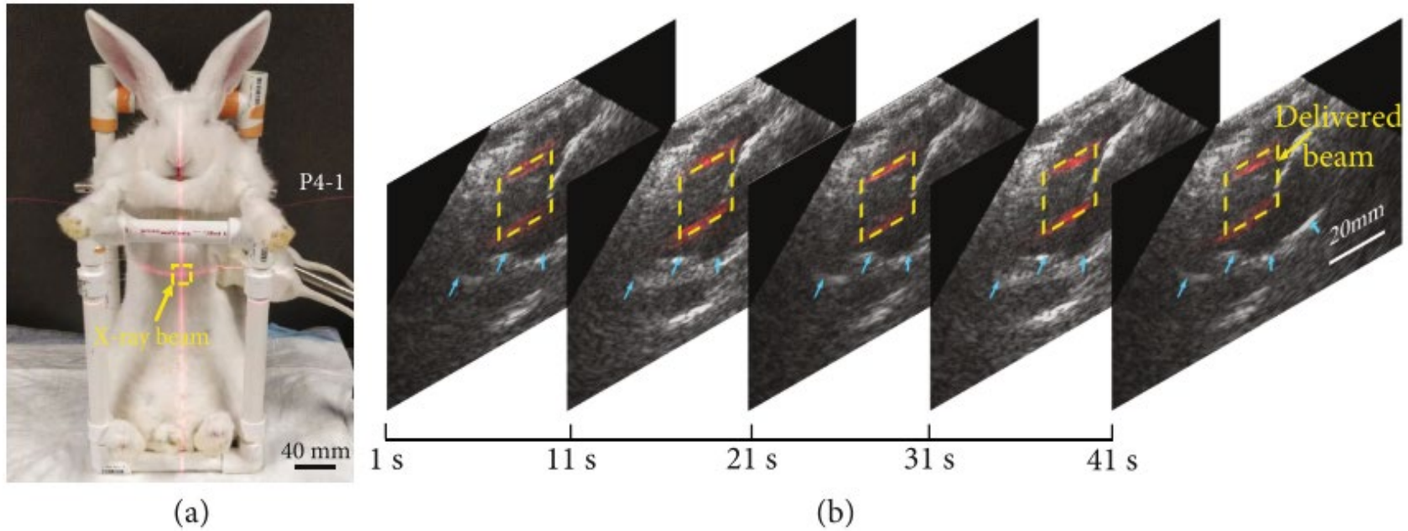
Dual modality x-ray induced radiation acoustic and ultrasound imaging

- Demonstrated in a rabbit model
- Real time imaging allows visualization of delivered beam position relative to anatomy of interest (edge of liver is indicated by blue arrows)



Zhang et al., BME Frontiers, 2020.

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Outlook: Radiation acoustics in the photon clinic

- Water tank dosimetry
  - Relative dosimetry measurements
  - 2D/3D dose mapping
  - Absolute dosimetry
- *In vivo* dosimetry/guidance
  - Combine radiation acoustic signal detection with ultrasound imaging to present dosimetric and anatomical information together
  - Expected to be applicable to the same clinical sites as anatomical ultrasound

<u>Advantageous characteristics of radiation acoustics</u>

- ✓ Dependent on temperature increase per radiation pulse
- ✓ No beam perturbation
- ✓ Inherently a 3D dosimeter
- ✓ Near real-time
- ✓ Non-invasive

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Future challenges

- Development of appropriate transducer arrays
  - Generate circular or cylindrical array for rapid water tank dosimetry measurements
  - Optimize placement for *in vivo* guidance
- Transducer technology
  - Sensitivity
  - Optimization of dual modality (radiation acoustic signal detection + anatomical ultrasound image generation) transducers
- Image reconstruction
  - Accuracy
  - Speed

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References

Bowen, T., et al., “Observation of ultrasonic emission from edges of therapeutic x-ray beams,” Phys Med Biol, 36 (4), 1991.

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Zhang, W., et al., “Dual modality x-ray-induced radiation acoustic and ultrasound imaging for real time monitoring of radiotherapy,” BME Frontiers, 2020.

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