Image-Guided Radiation Therapy Based On X-Ray Induced Acoustic Computed Tomography

Xueding Wang [1,2], Wei Zhang [1], Ibrahim Oraiqat [3], Hao Lei [2], Paul Carson [4], and Issam El Naqa [3]

[1] Department of Biomedical Engineering, University of Michigan, Ann Arbor, Michigan, USA
[2] Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA
[3] Department of Radiation Oncology, University of Michigan, Ann Arbor, Michigan, USA
[4] Department of Radiology, University of Michigan, Ann Arbor, Michigan, USA

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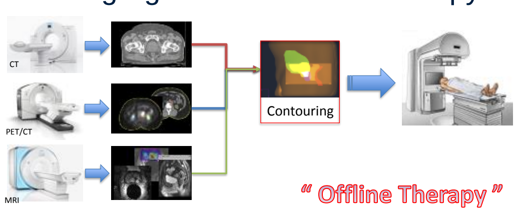
Image-guided Radiation Therapy



" Offline Therapy "

Sterzing et al. Dtsch Arztebl Int. 108(16), 2011

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Disadvantages of offline therapy

- **Positioning**: limited accuracy and reproducibility in positioning make it difficult to place the patient in exactly the same position as in planning.
- **Organ motion**: even with perfect positioning, the body movement and the respiratory motion can shift the organ by up to several centimeters.
- **Anatomic variations**: the difference in tissue density/geometry/property can affect the attenuation of X-ray beams before reaching the target.

Need: an imaging technology that can monitor the position and dose of the X-ray beam delivered to the target tissue **during** treatment.

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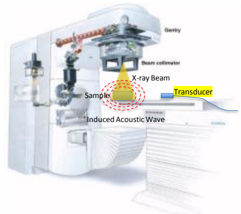
X-ray induced Acoustic Computed Tomography (XACT)

- Pulsed X-ray beam delivered to target tissue
- ↓ Acoustic wave generated by thermal-acoustic effect
- ↓ Transducer detect the induced acoustic wave
- ↓ Initial acoustic pressure reconstructed from detect signal



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Theory

- X-ray induced acoustic wave equation:

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

- Initial pressure

$$p_0(r) = \Gamma(r)\cdot H(r) \qquad \text{Where} \quad \Gamma = \frac{v_s^2 \beta}{C_p}$$

- X-ray dose to initial pressure

$$p_0(r) = \Gamma(r)\cdot \eta(r)\cdot D(r)\cdot \rho(r)$$

p = Acoustic Pressure
v_s = Speed of sound
β = Coeff of thermal expansion
C_p = Specific heat capacity
H = X-ray energy deposition
Γ = Grueneisen parameter
η = Mass attenuation coefficient
D = X-ray fluence
ρ = Physical density

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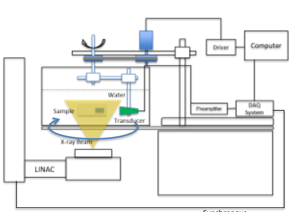
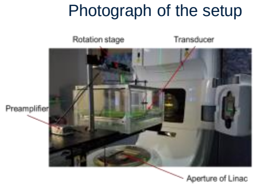
XACT System based on A Single Transducer



Photograph of the setup



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Experimental parameters

X-ray source:
- 6 MV photon beam delivered by clinical LINAC (Varian TrueBeam™)
- 4 µs pulse duration
- 330 pulse repetition rate

Detection parameters:
- Immersion transducer, 0.5 MHz, 1.0 in. Element diameter (V301, Olympus)
- X-ray induced acoustic signals acquired at 120 steps for tomographic imaging
- At each step, signal averaged over 660 times, 10 MHz sampling rate

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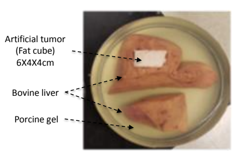
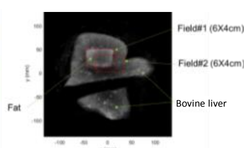
Experiment I – Detect beam/target misalignment

- **Aim:**
  - Examine the feasibility of XACT in monitoring the misalignment of the beam against the target

- Field #1 (on-target): align with the target
- Field #2 (off-target): away from the target



Photograph



US image from a B-mode US machine

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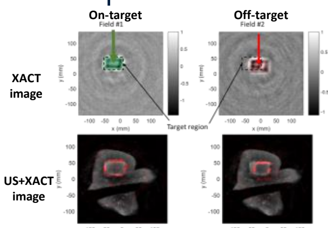
Experiment I – Beam / target misalignment



The XACT image (Pseudo color) super-imposed on the US image (Gray scale).

- **Conclusion:**
  - XACT image can show the field position and boundaries.
  - The misalignment of the beam and the target can be detected by combining the XACT image and the US image.

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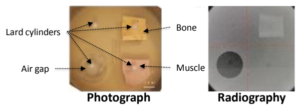
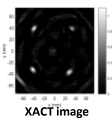
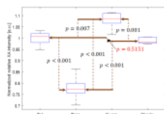
Experiment II – Difference in dose delivery

- **Aim:**
  - Evaluate whether XACT can measure the difference in delivered dose at the target due to the different attenuations in the covering tissues.







- **Conclusion:**
  - XACT images show the differences of the dose delivered to the targets passing through different materials

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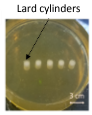
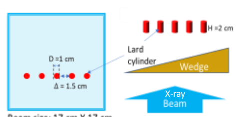
Experiment III – Quantitative dose estimation

- **Aim:**
  - Evaluate the sensitivity of dose measurement using XACT





- Wedges: metal wedges with different angles (15, 30, 45 degrees) were used for attenuating the X-ray beam to induce different **gradients** in delivered dose.

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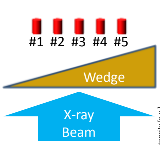
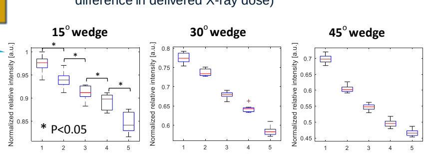
Experiment III – Quantitative dose estimation



- Ten XACT images of the phantom were acquired with each physical wedge (15^o, 30^o and 45^o).
  - Sensitivity of XACT: **2.9%** (the smallest detectable difference in delivered X-ray dose)



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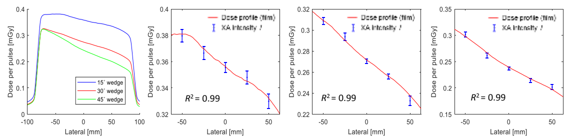
Experiment III – Quantitative dose estimation

- Radiochromic films were applied to measure the dose distributions under each wedge.
- For each wedge, the X-ray doses in lard cylinders measured by XACT match well with the profile extracted from the film result, *demonstrating that XACT can quantify the delivered X-ray dose with good sensitivity and accuracy*.



Dose profiles recorded by films **15° wedge** **30° wedge** **45° wedge**

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Limitations of XACT System based on a single transducer

- ❑ Time consuming
  20 minutes for each 2D image, due to the stepping of the transducer and the time for signal averaging
- ❑ Coupling medium
  Water was used as the coupling material
- ❑ Separated XACT system and B-mode ultrasound system
  Needs co-registration of XACT image and US image

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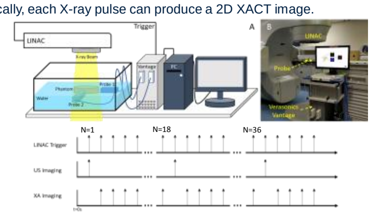
XACT System based on a B-mode Ultrasound Unit

- Acquire the US image and the XACT image at the same time using an integrated system built on a commercial US unit (Vintage 256, Verasonics).
- Theoretically, each X-ray pulse can produce a 2D XACT image.



Experimental parameters

X-ray source:

- 6 MV photon beam delivered by clinical LINAC (Varian TrueBeam™)
- 4 µs pulse duration
- 330 pulse repetition rate

Detection parameters:

- Commercial ultrasound system (Vantage 256-channel, Verasonics)
- Phased array, 1-4 MHz, 96 elements (P4-1, Philips ATL)
- 300 times average for XACT (quasi real-time with frame rate of 1.1 Hz), no average for US (real-time with frame rate of 18 Hz)

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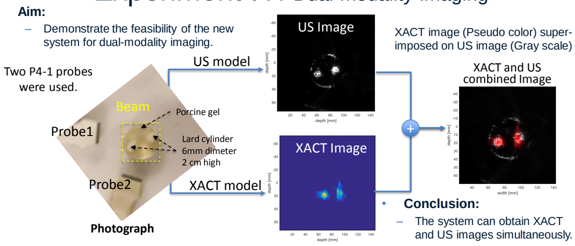
Experiment IV: Dual-modality Imaging

- **Aim:**
  - Demonstrate the feasibility of the new system for dual-modality imaging.



- **Conclusion:**
  - The system can obtain XACT and US images simultaneously.

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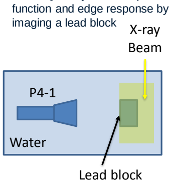
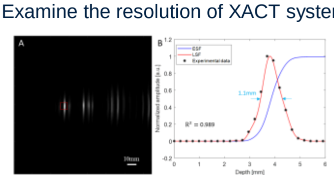
Experiment V: Examine the resolution of XACT system

- **Aim:** Quantify the line spread function and edge response by imaging a lead block





By quantified full width at half maximum (FWHM) of the line spread function and the 10%-90% distance of edge response, the spatial resolution is 1.1mm.

- **Conclusion:**
  - the spatial resolution of the current XACT system is better than 1.1 mm.

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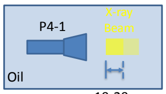
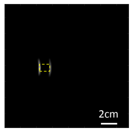
Experiment VI: Measure the sizes of delivered beam

- **Aim:** To verify the performance of the system in measuring the beam sizes of the X-ray beam.

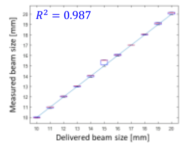
Beam size: lateral 10mm,
axial 10-20mm(1mm per step)



10-20mm



XACT image



Yellow dashed box indicates delivered beam.

- **Conclusion:**
  - XACT imaging is able to measure the beam size of Truebeam system with high accuracy. The minimum size variable of 1mm of a clinical linear accelerator can be detected.

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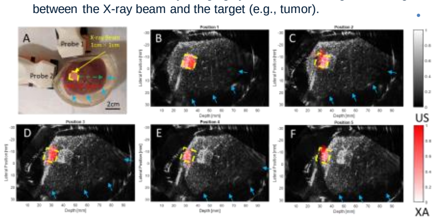
Experiment VII: Tracking the movement of target

- **Aim:** Test the dual-modality imaging system in monitoring the misalignment between the X-ray beam and the target (e.g., tumor).



- **Conclusion:**
  - This dual-modality (XACT and US) imaging system is capable of monitoring the misalignment between the target and the X-ray beam.

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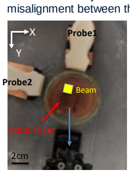
Experiment VIII: Real-time monitoring

- **Aim:**
  - Test the feasibility of the dual-modality imaging system for real-time monitoring of the misalignment between the X-ray beam and the target due to the sample motion



Beam Size：15mm X 15mm

- Sample (gel phantom containing a rabbit liver) was moved along the Y-axis, driving by a linear translation stage.
- Moving speed: 2.5 mm/s
- Move distance 2.75 cm

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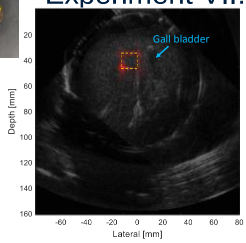
Experiment VII: Real-time monitoring



XACT image(Pseud color) super-imposed on US image(Grayscale)

Frame rate:
- US: 18 fps
- XA: 1.1 fps

- **Conclusion:**
  - The dual-modality system is able to monitor the misalignment between the X-ray beam and the moving target in real time.

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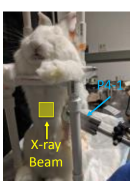
Experiment IX: In vivo monitoring on a rabbit model

- **Aim:**
  - Test the feasibility of the dual-modality imaging system in vivo.



X-ray source:
- 9 MeV photon beam delivered by Linatron
- 4 µs pulse duration
- 44 pulse repetition rate
- 2cm*2cm Beam

Detection parameters:
- Phased array, 1-4 MHz, 96 elements (P4-1, Philips ATL)
- 500 times average for XACT ,no average for US

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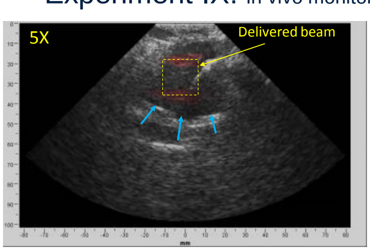
Experiment IX: In vivo monitoring on a rabbit model



XACT image (Pseud color) super-imposed on US image(Grayscale)

Frame rate:
- US: 18 fps
- XA: 0.09 fps

- **Conclusion:**
  - The dual-modality system is able to monitor the misalignment between the X-ray beam and the moving target in a quasi real-time manner in vivo.

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Conclusions

- XACT systems were established and tested for their performance in guiding radiotherapy via the experiments on soft-tissue phantoms and an animal model.
- The delivered X-ray dose in local target tissue can be measured by the XACT systems with an accuracy of better than 2.9%.
- The spatial resolution of the XACT system is 1.1 mm (mainly limited by the X-ray pulse duration).
- An XACT and US dual-modality system can examine the misalignment between the X-ray beam and the target in a quasi real-time manner in vivo (US frame rate of 18 Hz and XACT frame rate of 0.09 Hz).

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Thank you!

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