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

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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
Radiation acoustic theory

• Thermoacoustic 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 distribution:

\[ p(r)|_{t=0} = H(r) \cdot \Gamma(r) \quad \text{where} \quad \Gamma = \frac{v_s^2 \beta}{C_p} \]

• Relating pressure to dose:

\[ p(r) = D(r) \cdot \rho(r) \cdot \Gamma(r) \]
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.
First published detection of acoustic waves induced by clinical linac photon irradiation

Proposal of x-ray acoustic computed tomography

Xiang et al., Med Phys, 40 (1), 2013
X-ray acoustic computed tomography

1. Pulsed photon beam from linac deposits energy
2. Acoustic waves generated through the thermoacoustic effect
3. Acoustic waves detected by ultrasound transducers
4. Image of initial pressure/dose distribution reconstructed
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
Initial set-up for planar imaging

Beam’s eye view

- Primary field from FFF beam
- Transducer

Preamplifier

Oscilloscope

Hickling et al., Med Phys, 44(2), 2017
Initial XACT images in water

Field diagram

XACT image

XACT and ion chamber profiles

Hickling et al., Med Phys, 44(2), 2017
Improving reconstruction of x-ray induced acoustic images for absolute dosimetry

- Simulation study investigating different reconstruction algorithms
Radiation acoustics for therapy guidance/\textit{in vivo} dosimetry

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

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Advantageous characteristics of radiation acoustics
- Dependent on temperature increase per radiation pulse
- No beam perturbation
- Inherently a 3D dosimeter
- Near real-time
- Non-invasive
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
References


