Imaging of Radiation Dose Using Cherenkov Light

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Imaging of Cherenkov light during radiation therapy

- Quality assurance
- Surface dosimetry
- Molecular imaging

Thesis project goals

1. **Determination of optical correction factors necessary to perform Cherenkov dosimetry**

2. Examine feasibility of Cherenkov imaging on C-RAD Catalyst system
Outline

• Background
• Related Research
• Cherenkov Imaging Dosimetry
Cherenkov Radiation Production

Incident radiation (gamma or electron)

Index of refraction: \( n \)

Particle velocity: \( v_p \)

\( \theta_c = 43^\circ \) (2 MV beam in water)

Conical emission angle: \( \theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right) \)

Ratio of velocity to speed of light: \( \beta = \frac{v_p}{c} \)
Cherenkov Light Characteristics

• The number of photons, $N$, emitted per unit path due to the Cherenkov effect:

$$\frac{dN}{dx} \propto \left[ 1 - \frac{1}{\beta^2 n^2} \right] \frac{1}{\lambda^2} d\lambda$$

  Lower limit of Cherenkov emission

• For a 6 MeV electron beam delivering 100 cGy to water at a rate of 600 MU/min:
  • 600 photons/electron
  • 6-10 photons/electron from surface
  • $3 \times 10^{11}$ detectable photons
  • $8 \times 10^{-10}$ Watts
Cerenkov Light - Relationship to Dose

- Mono-energetic pencil beams, relationship is 1:1 between light emission and dose (<1%)
- Poly-energetic finite beam sizes, error is between 0-5%

Dose: \[ D = \frac{1}{\rho} \int \phi \frac{-dT}{dx} \, dE \]

Number of photons: \[ N_T = \frac{1}{\rho} \int \phi \frac{-dN}{dx} \, dE \]

Correlation ratio: \[ C = \frac{D}{N_T} \]

Set-up of Cherenkov Detection

- **Camera**
  - CMOS, CCD not as viable
  - Triggered to linac output

- **Target material**
  - Water tank or phantom
  - Patient

- **Computer**
  - Timing, camera, software

- **Radiation source**
  - Linear accelerator
  - Radiopharmaceutical

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Imaging of Radiation Beams in Water

10x10 cm, 6 MV beam in a quinine sulfate solution
30 sec exposure

2D projection of a C-treatment plan

3D reconstruction using tomography
30 min scan time
±1 mm resolution
Superficial Dosimetry during Radiation Therapy

- Cherenkov light can be related to dose through light intensity
  - Dose is deposited locally by charged particles
  - Cherenkov photons are generated and scattered via Mie and Rayleigh scattering

- ±5% error associated with variations in beam size, angle of incidence, and energy
- ±40% error associated with variations in surface geometry, composition, and tissue pigment

Superficial Dosimetry during Radiation Therapy

• Dosimetry is not possible with the current state of Cherenkov detection
  • Skin reaction detection
  • MLC motion tracking @ 2.5 fps

• Factors that are needed for absolute dosimetry:
  • Luminosity correction
  • Angular scattering correction
  • Absorption correction

  Optical factors = 40% error

• Correlation ratio

  Beam factors = 5% error

Cherenkov Dosimetry Correction Factors

\[ Dose = K_L \cdot K_S \cdot K_A \cdot C \cdot Intensity \]

- \textit{Dose} [Gy] is the dose received at the mean depth \((D_M)\)
- \textit{Intensity} [W] is the number of Cherenkov photons imaged on a pixel
- \(C = \text{Correlation ratio [Gy/Cher. photon] for a given beam size, particle, and energy}\)
- \(K_L = \text{Image luminosity correction}\)
- \(K_S = \text{Angular scattering correction}\)
- \(K_A = \text{Absorption correction}\)

Beam factor

Optical factors
Monte Carlo Simulations of Cherenkov Generation

- Gamos was used to determine $K_s$:
  - Beam size dependence (pencil - 20x20 cm$^2$)
  - Beam angle (0-75°)
  - Beam energy and particle type (6-20 MeV)
  - Mono and poly-energetic beams
  - Tissue and optical phantom materials
- Linac simulations were compared with experiment
Monte Carlo engine

- Physics model
- Particle source
- Geometry
- Radiological properties
- Optical properties
- Scoring filters

Text-based interface for Geant4 + optical transport

Output scoring filters

- High-energy photon transport
- Charged particle generation + transport
- Optical photon generation + transport

Geant4

GAMOS

- Cherenkov light scoring
- Dosimetry scoring
Optical Phantom Scattering Correction, $K_s$

The graph shows the normalized radiance $R/\Omega$ as a function of the observation angle $\theta_{\text{obs}}$ (degrees). The equation $K_s = \frac{1}{\text{Radiance}}$ is given, indicating the correction factor $K_s$ for optical phantom scattering. The graph includes different simulations and measurements:

- Photon beam sim.
- Electron beam sim.
- Optical phan. measured
- Human skin measured
- Lambertian

The graph illustrates the comparison between simulated and measured data, highlighting the scattering correction effect.
Stratified Skin Scattering Correction, $K_s$

$$K_s = \frac{1}{\text{Radiance}}$$
Summary

- Cherenkov light can be related to dose deposition – current measurements have high uncertainty
- $Dose = K_L K_S K_A C \text{ Intensity}$
- Monte Carlo simulations were used to find scattering correction factor $K_S$

Next Steps:
- Solving for $K_A$ and $K_L$
- Apply formula for skin dosimetry
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References


Image References

2. https://www.youtube.com/watch?v=X0LXJRYzovU, used with the permission of Jacqueline Andreozzi
3. http://www.scint-x.com/media/1748/scint_x_technology1.jpg
C-RAD Catalyst System

- Optically-based patient positioning system
- Uses optical triangulation to obtain 3D coordinates of detected surface
- Automatic patient positioning
- Respiratory gating
- Cherenkov detection?
- Luminosity correction?