THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History

Real-time Volumetric Scintillation Dosimetry for Radiation Therapy

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DISCLOSURES

- SB had a NIH/National Cancer Institute (R01 CA182450) and a NIH/NCI SBIR Phase I grant (1R43 CA153824) and SBIR Phase I grant (1R44 CA153824) with Standard Imaging.
- SB had phase I, II, III Sponsored Research Agreements with Radiadyne, LLC.
- The University of Texas MD Anderson Cancer Center has a license agreement with:
  - **Radiadyne, LLC**
  - **Standard Imaging, Inc**

- ***Scintillating Fiber Dosimetry Arrays.*** US Patent: 8,183,534, Date Issued: May 22, 2012.
- ***Real-time in vivo Radiation Dosimetry Using Scintillation Detectors.*** US Patent: 8,735,828 B2, Date Issued: May 27, 2014.
- ***Liquid Scintillator for 3D Dosimetry for Radiotherapy Modalities***. US Prov. 61/223,619, filed on 07/07/2009, Date issued May 2015.
- **Large-volume scintillator detector for real-time dose imaging of advanced radiation therapy modalities**, US Prov. 61/829,397 filed May 2013.

Introduction

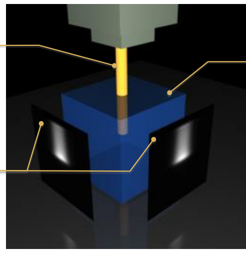
Increasing complexity of radiotherapy fields
- Photons (IMRT, VMAT, SBRT, etc…)
- Protons/Light & Heavy Ions/IMParticleT
  - Measurements at few depths are not sufficient
  - Steep dose gradients coupled with range uncertainties

Quality assurance for complex fields is challenging
- Large quantity of data required for complete field characterization
- Time consuming (~ hours per IMProtonT patient at PTCH)
- Resolution of ion chamber arrays or other detectors may not be sufficient

D. A. Low, J. M. Moran, J. F. Dempsey, L. Dong, and M. Oldham **Dosimetry tools and techniques for IMRT.** Med. Phys. **38**, 1313-38, **2011**

Concept of the 3D Detector

Introduction
Proton world
Photon world
Conclusion



Proton beam
- *Delivers a clinical plan to the volume scintillator*

Volume scintillator
- *Dose sensitive volume*
- *Convert proton energy into visible light*

CCD cameras
- *Orthogonal views*
- *Quantitative measure of proton spots*
- *Fast response*

Concept of the 3D Detector

Introduction
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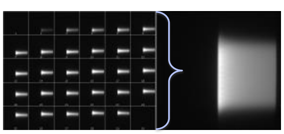
Photon world
Conclusion

- A 3D volume of Liquid Scintillator
- A pair of CCD cameras to capture images of the scintillation light
- Image acquisition coordinated with beam delivery
- Single acquisition for static fields or rapid acquisition for scanned fields



Beddar S, Archambault L, Sahoo N, Poenisch F, Chen GT, Gillin MT, and Mohan R. **Exploration of the potential of liquid scintillators for real-time 3D dosimetry of intensity modulated proton beams.** Med Phys **36**(5):1736-1743, **2009**

Measurement Procedure

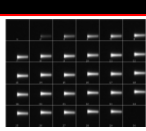
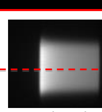
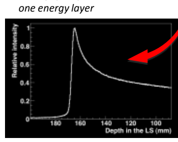


Image acquisition coordinated with beam delivery



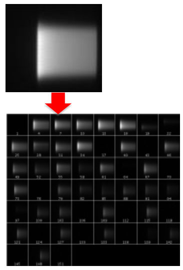
Sum of spots for one energy layer

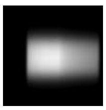


In each image frame
- Measure proton range
- Measure spot position
- Measure spot intensity

Measurement Procedure

- Combine the individual beams for each energy layer
- Combine all energy layers to evaluate the complete treatment





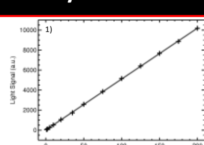
A simple SOBP

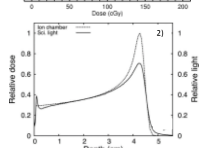
Liquid Scintillator Detector

- Cameras: Andor Luca S EMCCD
  - 658x496 pixels
  - TE cooling to -20 C
  - 27 full frames/s (30 ms)
  - Speeds > 300 frame/s achievable with binning
  - Effective resolution in tank: ~ 0.3 mm
- Liquid scintillator: OptiPhase Hi-Safe 3
  - Diisopropyl naphthalene solvent
  - PPO fluor w/ bisMSB wavelength shifter
  - **Density: 0.963 g/cm^3**
  - Peak emission: ~430 nm
  - Light emission decay time: < 20 ns
  - Index of refraction: 1.5325 (20°C)

Scintillation dosimetry

- Scintillator properties
  - fast response
    - < 20 ns decay time
  - linear dose response for photons
  - Linear energy transfer (LET)-dependence
    - called ionization quenching





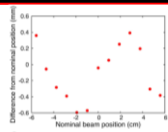
1) Ponisch F, Archambault L, Briere T M, Sahoo N, Mohan R, Beddar S and Gillin M T **Liquid scintillator for 2D dosimetry for high-energy photon beams** Med. Phys. **36** 1478-85 **2009**

2) Beddar S, Archambault L, Sahoo N, Poenisch F, Chen G T, Gillin M T and Mohan R **Exploration of the potential of liquid scintillators for real-time 3D dosimetry of intensity modulated proton beams** *Med. Phys.* **36** 1736-43 **2009**

Measurement of position and range

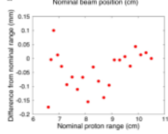
Lateral Position

- Average difference from nominal position: 0.1 mm
- Greatest deviation < 0.6 mm
- Standard deviation: 0.3 mm



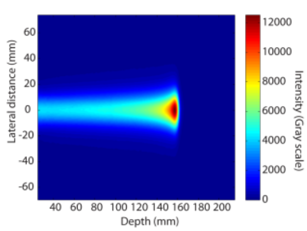
Proton Range

- Average difference from nominal position: -0.04 mm
- Greatest deviation < 0.18 mm
- Standard deviation: 0.07 mm



L. Archambault, F. Poenisch, N. Sahoo, D. Robertson, A. Lee, M. T. Gillin, R. Mohan and S. Beddar. **Verification of proton range, position, and intensity in IMPT with a 3D liquid scintillator detector system.** Med. Phys. **39**, 1239-1246, **2012**

Measurement of spot intensity



Volumetric Scintillation Dosimetry

Advantages
- Image entire dose distribution in a single measurement
- High spatial resolution (~ 0.3 mm)
- Dynamic features of beam delivery can be measured with high-speed video
- Scintillator material is water-equivalent

Disadvantages
- Optical artifacts
- Quenching
  - Non-linear scintillation response to proton and heavy ions beams

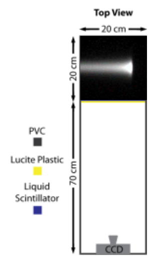
Volumetric Scintillation Dosimetry

Goal: **Fast, reusable, high-resolution, 3D detector**

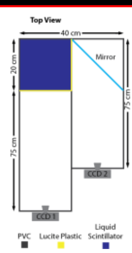
Mechanism: **Measure light emission from a volume of scintillator**

Instrumentation: **Liquid scintillator detector**

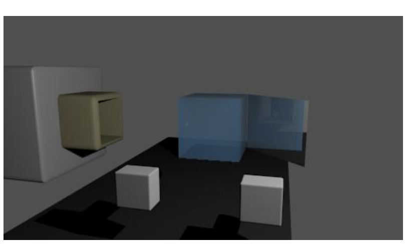
- Tank of organic liquid scintillator
    - nanosecond light emission
- CCD camera
    - Future systems will incorporate additional cameras to gather 3D light distributions



Volumetric Scintillation Dosimetry

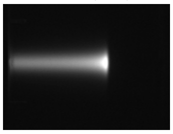


Volumetric Scintillation Dosimetry

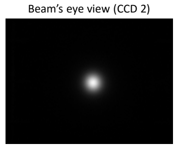


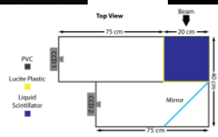
Example of Data

Side view (CCD 1)



Beam's eye view (CCD 2)





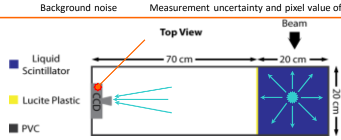
Beam range measurements

- Beam control file prepared for single irradiation
  - 60 beam energies
  - Range 4 - 19 cm
  - Central beam axis
  - Beam delivery time: ~ 2.5 min.
- Camera acquisition parameters:
  - 1 frame/s
    - Avoid overlapping beam energies (2 s required to change beam energy)

Playback at 5x original speed

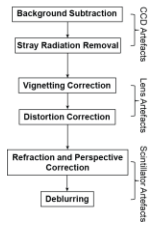
Optical Artifacts

Artifact source	Physical phenomenon	Effect
Light propagation in the scintillator and tank	Photon scattering Refraction Perspective	Blurring of light signal Changes in effective pixel size and intensity Changes in effective pixel size with depth
Optical train	Vignetting Lens distortion Lens PSF	Decreased brightness at image periphery Radial variation in pixel size and location Blurring of light signal
CCD chip	Stray radiation Background noise	Hot pixels and streaks Measurement uncertainty and pixel value offset



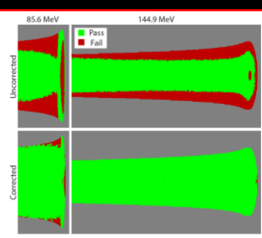
Optical Artifact Correction

- Proton pencil beams measured with scintillator detector
  - Optical artifact corrections applied to measurements
- 3D dose distributions calculated with validated Monte Carlo code
  - Quenching applied to calculated dose distributions to determine the expected 3D light distribution
  - 3D light signal collapsed to 2D for comparison with camera images
- Measured and calculated light signals compared using Gamma Analysis
  - 3% local dose, 3 mm to agreement
  - 2% local dose, 2 mm to agreement



Robertson D, Hui C, Archambault L, Mohan R, Beddar S **Optical artefact characterization and correction in volumetric scintillation dosimetry** Phys. Med. Biol. **59** 23-42, **2014**

Optical Artifact Correction Results



Gamma analysis pass maps with gamma criteria of **2% and 2mm** for 85.6-MeV (left) and 144.9-MeV (right) proton pencil beams. **Passing pixels** are in green, and **failing pixels** are in red. The gray pixels are **below the dose threshold** (5% of maximum dose) and were not considered in the gamma analysis.

Optical Artifact Correction Results

Efficacy of artifact correction measured by gamma analysis

- Corrected image compared to light signal from Monte Carlo
- Gamma analysis criteria: 2% local dose or 2 mm to agreement
  - Energies above 100 MeV: passing rate of 98% or better
  - 85.6 MeV: 94.9% passing rate

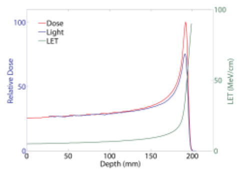
Gamma Criteria	85.6 MeV		100.9 MeV		144.9 MeV		161.6 MeV	
	Orig	Corr	Orig	Corr	Orig	Corr	Orig	Corr
3%/3mm	80.7%	99.1%	81.9%	99.7%	84.5%	100.0%	95.3%	100.0%
2%/3mm	80.3%	98.9%	81.5%	99.7%	84.0%	100.0%	94.9%	99.9%
1%/3mm	79.3%	98.7%	80.6%	99.6%	82.8%	99.7%	94.1%	99.8%
3%/2mm	61.2%	95.3%	63.5%	98.4%	65.3%	99.9%	76.2%	99.9%
2%/2mm	60.6%	94.9%	62.9%	98.3%	64.6%	99.9%	75.5%	99.8%
3%/1mm	31.8%	76.9%	31.7%	85.1%	37.7%	97.8%	43.9%	99.7%

Gamma analysis comparison between Monte Carlo light signals and measured light signals before ('Orig') and after correction for optical artifacts ('Corr').

Scintillator Quenching

- Quenching is caused by high ionization density
- Quenching is proportional to linear energy transfer (LET)
- Birks formula:

$$\frac{dS}{dx} = \left(A\frac{dE}{dx}\right) \Big/ \left(1 + kB\frac{dE}{dx}\right)$$



dS/dx: scintillation response per particle track distance → Measured light
dE/dx: LET (average stopping power) → Calculated with Monte Carlo
A: scintillation efficiency
kB: quenching coefficient → Determined by fit to Birks formula

Quenching Correction - Results

- Bragg peak intensity corrected to within 3% for most energies
- Poorer agreement at low beam energies
  - Sharp Bragg peaks
    - Detector size effects
    - Greater sensitivity to misalignment between LET and measured light
  - Beam measurements and Monte Carlo models are less accurate at low energies

Percent Difference in Peak Height

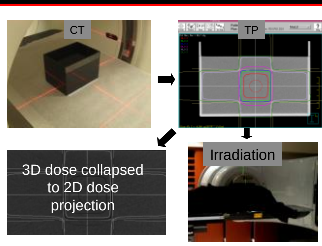
Energy (MeV)	Measured Signal (%)	Corrected Signal (%)
85.6	37.3	9.7
100.9	31.1	2.4
144.9	26.2	0.9
161.6	26.1	1.6

Robertson D, Mirkovic D, Sahoo N and Beddar S **Quenching correction for volumetric scintillation dosimetry of proton beams** *Phys. Med. Biol.* 58 261-73 2013

➢ *Alsanea F., TH-CD-201-3 (Thursday, August 4, 2016) 10:00 AM - 12:00 PM Room: 201)*

Photon QA – 2D with 1 CCD

Introduction
Proton world
Photon world
Conclusion



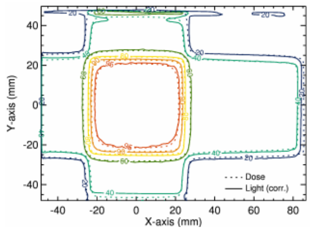
Pönisch F, Archambault L, Briere TM, Sahoo N, Mohan R, Beddar S, and Gillin MT. **Liquid scintillator for 2D dosimetry for high-energy photon beams.** Med Phys **36**(5):1478-1485, **2009**

Photon QA - Results

Comparison between light signal and expected dose

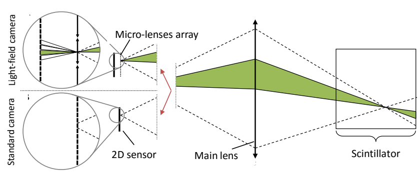
Gamma Evaluation
(3%,3mm)

Excellent agreement



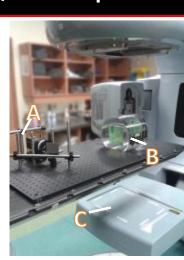
Other Method – Light-field imaging

- Standard CCD/CMOS detector with micro-lenses add-on
- Two main differences:
  - Incident optical ray angle discrimination
  - Smaller angle spread per sensor pixel, coarser spatial resolution



IMRT/VMAT QA – Set-up

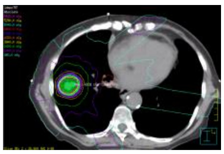
- A : light-field camera
- B : scintillator phantom
- C : EPID
  - Beam's eye view projection of the incident radiation field
- A + B are static with respect to the linac
  - Real-time light signal acquisition

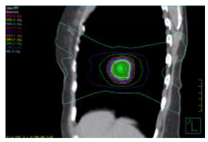


Goulet M, Rilling M, Gingras L, Beddar S, Beaulieu L, Archambault L. **Novel, full 3D scintillation dosimetry using a static plenoptic camera.** Med Phys **41**(8):082101, **2014**

IMRT QA - SBRT

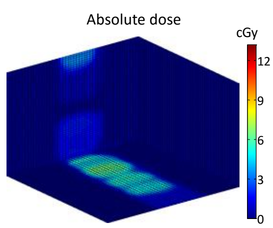
- 7 coplanar
- 2 non-coplanar fields
  - 90 degree couch angle
  - 335, 30 degrees gantry angle
- All fields < 4x4 cm^2





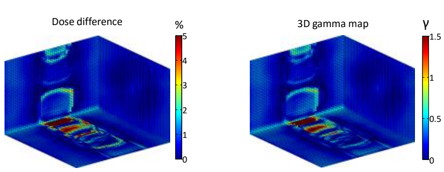
3D dose measurements

- Acquisition rate : one light-field image per second
  - Dose as a function of delivery time (real-time)
- Reconstructed matrix resolution: 2x2x2 mm^3
  - Contiguous (no gap between voxels)
  - 10x10x10 cm^3 volume :
    - 125 000 dose points



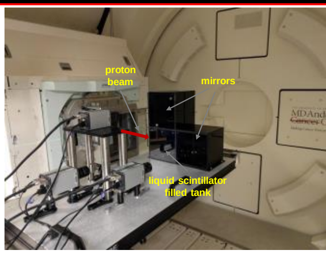
Dose comparison

Comparison with TPS:



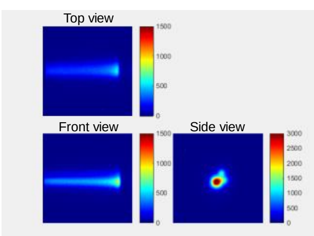
Mean absolute dose difference = 1.3%
($D > 10\% D_{max}$)

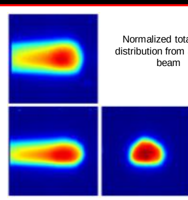
Actual system setup



- Measurements at Proton Therapy Center at MD Anderson Cancer Center, Houston
- Discrete spot scanning system uses synchrotron accelerator and scanning beam nozzle
- Energy range: 72.5 MeV to 221.8 MeV

Imaging Patient treatment plans





Normalized total light distribution from a lateral beam

- Prostate treatment plan (1 lateral beam)
- 17 total energies: 163.9 MeV – 203.7 MeV
- 40 MU total delivered dose

CONCLUSION

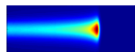
- Volumetric scintillation detector characteristics:
  - High spatial resolution (0.24 mm/pixel)
  - High temporal resolution:
  - Large volume detection (20 cm^3) covers most treatment plans
- System capable in quantifying QA parameters with high accuracy
  - Range verification (Mean diff between measured and nominal: ~0.10 mm (σ = 0.11 mm)
  - Precise determination of beam location
  - 3D dose distribution measurements
- Volumetric scintillation detectors have the potential to become a useful tool for real-time 3D photon and proton beam QA (Machine QA and Patient QA verification)
- Potential to significantly improve the efficiency and completeness of quality assurance for scanned proton beam delivery systems
  - Increased patient safety
  - Improved capacity to detect beam delivery errors

ACKNOWLEDGEMENTS

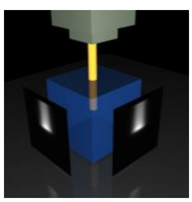
NCI/NIH Award # R01 CA182450

Scintillation Dosimetry Lab

Fahed Alsanea, MS
Louis Archambault, PhD (Laval Univ.)
Chinmay Darne, PhD
Gustavo Kertzscher, PhD
Becket Hui, PhD (University of Virginia)
Saleh Ramezani, MS
Daniel Robertson, PhD



Landon Wootton, PhD (Univ. of Washington)
Francois Therriault-Proulx, PhD
Hanen Ziri, MS (Grenoble Univ.)



THANK YOU