

Patient-specific quality assurance for spot scanning proton beams using a large-volume liquid scintillator detector

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Abstract. A large-volume liquid scintillator detector was used to measure individual energy layers from a clinical prostate treatment plan on a scanning proton beam system. Lateral and beam's-eye view images of the dose distribution were acquired with two CCD cameras facing adjacent sides of a scintillator tank. The measured dose images were compared with calculated dose distributions from a validated Monte Carlo model. The measured and calculated dose distributions showed good agreement, with the exception of the Bragg peak region of the lateral view, which exhibited ionization quenching. The beam's-eye and lateral views achieved gamma analysis passing rates of 99.7% and 92.5%, respectively, using gamma criteria of 3%, 3 mm. Large-volume scintillator detectors show promise for quick and accurate measurements of patient treatment fields for scanning proton beam systems.

1. Introduction

Proton radiation therapy can produce physical dose distributions that are superior to photon-based treatments because of the proton Bragg peak and the finite range of proton beams in tissue. Most new proton therapy centers employ magnetic beam scanning, which is capable of delivering intensity-modulated proton therapy (IMPT) treatments. However, the complexity of IMPT treatments leads to challenges in treatment plan verification measurements. The steep dose gradients and finite range characteristic of IMPT fields necessitate the use of high-resolution detectors and require measurements at multiple depths in order to verify that the treatment plan is correctly delivered. As a result, patient-specific quality assurance for IMPT is labor-intensive, and it is only practical to measure a subset of locations within each field.

In recent years, interest has grown in the use of large-volume organic scintillator detectors for quality assurance of radiation therapy delivery systems and patient treatment plans. Detectors consisting of plastic or liquid scintillators imaged by CCD cameras have been developed and tested for applications including proton beam range measurement [1-4], proton beam scanning position [5], and measurement of photon-based patient treatment plans [6, 7]. Large-volume scintillator detectors are particularly promising for verification of IMPT patient plan delivery because of their high resolution, their speed, and their ability to image the entire dose distribution in a single measurement. All of these studies have either used a single CCD camera or a relatively small detector volume.

The objective of this study was to evaluate the use of a large-volume scintillator detector employing two orthogonal cameras to measure dose distributions from scanning proton beam treatments.



2. Materials and Methods

A large-volume liquid scintillator detector was constructed, comprising a cubic plastic tank filled with liquid scintillator, two CCD cameras, and a mirror. The inner dimensions of the scintillator tank were $20 \times 20 \times 20 \text{ cm}^3$, and the CCD cameras were placed 75 cm from two adjacent faces of the tank. A mirror, oriented at 45 degrees relative to one face of the tank, was used to re-direct the light towards one of the cameras. The mirror enabled one camera to obtain a beam's eye view of the proton beam without putting the camera's sensitive electronics at risk from radiation damage (Figure 1).



Figure 1. The large-volume liquid scintillator detector, including the tank and two cameras, in position on the patient couch of the Proton Therapy Center - Houston scanning gantry.

The images from the scintillator detector were processed to remove lens distortions, vignetting, blurring, and hot pixels and streaks caused by stray radiation striking the cameras [8]. The images were also corrected for refraction at the tank-air interface [4].

Individual energy layers of a scanning beam prostate treatment were delivered to the scintillator detector and measured with the CCD cameras. The timing structure of scanning beam delivery at the Proton Therapy Center - Houston includes rapid scanning at a given proton energy, followed by a 2-second pause while the synchrotron energy is changed. Consequently, it is convenient to measure one energy layer at a time, allowing the camera data to be read out during the pause in beam delivery. The analysis presented herein is for the 161.6 MeV energy layer of a scanning beam prostate treatment plan. This energy was selected because it was in the center of the field, covering a large area and featuring an unusually-shaped dose distribution. Beam's-eye view and lateral images of the dose distribution were obtained simultaneously during one single delivery of the field.

The dose distribution was calculated using a Monte Carlo proton dose calculation system featuring a validated model of the Proton Therapy Center - Houston scanning beamline [9]. The calculated and measured dose distributions were normalized in the proximal buildup region for the lateral (depth-dose) view, and in a high-dose, low-gradient region in the beam's eye view. The calculated dose distribution was compared with the measured light signal using profile comparisons and gamma analysis [10].

3. Results and Discussion

On visual inspection, the Monte Carlo calculations and measured scintillation light show good agreement, with all features of the calculated dose distribution readily visible in the measured light (Figure 2). Line profiles indicate excellent agreement for the beam's-eye view, while revealing a substantial quenching of the Bragg peak in the scintillator signal (Figure 3). Ionization quenching is caused by linear-energy dependence of the scintillator [11]. Methods have been developed to correct for quenching in scintillator detectors [12]. The beam's-eye view is relatively unaffected by quenching, which decreases the intensity of the distribution without altering its shape. However, it is clear from the lateral camera view that quenching correction is necessary to obtain agreement in the depth direction.

The agreement of the calculated and measured dose distributions was evaluated using gamma analysis. Regions with 10% of the maximum dose or greater were evaluated. Figure 4 shows gamma maps for criteria of 3% dose difference and 3 mm distance to agreement. While the passing rate was above 90%, quenching led to very high gamma values in the Bragg peak in the lateral view. This illustrates the importance of quenching correction when evaluating in the depth direction.

Gamma analysis was repeated using criteria of 2%, 2mm and 1%, 1mm. The passing rates are given in Table 1. At 3%, 3mm, the passing rates were very high, even for the lateral view without quenching correction. This suggests that 3%, 3 mm is too generous a criteria to effectively evaluate the accuracy of IMPT treatment plan delivery. While the individual gamma values in the Bragg peak were very high in the lateral view, they were confined to a small region, leading to passing rates similar to the beam's-eye view. If the entire field, including all energy layers, was evaluated together, passing rates for the lateral view would likely drop due to the presence of multiple Bragg peaks.

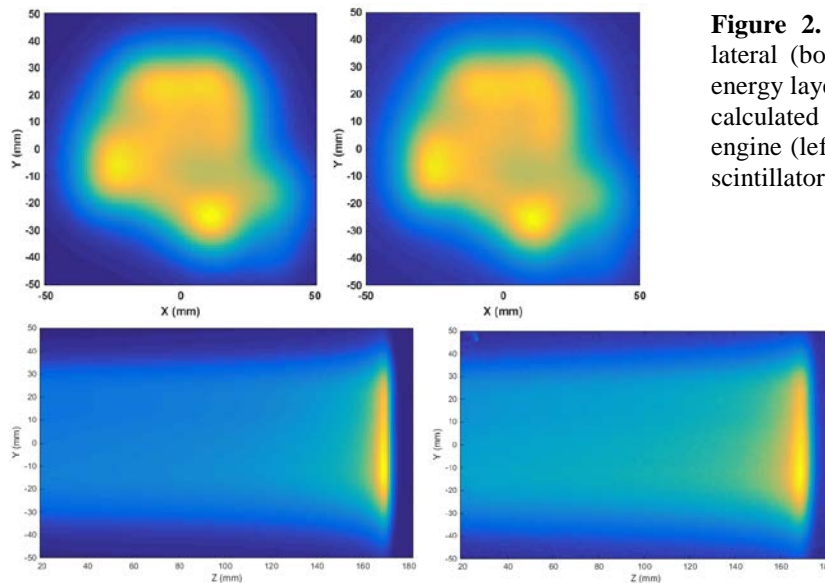


Figure 2. Beam's-eye view (top) and lateral (bottom) projections of a single energy layer of a prostate treatment plan, calculated using a Monte Carlo dose engine (left) and measured with a liquid scintillator detector (right).

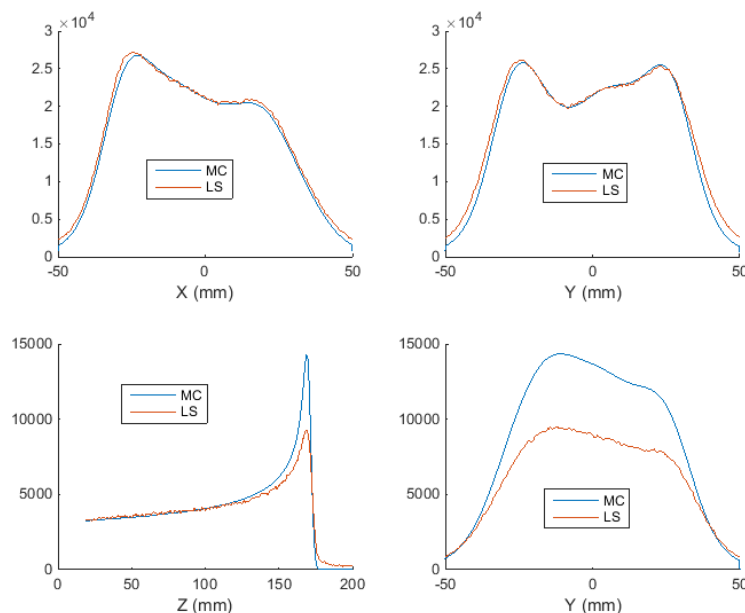


Figure 3. Line profiles of the Monte Carlo-calculated (MC) and liquid scintillator-measured (LS) dose distributions for the beam's-eye view (top) and lateral view (bottom). All profiles pass through the center of the images, with the exception of the bottom right figure, which passes through the Bragg peak.

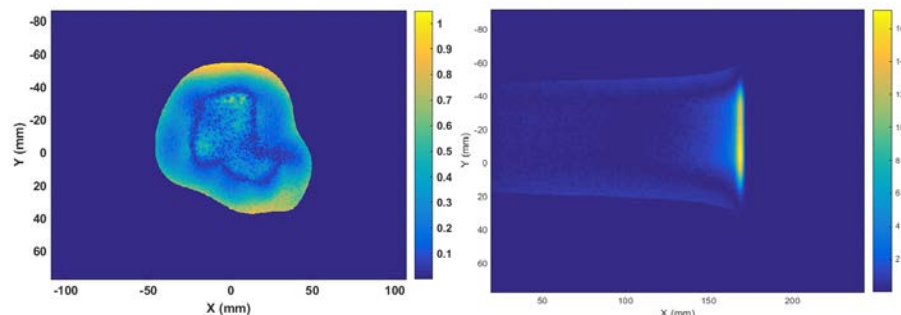


Figure 4. Gamma analysis maps (3%, 3 mm) comparing the measured and calculated doses for a single energy layer, including the beam's-eye view (left) and a lateral view (right).

Table 1. Gamma analysis passing rates for the beam's-eye and lateral views.

Gamma Analysis Criteria	Beam's eye view	Lateral view
3%, 3 mm	99.7%	92.5%
2%, 2 mm	90.4%	88.7%
1%, 1 mm	55.5%	66.5%

4. Conclusions

Patient-specific dose distributions measured with a large-volume liquid scintillator detector agreed well with calculated doses for a single energy layer of a scanned proton beam treatment plan, with the exception of ionization quenching in the Bragg peak. Gamma analysis is useful for comparing measured and calculated dose distributions, but the gamma criteria should be selected carefully to ensure the sensitivity of the test. It is convenient to measure one energy layer at a time using the scintillator detector, and separating the image data into individual energy layers opens the way for application of energy-dependent quenching correction factors. Large-volume scintillator detectors show promise for quick and accurate measurements of patient treatment fields for scanning proton beam systems.

5. Acknowledgements

The authors would like to thank Dr. Dragan Mirkovic and Dr. Narayan Sahoo for their valuable inputs and contributions to this project. The research reported in this publication was supported by the National Cancer Institute of the National Institutes of Health under Award Number R01CA182450. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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