Published in final edited form as:

Biomed Phys Eng Express. 2015 August ; 1(2): . doi:10.1088/2057-1976/1/2/025204.

Fast range measurement of spot scanning proton beams using a volumetric liquid scintillator detector

CheukKai Hui¹, Daniel Robertson¹, Fahed Alsanea², and Sam Beddar^{1,2}

¹Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX 77030, USA

²The University of Texas Graduate School of Biomedical Sciences at Houston, Houston, TX 77030, USA

Abstract

Accurate confirmation and verification of the range of spot scanning proton beams is crucial for correct dose delivery. Current methods to measure proton beam range using ionization chambers are either time-consuming or result in measurements with poor spatial resolution. The large-volume liquid scintillator detector allows real-time measurements of the entire dose profile of a spot scanning proton beam. Thus, liquid scintillator detectors are an ideal tool for measuring the proton beam range for commissioning and quality assurance. However, optical artefacts may decrease the accuracy of measuring the proton beam range within the scintillator tank. The purpose of the current study was to 1) develop a geometric calibration system to accurately calculate physical distances within the liquid scintillator detector, taking into account optical artefacts; and 2) assess the accuracy, consistency, and robustness of proton beam range measurement using the liquid scintillator detector with our geometric calibration system. The range of the proton beam was measured with the calibrated liquid scintillator system and was compared to the nominal range. Measurements were made on three different days to evaluate the setup robustness from day to day, and three sets of measurements were made for each day to evaluate the consistency from delivery to delivery. All proton beam ranges measured using the liquid scintillator system were within half a millimeter of the nominal range. The delivery-to-delivery standard deviation of the range measurement was 0.04 mm, and the day-to-day standard deviation was 0.10 mm. In addition to the accuracy and robustness demonstrated by these results when our geometric calibration system was used, the liquid scintillator system allowed the range of all 94 proton beams to be measured in just two deliveries, making the liquid scintillator detector a perfect tool for range measurement of spot scanning proton beams.

Keywords

proton beam quality assurance; proton beam range measurement; liquid scintillator detector

1. Introduction

In spot scanning proton therapy, the treatment dose is deposited in a spot-by-spot fashion. The range of a particular spot is controlled by setting the proton energy. Although the finite range and rapid dose drop-off of proton beams allow highly localized dose delivery, very accurate knowledge of the delivered dose range is also required for accurate treatment planning with proton beams. The current standard to measure the spot scanning proton beam range is to perform measurement using a water tank with an ionization chamber. However, this method is very time-consuming because a large number of measurements is needed at each location. Moreover, many proton energies are available. For example, a total of 94 different proton energies are available for spot scanning proton therapy at The University of Texas MD Anderson Cancer Center Proton Therapy Center at Houston (PTC-H). It is impractical to regularly measure the proton ranges of all available proton energies.

Several other alternative methods have been proposed to measure proton beam range. Nohtomi *et al.* (2003) proposed to measure proton range using an imaging plate oblique to the proton beam. Boon *et al.* (1998) used a system with a water tank, scintillating screen, and charge-coupled device (CCD) camera to obtain the lateral proton beam profile. Radiochromic film was proposed by Vatnitsky (1997) to measure the proton beam profile. Fukushima *et al.* (2006) proposed using a plastic scintillator block for range measurement. Recently, Dhanesar *et al.* (2013) used a multilayer ionization chamber system for fast depth dose measurement. The advantages and disadvantages of different methods were described in a recent review by Karger *et al.* (1999).

We have previously described the potential of using a large-volume liquid scintillator detector to measure the dose distribution of spot scanning proton beams (Archambault *et al.*, 2008; Beddar *et al.*, 2009). The proposed liquid scintillator system can measure the profile of spot scanning proton beams in real time and has submillimeter spatial resolution, making it an ideal tool for proton beam range measurements. However, the current calibration method has relied on scaling the scintillator measurements with Monte Carlo or ionization chamber data (Archambault *et al.*, 2012; Ponisch *et al.*, 2009). We have characterized some optical artefacts of the liquid scintillator system (Robertson *et al.*, 2014). By understanding the optical artefacts, we could obtain the physical distances within the scintillator tank. In the current study, we developed a geometric calibration system that accounts for optical artefacts to allow accurate measurement of the physical location within the scintillator tank. In addition, we investigated the effects of optical artefacts that could not be corrected on the range measurement of the spot scanning beam. Finally, we studied the reproducibility of the range measurements using the proposed liquid scintillator system.

2. Materials and methods

2.1. Liquid scintillator detector system

Our liquid scintillator setup consisted of a tank filled with OptiPhase HiSafe 3 liquid scintillator (Perkin Elmer, Waltham, MA). The density of the liquid scintillator was $0.96 \text{ g} \cdot \text{cm}^{-3}$, and the refractive index was between 1.53 and 1.57 within the frequency range of visible light (Kossert, 2013). The tank wall was made of polyoxymethylene and the window

material was poly(methyl methacrylate). The refractive index of the window was 1.49. The scintillator converted energy deposited by the proton beam into visible light. The scintillation light was collected by a camera system consisting of an objective lens (JML Optical Industries, Rochester, NY) and a Luca^{EM} S CCD camera (Andor Technology, Belfast, Northern Ireland). The dimension and setup of the liquid scintillator system is depicted in figure 1.

2.2. Geometric calibration for physical location

Geometric calibration is used to accurately convert the pixel location in the camera frame to the physical location in the scintillator frame. Multiple factors can affect the scintillation light path from its origin to the camera image. In our previous study, we described three optical artefacts that can affect geometric calibration: refraction, perspective, and lens distortion (Robertson *et al.*, 2014). In the current study, we investigated three additional parameters that must be accounted for to perform geometric calibration. These are 1) the effective distance between the tank wall and the center of the lens, y_s ; 2) the rotational shift, α ; and 3) the translational shift, x , of the camera relative to the scintillator tank. The schematic of the scintillation light path is depicted in figure 2. Owing to the similar refractive indices between the liquid scintillator and the window material (difference < 0.1) and the small thickness of the window material ($< 2\%$ of the entire light path), a single refractive index, $n_s = 1.49$, was used to simplify the calculation. The pixel location in the camera frame, x_p , is a function of the angle θ_a described by

$$x_p = f_c \tan(\theta_a + \alpha) \quad (1)$$

where f_c is the focal length (in pixels) of the objective lens. The location x_s within the scintillator tank at perpendicular distance y_s can be calculated using the following equation:

$$x_s = x_1 + x_2 + x_3 \quad (2)$$

The two orthogonal components in x_1 and x_3 were solved independently:

$$x_1 = \frac{y_s \cdot \frac{n_a}{n_s} \sin \theta_a}{\sqrt{1 - \left(\frac{n_a}{n_s} \sin \theta_a\right)^2}} \quad (3)$$

$$x_3 = y_s \tan \alpha + \Delta x$$

where n_a is the refractive index of air and n_s is the refractive index of the scintillator. The two orthogonal components in x_2 were calculated by solving the following linear equations:

$$\begin{pmatrix} y_a \\ y_a \end{pmatrix} = \begin{pmatrix} \frac{\cos \alpha_i}{\tan(\theta_{ai} + \alpha_i)} + \sin \alpha_i & \sin \alpha_j \\ \sin \alpha_i & \frac{\cos \alpha_j}{\tan(\theta_{aj} + \alpha_j)} + \sin \alpha_j \end{pmatrix} \begin{pmatrix} x_{2i} \\ x_{2j} \end{pmatrix} \quad (4)$$

where the subscripts i and j represent the two orthogonal components on the imaging plane.

For geometric calibration, eight pictures were taken with a white plastic ruler (Radiation Products Design, Albertville, MN) immersed and placed at different locations within the scintillator tank. The locations and orientations in which the ruler was placed (with respect to the camera frame) were left vertical and right vertical at 0 cm, 10 cm, and 20 cm from the tank window and at a slant orientation at 0 cm and 20 cm from the tank window. Examples of the images are shown in figure 3. We extracted 12 pairs of numbers representing physical distance and pixel distance using images with the ruler placed at 0 cm and 20 cm from the tank window. The parameters y_s and α were then computed by minimizing the square difference between the measured and calculated distance (using pixel distance and equation (2)). Because x is cancelled out when calculating the distance between two x_s values, the pixel locations of the tank edges were determined using images with a ruler placed at 10 cm from the tank window to calculate x .

2.3. Effects of optical artefacts on proton range determination

Proton range is determined using the depth dose measurement integral depth dose (IDD) (Zhu *et al.*, 2013). The IDD is defined as the integral dose for a single spot over a large plane perpendicular to the beam axis. In our liquid scintillator system, each pixel collected data that were already integrated in one of the dimensions. However, as shown in figure 4, the integrated data collected by the liquid scintillator system were not equal to the IDD measurement. Therefore, the depth dose measurement may vary depending on the perpendicular distance from the tank window and the lateral location of the measurement.

Unfortunately, this artefact cannot be corrected because the collected data are already integrated. To investigate the effect of the optical artefact on range measurement, we performed Monte Carlo simulations to calculate the three-dimensional dose of the spot scanning proton beam in the liquid scintillator (Sawakuchi *et al.*, 2010). Two proton energies (85.6 MeV and 161.6 MeV) were applied to obtain two distinctive spot profiles. The two proton beams were shifted laterally to five different tank locations such that the maximum dose was located at -84 mm, -42 mm, 0 mm, +42 mm, or +84 mm relative to the scintillator tank center. The dose grids were then numerically projected to the CCD camera (Hui *et al.*, 2014) and proton beam ranges were calculated and compared.

2.4. Spot scanning proton beam measurement

All measurements were carried out at the PTC-H on the scanning beam gantry. The detector was placed on the treatment couch and the beam isocenter was aligned with the center of the entrance wall surface of the scintillator tank. The gantry angle was set to 270°. Before acquiring the proton beam data, we performed geometric calibration as described in section 2.2. Spot scanning beams were delivered spot by spot into the scintillator tank perpendicular to the camera axis. For each measurement, five spots were delivered for a total of 0.15 MU, and the image exposure time was set to 0.2 seconds per frame for the CCD camera.

2.5. Water equivalency of the liquid scintillator

We investigated the water equivalency of the liquid scintillator by taking images of 161.6 MeV proton beams with plastic water placed in front of the entrance wall. Plastic water buildups with nominal thicknesses of 0 cm, 2.5 cm, 5 cm, 7.5 cm, and 10 cm were used.

Three measurements were made on three separate days. The shift of the proton beam range was then compared with the water-equivalent thickness of the plastic water buildups. The ratio of water stopping power to scintillator stopping power was then calculated to convert the range in the scintillator to the range in water.

2.6. Range measurements of the spot scanning proton beam

We measured the proton range using the liquid scintillator system and compared it with the nominal range. Because a maximum of 60 different energies can be used during each delivery from the synchrotron, two separate deliveries were used to obtain the scintillation light profiles of all 94 beam energies. One of the two deliveries contained the 60 low beam energies, ranging from 72.5 MeV to 141.6 MeV, and the other delivery contained 42 high beam energies, which ranged from 127.4 MeV to 221.8 MeV. Because the range of the high-energy proton beams was longer than the tank dimension, plastic water buildups of 10.5 cm nominal thickness were placed in front of the entrance wall to capture the scintillation light profiles of the Bragg peak of the high-energy proton beams. To evaluate the setup robustness of the liquid scintillator system, we made measurements on three different days with the system set up by three different physicists. To evaluate the consistency of the measurements between deliveries, we took three sets of measurements for each experiment.

2.7. Proton beam range calculation

The range of the spot scanning beams at the PTC-H is defined by the 90% IDD distal to the Bragg peak in water (Gillin *et al.*, 2010). An algorithm was implemented to automatically calculate the range from the collected images. In our previously published work, we have described various techniques to correct for optical artefacts (Robertson *et al.*, 2014). However, previous correction techniques were inadequate because they did not account for the new geometrical parameters. As a result, the central process described here is entirely different from our previous work, with the exception of background subtraction.

The first step was to subtract the background from the exposed images. The subtracted image was then summed vertically (orthogonal to the beam axis) to create the one-dimensional integrated signal. The algorithm then searched for the zero intercept from the derivative of the integrated signal as the location of the Bragg peak, and a cubic interpolation method was used to calculate the signal value at the Bragg peak. The pixel location of the 90% of maximum distal to the Bragg peak, p_{90} , was identified in the camera frame using linear interpolation. Finally, the physical location of the 90% of maximum, x_{90} , was calculated from p_{90} using equations (1) and (2). The range of a spot scanning proton beam in water, R , was then calculated using the following equation:

$$R = S_{\text{scin}}^{\text{water}} (x_{90} - x_{\text{edge}} + \Delta x_{\text{wall}}) + \Delta x_{\text{bu}} \quad (5)$$

where x_{edge} is the physical location of the tank edge and x_{wall} is the scintillator-equivalent thickness of the entrance wall, which was equal to 17.5 mm in the liquid scintillator system. The scaling factor, $S_{\text{scin}}^{\text{water}}$, is the ratio of stopping powers. x_{bu} is the water-equivalent thickness of the plastic water buildup placed in front of the entrance wall.

3. Results

3.1. Effects of optical artefacts on proton range determination

As shown in figure 4, light emitted further from the tank center is subject to greater optical artefacts. Under the current setup of the liquid scintillator system, the light path originating from the edge of the tank would be at an angle of 4.2° from the normal of the front window. Owing to refraction, the pixel size could change slightly at different locations on a viewing plane within the scintillator tank. Along the axis of the spot scanning beam at 10 cm from the tank window, the pixel size was 0.340 mm at the center of the tank and reduced to 0.339 mm around the edge of the tank. For notation purposes, the proton beam was traveling from negative to positive coordinates in the scintillator frame and from 0 to positive in the camera frame.

Figure 5 shows the shift in x_{90} due to the nonorthogonal data integration. We found that the discrepancy from the low-energy 85.6 MeV beam was larger than that from the high-energy 161.6 MeV beam. As expected, the difference in x_{90} between the original and the projected data increased as the distance from the center of the tank increased. Nevertheless, all of the shifts we calculated in the simulation study were less than one pixel size. This shows that range measurement using the liquid scintillator system should be minimally affected by optical artefacts. It is also interesting to note that all shifts in the simulation were negative, meaning that x_{90} obtained from the projected camera data shifted toward the source direction.

3.2. Water equivalency of the liquid scintillator

As a general practice at the PTC-H, a scaling factor of 0.995 is applied to convert the nominal thickness of the plastic water buildup to water-equivalent thickness. We used x_{90} to determine water equivalency because it was shown in section 3.1 that x_{90} was relatively insensitive to the artefact caused by nonorthogonal integration. Figure 6 shows the water-equivalent thickness of the plastic water buildup compared with its corresponding x_{90} in the liquid scintillator. The slope of the linear fit of the data was -0.991 ± 0.001 . The negative of the slope was then used as the stopping power ratio $S_{\text{scin}}^{\text{water}}$ in equation (5).

3.3. Range measurements of the spot scanning proton beam

Figure 7 shows the background-subtracted images of the delivery of the 60 low-energy proton beams. The range of the spot scanning proton beam in water was calculated using equation (5), with $S_{\text{scin}}^{\text{water}}$ equal to 0.991 and x_{bu} equal to 0 mm for the low-energy beam delivery and 104.48 mm for the high-energy beam delivery. Although 42 different energies were used for the high-energy beam delivery, the scintillator detector was able to capture only 41 beams because the 129.2 MeV beam was completely attenuated before entering the scintillator tank. Eight of the lowest energy beams, ranging from 131 MeV to 141.6 MeV, were not used for the high-energy beam range measurements because they were duplicates from the low-energy beam delivery, and the x_{90} values of their counterparts from the low-energy beam delivery were closer to the less-artefactual tank center.

The measured range was compared with the nominal range that was used at the PTC-H. On average, the difference between the measured and nominal ranges, R , was -0.67 mm. R was -1.02 mm for high-energy beam delivery and -0.47 mm for low-energy beam delivery. Interestingly, we found that R depended on the location of x_{90} . The larger x_{90} was, the more negative R was. Figure 8 illustrates the relationship between R and x_{90} . From this plot, we found that the measured range was uniformly shifted by -1.04 mm from the nominal range in the high-energy beam delivery. The shift in the low-energy beam delivery was different: -0.64 mm. In addition, we observed a linear trend between R and x_{90} ($R^2 > 0.8$ in both deliveries), and the slope extracted from the high-energy beam delivery was within 10% of that from the low-energy beam delivery. These findings suggested that we might have underestimated the scaling factor that converts nominal thickness into water-equivalent thickness for the plastic water buildup.

On the basis of the difference in the uniform shift between the high-energy and low-energy beam deliveries shown in figure 8, we adjusted the scaling factor for the plastic water to 0.999 instead of the 0.995 commonly used at the PTC-H. Although the change was very small and nearly unnoticeable from the original data in figure 6, the corrected scaling factor yielded a different slope. This resulted in a $S_{\text{scin}}^{\text{water}}$ of 0.995 ± 0.001 . Figure 9 plots R against x_{90} using the new plastic water scaling factor and $S_{\text{scin}}^{\text{water}}$. The linear trend between R and x_{90} was greatly reduced ($R^2 < 0.2$) and the constant shift was reduced to -0.18 mm and -0.16 mm for the two deliveries. On average, R was -0.20 mm for all energies; R of the high-energy beam deliveries was -0.16 mm and R of the low-energy beam deliveries was -0.22 mm.

In addition to the accuracy of the range measurement, we also investigated consistency between deliveries and setup robustness of the scintillator system. We calculated the standard deviation of the three range measurements of each beam on each measurement day. The standard deviations in all three measurement days were then averaged to compute the consistency of the scintillator tank system. The average delivery-to-delivery standard deviation was 0.04 mm. For the setup robustness, we calculated the standard deviation of the average ranges for each of the three measurement days. The average day-to-day standard deviation was 0.10 mm.

4. Discussion

In the current study, we successfully developed a geometric calibration system to accurately map a pixel location from the camera back to the physical location in the scintillator. The ability to determine the physical location provides a platform to perform various quality assurance tasks. One of these tasks is to measure the range of the spot scanning proton beam. As a result of the geometric calibration system, we were able to investigate the accuracy, consistency, and robustness of proton range measurement using the liquid scintillator system.

One of the concerns with using a liquid scintillator system for proton beam range measurement is the effect of optical artefacts. In particular, the nonorthogonal integration of data toward the edge of the picture is not correctable. Fortunately, most of the dose from the

spot scanning beam is deposited close to the beam axis; therefore, the effect is not expected to be severe. In addition, the nonorthogonal integration causes different effects on the range measurement that potentially cancel each other out. Similar to almost all other optical artefacts, nonorthogonal integration causes a decrease in the maximum value at the Bragg peak, which shifts the location of x_{90} distally away from the Bragg peak. However, at the original artefact-free x_{90} , the dose drop-off on the Bragg peak side is less than that on the side away from the Bragg peak. As a result, nonorthogonal integration causes a decrease in measurement at the original x_{90} , which shifts the range proximally toward the Bragg peak. In addition, the attenuation of the scintillation lights can also affect the light detection and hence the range measurement. The exact effect, however, depends on the lateral dose profile and the dose drop-off distal to the Bragg peak. We therefore investigated the effects with two different proton energies using simulations.

Our simulations showed that the discrepancies caused by nonorthogonal integration were higher for the proton beams with lower energy. This was due to the sharper dose drop-off and broader lateral dose profile for the proton beam with lower energy. We also found that the range measurement was slightly shifted toward the Bragg peak. Nevertheless, the accuracy of the range measurement was shown to be within one pixel size, or 0.34 mm. Therefore, the effect of optical artefacts on the range measurement is negligible. The sub-pixel accuracy could also be explained partially by the calculation of p_{90} using linear interpolation. Because the interpolation was performed at a rapid dose drop-off region, the position of p_{90} changed slowly relative to the percent change in dose. As a result, variations in pixel values due to optical artefacts did not affect the range determination.

All the differences between the measured and nominal ranges were negative. One of the possible causes of the negative difference was that we might have underestimated the scintillator-equivalent thickness of the entrance wall by about 0.17 mm. However, this difference in wall thickness was too small to detect with the liquid scintillator system. The negative slopes shown in figure 9 could be a result of the nonorthogonal data integration. As shown in figure 5, the difference between the measured range and actual range was more negative for proton beam with lower energy, and was expected to be smaller than a pixel size. In addition to optical artefacts, we anticipated some energy- and linear energy transfer-dependent artefacts that would affect the accuracy of the range measurement. However, we did not observe that results were affected much by these artefacts. Among all measurements, the maximum difference between the measured and nominal range was -0.31 mm. This suggests that the liquid scintillator system can measure the range of the spot scanning proton beam at the size of a pixel.

Delivery-to-delivery variation included variation of the proton beam, variation in the scintillation light, and uncertainty originated from the counting statistics. However, these variations are expected to be relatively small. The day-to-day variation was dominated by differences in the setup of the scintillator system. Both the translational and rotational shift of the scintillator tank relative to the proton beam could contribute to the setup variation. In our study, the scintillator system was set up carefully by different physicists on different days to increase the potential variability. Overall, we found that the system was consistent

from delivery to delivery and robust from setup to setup; both standard deviations were negligible compared with the pixel size of the liquid scintillator system.

We also found that we might have underestimated the scaling factor for the plastic water. A correction of the scaling factor from 0.995 to 0.999 yielded more accurate range measurements. In addition, we measured and calculated the stopping power ratio, $S_{\text{scin}}^{\text{water}}$, to be 0.995 ± 0.001 . This ratio matched that found in an independent study recently conducted by our group, within the respective standard deviations (Ingram *et al.*, 2015). It is worth mentioning that the original calculated $S_{\text{scin}}^{\text{water}}$ differed by only 0.4%. This shows that the liquid scintillator system requires calibration factors of 0.1% accuracy.

We have shown previously that, in theory, a profile-based iterative reconstruction method can account for all optical artefacts and reconstruct the three-dimensional light distribution. However, iterative reconstruction requires a three-camera system and is relatively time-consuming. For quality assurance of the spot scanning beam, in which only the range is required, a swift calculation is highly desirable. The proposed liquid scintillator system is well suited to this purpose.

Currently, the geometric calibration procedure requires acquisition of multiple ruler images. For the next generation of liquid scintillator, we will engrave multiple markers on the tank walls as fiducial markers. Only a single picture will then be needed for geometric calibration. This will eliminate 30 minutes of taking multiple images and further improve the efficiency of using the liquid scintillator detector system.

5. Conclusions

Although the traditional method to measure the range of spot scanning proton beams using an ionization chamber required multiple measurements, the liquid scintillator system tested in the current study can measure the range of all 94 beams in just two deliveries. In addition, the liquid scintillator system can measure proton range with submillimeter accuracy, and the measurements were shown to be consistent between deliveries and setups. Therefore, we conclude that the liquid scintillator system provides a reliable and convenient tool for proton range measurement.

Acknowledgments

We thank Dr. Narayan Sahoo for his expert opinions on spot scanning proton beams and Dr. Landon Wootton for setting up the liquid scintillator system. This project was supported in part by award number CA182450 from the National Cancer Institute. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Cancer Institute or the National Institutes of Health.

References

- Archambault L, Poenisch F, Sahoo N, Robertson D, Lee A, Gillin MT, Mohan R, Beddar S. Verification of proton range, position, and intensity in IMPT with a 3D liquid scintillator detector system. *Medical Physics*. 2012; 39:1239–1246. [PubMed: 22380355]
- Archambault L, Polf JC, Beaulieu L, Beddar S. Characterizing the response of miniature scintillation detectors when irradiated with proton beams. *Physics in Medicine and Biology*. 2008; 53:1865–1876. [PubMed: 18364543]

- Beddar S, Archambault L, Sahoo N, Poenisch F, Chen GT, Gillin MT, Mohan R. Exploration of the potential of liquid scintillators for real-time 3D dosimetry of intensity modulated proton beams. *Medical Physics*. 2009; 36:1736–1743. [PubMed: 19544791]
- Boon SN, van Luijk P, Schippers JM, Meertens H, Denis JM, Vynckier S, Medin J, Grusell E. Fast 2D phantom dosimetry for scanning proton beams. *Medical Physics*. 1998; 25:464–475. [PubMed: 9571612]
- Dhanesar S, Sahoo N, Kerr M, Taylor MB, Summers P, Zhu XR, Poenisch F, Gillin M. Quality assurance of proton beams using a multilayer ionization chamber system. *Medical Physics*. 2013; 40:092102-1–092102-9. [PubMed: 24007171]
- Fukushima Y, Hamada M, Nishio T, Maruyama K. Development of an easy-to-handle range measurement tool using a plastic scintillator for proton beam therapy. *Physics in Medicine and Biology*. 2006; 51:5927–5936. [PubMed: 17068374]
- Gillin MT, Sahoo N, Bues M, Ciangaru G, Sawakuchi G, Poenisch F, Arjomandy B, Martin C, Titt U, Suzuki K, Smith AR, Zhu XR. Commissioning of the discrete spot scanning proton beam delivery system at the University of Texas M.D. Anderson Cancer Center, Proton Therapy Center, Houston. *Medical Physics*. 2010; 37:154–163. [PubMed: 20175477]
- Hui C, Robertson D, Beddar S. 3D reconstruction of scintillation light emission from proton pencil beams using limited viewing angles—a simulation study. *Physics in Medicine and Biology*. 2014; 59:4477–4492. [PubMed: 25054735]
- Ingram SW, Robertson D, Beddar S. Calculations and measurements of the scintillator-to-water stopping power ratio of liquid scintillators for use in proton radiotherapy. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2015; 776:15–20.
- Karger CP, Jäkel O, Hartmann GH, Heeg P. A system for three-dimensional dosimetric verification of treatment plans in intensity-modulated radiotherapy with heavy ions. *Medical Physics*. 1999; 26:2125–2132. [PubMed: 10535629]
- Kossert K. Measurement of wavelength-dependent refractive indices of liquid scintillation cocktails. *Applied Radiation and Isotopes*. 2013; 82:382–388. [PubMed: 24185505]
- Nohtomi A, Sakae T, Terunuma T, Tsunashima Y, Hosono K, Hayakawa Y. Measurement of depth-dose distribution of protons by an imaging plate. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2003; 511:382–387.
- Ponisch F, Archambault L, Briere TM, Sahoo N, Mohan R, Beddar S, Gillin MT. Liquid scintillator for 2D dosimetry for high-energy photon beams. *Medical Physics*. 2009; 36:1478–1485. [PubMed: 19544763]
- Robertson D, Hui C, Archambault L, Mohan R, Beddar S. Optical artefact characterization and correction in volumetric scintillation dosimetry. *Physics in Medicine and Biology*. 2014; 59:23–42. [PubMed: 24321820]
- Sawakuchi GO, Mirkovic D, Perles LA, Sahoo N, Zhu XR, Ciangaru G, Suzuki K, Gillin MT, Mohan R, Titt U. An MCNPX Monte Carlo model of a discrete spot scanning proton beam therapy nozzle. *Medical Physics*. 2010; 37:4960–4970. [PubMed: 20964215]
- Vatnitsky SM. Radiochromic film dosimetry for clinical proton beams. *Applied Radiation and Isotopes*. 1997; 48:643–651. [PubMed: 9204523]
- Zhu XR, Poenisch F, Lii M, Sawakuchi GO, Titt U, Bues M, Song X, Zhang X, Li Y, Ciangaru G, Li H, Taylor MB, Suzuki K, Mohan R, Gillin MT, Sahoo N. Commissioning dose computation models for spot scanning proton beams in water for a commercially available treatment planning system. *Medical Physics*. 2013; 40:041723-1–041723-15. [PubMed: 23556893]

Figure 1. Top view of the liquid scintillator detector system. The wall was made of polyoxymethylene (POM) and the window material was poly(methyl methacrylate) (PMMA). The photon generated by the liquid scintillator is collected by the charge-coupled device (CCD) camera.

Figure 2.

Two-dimensional representation of the light path from point $\times$ in the scintillator to the camera. The location $x_s = x1 + x2 + x3$ in the scintillator frame at a depth of y_s from the tank window is projected to $x_p = f_c \tan(\theta_a + \alpha)$ in the camera frame. The translational shift, x , is equal to the camera center ($\square$) minus the scintillator center ($\circ$).

Figure 3.

Images of a ruler immersed into the scintillator for geometric calibration. (a) Vertical ruler placed on the right side of the tank and pressed against the tank window (0 cm from the tank window). (b) Vertical ruler placed on the left side of the tank and pressed against the back wall (20 cm from the tank window). (c) Ruler at a slant orientation pressed against the back wall. (d) Vertical ruler pressed against the left side of the wall halfway between the front window and the back wall (10 cm from the tank window).

Figure 4.

An illustration of the differences between integral depth dose (IDD) measurement and measurement using the liquid scintillator system. For IDD measurements, each data point represents the integral dose in a perpendicular plane, and a plane of the same shape and volume is used regardless of location in the tank. For measurements obtained using the liquid scintillator system, the shape and volume of the integrated plane are not orthogonal to the beam axis and are different depending on the location of the measurement.

Figure 5.

Difference in the physical locations of 90% of maximum, x_{90} , at different locations in the scintillator. The difference was computed by subtracting x_{90} calculated from the projected camera data from x_{90} calculated from the original volumetric grid. The dotted lines indicate the width of 1 pixel.

Figure 6.

Water-equivalent thickness (WET) of the plastic water buildup compared with the corresponding location of the 90% of maximum (x_{90}) of the proton beam in the liquid scintillator. Using a scaling factor of 0.995 to convert the nominal plastic water thickness into water-equivalent thickness, we found that the slope of the resulting data was -0.991 ± 0.001 .

Figure 7.

Image of the 60 low-energy (72.5 MeV to 141.6 MeV) proton beams collected by the liquid scintillator detector system. Only the center 11 pixels at the beam axis are shown for each beam. The red line represents the pixel location of the 90% of maximum (p_{90}) for each energy. Some proton beams were less intense because some of their five spots were delivered in between camera exposures and were not captured. However, because the percentage was used to calculate proton beam range, the hypointensity did not cause any abnormality in the calculation of p_{90} .

Figure 8.

Shifts between the measured and nominal ranges (ΔR) at different locations in the scintillator. $\square$ represents data from the low-energy beam delivery and $\circ$ represents data from the high-energy beam delivery. The range was calculated using equation (5) with the plastic water scaling factor = 0.995 and the resulting $S_{\text{scin}}^{\text{water}} = 0.991$. R was computed by subtracting the average measured range from the nominal range, and the location in the scintillator was defined at the 90% of maximum (x_{90}). Each data point represents one unique proton energy. The x_{90} of proton beam with higher energy located further toward the positive direction of the tank and vice versa. The high-energy beam delivery included a 10.5 cm nominal plastic water buildup. A linear fit was performed on the two sets of data. The best fitted lines for the low-energy beam delivery (dash line) and high-energy beam delivery (solid line) with their respective equations are shown with the data points.

Figure 9.

Shifts between the measured and nominal ranges (ΔR) at different locations in the scintillator. $\square$ represents data from the low-energy beam delivery and $\circ$ represents data from the high-energy beam delivery. The range was calculated using equation (5) with the plastic water scaling factor = 0.999 and the resulting $S_{\text{scin}}^{\text{water}} = 0.995$. ΔR was computed by subtracting the average measured range from the nominal range, and the location in the scintillator was defined at the 90% of maximum (x_{90}). Each data point represents one unique proton energy. The x_{90} of proton beam with higher energy located further toward the positive direction of the tank and vice versa. The high-energy beam delivery included a 10.5 cm nominal plastic water buildup. A linear fit was performed on the two sets of data. The best fitted lines for the low-energy beam delivery (dash line) and high-energy beam delivery (solid line) with their respective equations are shown with the data points.