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Passively scattered proton beam entrance dosimetry with a plastic scintillation detector

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Abstract

We tested the feasibility of using plastic scintillation detectors (PSDs) for proton entrance dosimetry. A PSD built with BCF-12 scintillating fiber was used to measure the absolute entrance dose of a passively scattered proton beam for energies ranging from 140 MeV to 250 MeV, and for a range of spread out Bragg peak (SOBP) widths at 2 energies, to quantify the effect of ionization quenching on the response of the detector and to determine the necessity of Cerenkov radiation correction in proton beams. The overall accuracy and precision of the PSD was evaluated by measuring lateral beam profiles and comparing the results with profiles measured using film. The PSD under-responded owing to ionization quenching, exhibiting approximately a 7% loss of signal at the highest energy studied (250 MeV) and a 10% loss of signal at the lowest energy studied (140 MeV). For a given nominal energy, varying the SOBP width did not significantly alter the response of the PSD. Cerenkov radiation contributed negligibly to the PSD signal and can be safely ignored without introducing more than 1% error in the measured dose. Profiles measured with the PSD and film agreed to within the uncertainty of the detector, demonstrating good relative accuracy. Although correction factors were necessary to account for ionization quenching, the magnitude of the correction varied minimally over a broad range of energies; PSDs therefore represent a practical detector for proton entrance dosimetry.

I. Introduction

The popularity of proton therapy as a treatment modality is growing rapidly owing to advantageous characteristics of protons such as a finite range and a characteristic dose depth curve wherein dose is concentrated at the end of that range. As a result, protons are useful for highly targeted therapy with low integral dose to normal tissue. However, these unique benefits bring with them important considerations when treating patients.

One such consideration is the lack of skin sparing. Whereas therapeutic photon beams exhibit a skin sparing effect owing to a buildup of secondary electrons over a small distance, protons interact directly and do not have this quality. Furthermore, proton treatments typically use fewer beams than photon treatments (particularly compared with intensity-modulated radiation therapy and volumetric modulated arc therapy), which exacerbates the lack of skin sparing. As a result, patients commonly experience skin reactions such as

radiation dermatitis (Chang *et al.* 2011, Sejpal *et al.* 2011, Zenda *et al.* 2011). Skin dose is therefore an important consideration in proton therapy and can even be a limiting factor when planning treatment for sites such as the lung or breast (Whaley *et al.* 2013).

In vivo entrance dosimetry (also called skin dosimetry) can be used to investigate skin reactions. Comparing accurate measurements of delivered skin dose with skin reactions in individual patients can help physicians better quantify risks of toxic effects. These risks could then be used to refine treatment strategies and evaluate treatment plans. As an added benefit, *in vivo* entrance dosimetry can catch gross errors in treatment administration that result in a deviation from the planned entrance dose (such as incorrect SSD, malfunction of the delivery system dose monitor, etc.).

A few detectors have already been used to measure skin dose during treatment. The commercial MOSFET detector, OneDose, has been used with success (Cheng *et al.* 2010). However, OneDose has a few drawbacks, including the single-use nature of each detector (requiring calibration of a few detectors from each batch to account for detector variability) and variation in response depending on the angle and radiation energy. Thermoluminescent dosimeters have also successfully been used to measure proton dose with an accuracy of $\pm 3\%$ (Zullo *et al.* 2010), but the necessity of waiting 2 to 3 days before reading the dose is not ideal.

Plastic scintillation detectors (PSDs), however, do not suffer from any of the shortcomings listed above. They can be reused extensively, do not exhibit an orientation-dependent response, and provide real-time results. PSDs can be very small (~1 mm in diameter) and are water-equivalent (Beddar *et al.* 1992a, 1992b). PSDs can therefore make measurements in a beam without significantly perturbing it (Beddar *et al.* 2001). Finally, PSDs have been used for *in vivo* dosimetry in photon-based therapy already (Wootton *et al.* 2014). Although there are some drawbacks to using PSDs, such as ionization quenching, which we address in the current study, PSDs are nonetheless promising candidates for *in vivo* entrance dosimetry in proton therapy.

The aims of this study are threefold, with the overall goal of establishing the feasibility of using PSDs for *in vivo* entrance dosimetry for a passively scattered proton beam. The first is to evaluate the effect of ionization quenching on a PSD used for entrance dosimetry. Ionization quenching is an under-response of the PSD due to high linear-energy transfer associated with heavy charged particles (Birks 1964). Previous PSD studies have evaluated this effect in the context of relative dosimetry using Monte Carlo and measurements (Torrisi 2000, Archambault *et al.* 2008, Wang *et al.* 2012), but measurements have not been performed to establish the effect of quenching on absolute dosimetry and the practicality of correcting it. The second is to determine whether the generation of Cerenkov radiation in the PSD can be safely ignored. Cerenkov radiation is most intense at the entrance of a proton beam (Glasser *et al.* 2014), so although previous studies have found that Cerenkov radiation can be ignored for measurements at depth, measurements at the entrance of the beam merit investigation. The final aim is to investigate general dosimetric characteristics of PSDs used for entrance dosimetry, such as accuracy and precision.

II. Methods and Materials

II.A. Detectors

A PSD was fabricated from 3 mm of BCF-12 scintillating fiber (Saint-Gobain Crystals, Hiram, OH) with a diameter of 1 mm; the scintillating fiber was optically coupled to 3 m of clear plastic optical fiber. A photodiode was used to convert the scintillation light transmitted by the optical fiber into electrical charge. The photodiode had dual channels sensitive to different wavelength so that it could quantify the signal in the blue and green portions of the spectrum separately. This allowed for analysis via the chromatic removal technique (Fontbonne *et al.* 2002, Frelin *et al.* 2005, Archambault *et al.* 2006), which is necessary for eliminating the light contribution from Cerenkov radiation in the plastic optical fiber (Beddar *et al.* 1992c). The photodiode was chosen because it could be placed in the treatment vault, thus converting scintillation light to an electric signal near the point of measurement. This offered an advantage over charge-coupled device cameras and photomultiplier tubes, 2 other devices commonly used for light quantification, which are more sensitive to radiation and should be placed outside of the vault. In such a setup, a significant loss of signal would result from attenuation of scintillation light as it passed through the long optical fiber required to reach outside the vault. In contrast, minimal signal is lost over a triaxial cable, as was used in our setup. The signals from the photodiode were measured using a SuperMax electrometer (Standard Imaging, Madison, WI).

The PSD was calibrated on a Cobalt 60 unit, chosen for the high degree of accuracy and precision achievable owing to the highly stable and well-characterized output of Cobalt 60, using the chromatic removal technique (Fontbonne *et al.* 2002, Frelin *et al.* 2005, Archambault *et al.* 2006). The resulting calibration was independently verified by irradiating the PSD with a known dose on a Varian linear accelerator, and the calibration was found to be accurate to within 1%.

For absolute dose comparison in the proton beam, a calibrated parallel plane ion chamber (PTW TN23343, PTW, Freiburg, Germany) was used (International Atomic Energy Agency TRS 398 Report 2001), with an entrance window thickness of 0.9 mm (acrylic) and an active volume of 0.02 cm³. All ion chamber readings were corrected for ambient pressure and temperature. The ion chamber was operated at +300V and the charge was read out using a Scanditronix/Wellhofer electrometer (Scanditronix Wellhofer North America, Bartell, TN). Background subtraction was used for both the SuperMax and Wellhofer electrometers to ensure accuracy. The absolute dose was calculated using the method described in the International Atomic Energy Agency TRS 398 Report (2001).

Finally, radiochromic film was used to measure lateral profiles of proton beams for comparison with profiles measured using the PSD (Vatnitsky 1997, Niroomand-Rad *et al.* 1998, Zhao and Das 2010). Gafchromic EBT3 film (Ashland Inc., Covington, KY) was chosen for its large dynamic range and ease of use (i.e., no development necessary). Calibration curves were generated for each energy at which film was used to measure profiles. Films were scanned before irradiation and 48 hours after irradiation on an Epson flatbed scanner (Epson Corp., Suwa, Japan) in transmission mode at a resolution of 400 dpi. The pre-irradiation film images were used for background subtraction. Per manufacturer

specifications, only the red channel of the scanned image was used because of its high sensitivity in the range of doses used in the study.

II.B. Setup

The passive scattered beam in the fixed beamline treatment vault at our institution's proton center was used. A brass aperture with a 12×12 cm cutout in the center shaped the field for all measurements. The full range of energies available on this beamline (140 MeV to 250 MeV) were investigated in this study.

Acrylic blocks were placed on the treatment couch with the surface of the blocks at an SSD of 270 cm (a 48 cm air gap). For measurements using the ion chamber, an acrylic block with a custom-milled cavity designed to hold the ion chamber surface flush with the surface of the block was used. For measurements with film, a plain acrylic block was used and the film was affixed to it with tape. When these blocks were switched out or other adjustments were made that might disturb the setup, the SSD was re-verified using the treatment positioning lasers.

When direct comparisons were made between ion chamber measurements and PSD measurements, the ion chamber was centered on the beam's central axis and the PSD was attached to the surface of the block immediately adjacent to the ion chamber (rather than directly in front of the ion chamber). This was done because the charge measured by the ion chamber increased by 1% when the PSD was placed in front of it, relative to the charge measured when the PSD was placed adjacent to the ion chamber, for a 140-MeV beam. The PSD response was the same in both positions. For a 250 MeV beam, no change was observed in the PSD or ion chamber signal between the 2 scenarios (i.e., PSD in front of the ion chamber or adjacent to it). Placing the PSD adjacent to the ion chamber allowed concurrent measurement of the entrance dose and eliminated fluctuations in beam output as a contributor to differences between the dose measured with the ion chamber and the dose measured with the PSD.

A diagram of the setup is provided in Figure 1.

II.C. Ionization Quenching Characterization

First, absolute entrance dose on the central axis of the beam was measured using the ion chamber and the PSD for a range of nominal proton energies between 140 MeV and 250 MeV, with a fixed spread out Bragg peak (SOBP) width of 8 cm. The purpose of this was to quantify the effect of ionization quenching on the PSD as a function of beam energy. Three irradiations of 50 MU were performed at each energy. The difference between the dose measured with the ion chamber, considered to represent the correct dose, and the dose measured with the PSD was calculated for each irradiation. The mean and standard deviation of these differences were then calculated. The difference was also used to calculate correction factors for the dose measured with the PSD.

Next, absolute entrance dose was measured for a variety of SOBP widths at fixed energies of 225 MeV and 140 MeV. The purpose of this was to determine what effect the introduction of low-energy protons, necessary for widening the SOBP, had on the quantity

of ionization quenching in the PSD. SOBP widths of 1, 4, 8, 12, and 16 cm were used for the 225 MeV beam, and widths of 1, 2, 4, 8, and 10 cm were used for the 140 MeV beam. (One centimeter is the minimum SOBP width allowed by our system, 16 cm is the maximum SOBP width allowed for the 225 MeV beam, and 10 cm is the maximum SOBP width for the 140 MeV beam.) Again, 3 irradiations of 50 MU each were performed for each setting, and the mean difference and standard deviation were computed.

II.D. Cerenkov Radiation Removal

Next, the contribution of Cerenkov radiation was investigated. The PSD was first irradiated in the normal setup and then irradiated again with extra optical fiber coiled into the beam to increase the generation of Cerenkov radiation. All other conditions were held constant. The normal setup had approximately 6 cm of fiber in the field, whereas roughly 20 cm of fiber was coiled into the field for the second irradiation. This was done at 225 and 140 MeV, and the increase of signal in each channel was quantified as an indicator of Cerenkov light produced in the clear optical fiber.

To quantify the effect of neglecting Cerenkov production on the accuracy of the system, the PSD was calibrated at the lowest energy assuming no Cerenkov radiation (i.e., a single calibration factor was generated, equal to the ratio of the dose delivered to the total light output). This calibration was used to recalculate the dose for the measurements performed in section II.C. The dose calculated at each energy level was then corrected for ionization quenching using the results from the previous section; the remaining discrepancy was therefore assumed to be an artifact of Cerenkov radiation contamination.

II.E. Accuracy and Precision of Relative Dose Measurements

Lateral half profiles were measured using the PSD for the 225 MeV and 140 MeV beams and compared with profiles measured using film. The purpose of this measurement was to validate the relative accuracy of the PSD, specifically in the steep dose gradient of the beam penumbra. The PSD profile was acquired by centering the detector's active volume on the central axis of the beam using the lasers. The PSD was oriented vertically so that the lateral resolution corresponded to the diameter of the scintillating fibers (1 mm) and not the length (3 mm). At each position, 3 separate irradiations of 50 MU were measured, and then the couch was translated laterally to move the PSD through the field with high accuracy and precision.

The EBT3 radiochromic film was cut into long strips approximately 4 cm tall and 20 cm wide to encompass the entire lateral extent of the beam. A vertical mark was placed on the film with marker above the central axis of the beam, and 2 lateral marks were placed on either side of the central axis of the beam using the gantry lasers. The lateral marks were used in analysis to account for rotation of the film strip relative to the beam. The vertical mark indicated the precise center of the profile, to facilitate direct comparison between the film profile and the PSD profile. As mentioned previously, the film was scanned before irradiation and 48 hours after irradiation. The red channel of the pre-irradiation image was subtracted from the post-irradiation red-channel, and the pixel values were converted to dose using a previously acquired calibration curve with a computer script. Pixel-by-pixel dose

values were averaged in a narrow vertical band, approximately 2 cm tall, centered on the lateral plane to improve the signal-to-noise ratio (SNR). No smoothing was done along the profile. The central mark on the film and the scanner resolution were used to assign absolute locations (i.e., distance from 0) for each point in the profile. The PSD measurements were normalized to the measurement on the central axis, and the film measurements were normalized to the flat region at the center of the profile.

Finally, the SNR of the PSD was measured as a function of dose at 225 MeV and 140 MeV. Three sets of 3 irradiations were measured using 1, 10, and 100 MU, for a total of 9 irradiations at each energy. The SNR was calculated as the standard deviation of the measurements divided by the average value for each energy and MU combination.

III. Results

III.A. Response vs Range

The difference in doses measured by the PSD and the ion chamber is shown in Figure 2. For energies between 200 and 250 MeV, the PSD under-responded by 7% with an average uncertainty of $\pm 1\%$ (with uncertainty expressed in percentage points, i.e., the under-response of the PSD is between 6% and 8%). The under-response increased to approximately $10\% \pm 1\%$ of the dose measured by the ion chamber for energies between 180 and 140 MeV. Within these energy ranges, the loss of signal owing to ionization quenching was stable (i.e. it did not vary by more than 1%).

III.B. Response vs SOBP Width

The dose measured by the PSD relative to the dose measured by the ion chamber did not change appreciably as a function of SOBP width for either the 225 MeV beam or the 140 MeV beam, with one possible exception. The dose measured by the PSD for the 10 cm wide SOBP configuration of the 140 MeV beam, which has a 10 cm range in water, decreased to 89% of the dose measured by the ion chamber, compared with 90% of the dose measured by the ion chamber for other SOBP widths. However, given the uncertainty of the measurements, the decrease to 89% may not be due to the SOBP width. The dose measured by the PSD was approximately 93% of the dose measured by the ion chamber for the 225 MeV beam and 90% of the dose measured by the ion chamber for the 140 MeV beam, in good agreement with the measured values from the previous section. Detailed results are presented in Figure 3.

III.C. Cerenkov Radiation Contribution

Increasing the optical fiber in the proton field from 6 cm to approximately 20 cm resulted in a small change in the channel readings for the 140 MeV beam. A 0.2% increase in blue channel signal, a 2.5% increase in green channel signal, and an overall 0.9% increase in light output was observed. The same procedure resulted in a slightly larger change for the 225 MeV beam: a 1.7% increase in blue channel signal, a 3.1% increase in green channel signal, and an overall 2.1% increase in light output. These results are presented in Figure 4. The absolute signal of the blue channel was about twice that of the green channel, which is why the blue channel contributed more to the overall increase in signal.

Calibrating the PSD on the basis of total light output (i.e., assuming no Cerenkov radiation) per dose revealed that the contribution of Cerenkov to measured dose was very small. This calibration factor was used to calculate dose measured at higher energies, and after ionization quenching was accounted for, the measured dose did not deviate from the actual dose by more than 1% at any energy (Figure 5).

III.D. Profile Measurements

The lateral beam profiles measured using the PSD were in excellent agreement with those measured using film for both the 225 MeV beam and the 140 MeV beam; the film measurements fell within the uncertainty of the PSD measurements. Both profiles are plotted in Figure 6.

III.E. SNR

For the 225 MeV beam, the SNR value (calculated as the standard deviation of repeated measurements divided by the average signal) was 7 for the 1-MU irradiation, 30 for the 10-MU irradiation, and 385 for the 100-MU irradiation, with 1 MU corresponding to a dose of 0.67 cGy at the beam entrance (1.09 cGy at the SOBP center).

For the 140 MeV beam, the SNR values were 19 for the 1-MU irradiation, 169 for the 10-MU irradiation, and 294 for the 100-MU irradiation, with 1 MU corresponding to 0.63 cGy at the beam entrance (0.78 cGy at the SOBP center). The noise, quantified by taking the standard deviation of sets of 3 measurements, was consistent regardless of the dose delivered (approximately 0.2 cGy). Thus, the SNR of the detector appeared to be largely a function of the dose.

IV. Discussion

Our results showed that although ionization quenching correction factors were needed for PSD dosimetry, the PSD measured the lateral beam profile accurately and SOBP width variation and Cerenkov radiation contributed negligibly to the performance of the PSD, indicating that PSDs represent a practical solution for proton entrance dosimetry.

As expected, ionization quenching was found to be responsible for a nonnegligible loss of signal in the PSD at all energies. This result is in agreement with the literature; Archambault *et al.* (2008) performed Monte Carlo calculations to determine linear energy transfer in proton beams and used the Birks quenching correction formula to predict an under-response of 13% at the entrance for energies between 150 MeV and 250 MeV on the basis of the Birks formula. This under-response is greater than what we observed. However, Archambault *et al.* applied the semi-empirical Birks formula under different conditions than those used in our study. Thus, some discrepancy in the absolute value of the under-response is not surprising.

Although ionization quenching effects are present at all proton energies, the correction required to determine the entrance dose is straightforward relative to those required to measure depth-dose curves. For depth-dose measurements, Monte Carlo is used to determine linear energy transfer values for a proton beam of interest, and then these values are used to

calculate quenching correction factors using the Birks formula. These factors are then applied to measured values. The quenching correction factors increase rapidly at the end of a proton beam, so for measurements to be corrected effectively, the position of the PSD in the beam must be known with a high degree of accuracy. In contrast, our results show that one correction factor could be used with an accuracy of $\pm 1\%$ for nominal beam energies of 200 MeV to 250 MeV for all SOBP widths. A second correction factor would be sufficient for beams with energies of 140 MeV to 180 MeV with the same 1% accuracy.

Furthermore, the range of correction factors for entrance dosimetry is narrow compared with those required for depth-dose measurements. In our study, ionization quenching at the surface resulted in 7% to 11% loss of signal for all energies and SOBPs considered. In contrast, the ionization quenching calculated by Archambault *et al.* (2008) in a 150 MeV pristine beam resulted in 13% loss of signal at the entrance and 30% loss of signal at the Bragg peak.

Variation in the SOBP width did not have an observable effect on ionization quenching. In the 140 MeV beam, the under-response increased to 11% from 10% for the widest SOBP, but because of the uncertainty in the measurements, it cannot be definitively concluded that this effect is real. However, there is a physical reason to suspect that the effect might be real: the SOBP width was equal to the beam range in water, bringing the most proximal Bragg peak to the surface. Regardless, even if the effect is real, the difference is very small. The likely reason for the lack of influence of the SOBP width on ionization quenching is the energy distribution of protons required to achieve the SOBP. The highest energy protons, corresponding to the most distal portion of the beam, contribute more dose at the surface than any other portion of the beam. This is because the highest energy protons must supply the full dose at the distal end of the beam, whereas lower energy protons (corresponding to more proximal regions of the beam) need only supply the difference between the desired dose and the dose contributed by higher energy protons. For this reason, for very wide beams, the most proximal Bragg peak, or the lowest energy component of the SOBP, contributes only a very small amount to the entrance dose. This is illustrated in Figure 7.

Cerenkov radiation was demonstrated to be essentially negligible for our setup, in agreement with prior studies using PSDs for relative dosimetry. A relatively large field was used and the measurements were performed at the surface, which constitute a worst-case scenario in terms of Cerenkov contamination. Therefore, it is unlikely that Cerenkov radiation is an important consideration when using PSDs for proton beam dosimetry under any circumstances. The source of the Cerenkov radiation is not the protons themselves because the threshold energy (determined as the energy necessary for the protons to move faster than the local speed of light in media) for Cerenkov production is approximately 320 MeV. However, the required energy for electrons to produce Cerenkov radiation is only 0.175 MeV owing to the smaller mass of electrons relative to protons (these calculations assume an index of refraction of 1.5, which corresponds to PMMA, polyethylene, and many other plastics that are used as optical fiber). The maximum secondary electron energy for a given proton energy can be calculated (Beringer *et al.* 2012), and doing so reveals that 250 MeV and 140 MeV monoenergetic proton beams can produce electrons with maximum energies of 0.616 (250 MeV beam) and 0.352 MeV (140 MeV beam). Thus, some of the secondary

electrons produced will be capable of producing Cerenkov radiation. However, most of the secondary electrons produced will be of much lower energy and will not produce Cerenkov radiation. For this reason, the quantity of Cerenkov radiation produced in proton beams is much lower than that of photon or electron beams.

The profile measurements in our study demonstrate the high spatial resolution and sensitivity of the PSD, without which accurate measurements of the beam penumbra would be difficult. Furthermore, the good agreement between profiles measured using the PSD and those measured using film at all locations implies that the results obtained on the central axis of the beam (with regard to ionization quenching and Cerenkov radiation) can be generalized to a PSD measuring the entrance dose off axis. If this were not the case, the relative profiles would not be expected to agree.

The SNR of the PSD was reduced by ionization quenching (an unsurprising result given that quenching reduces the scintillation signal), but the SNR was still excellent (>200) at all energies for moderate doses (100 MU corresponded to approximately 60 cGy).

One limiting factor in the current study is that most of the results are obtained by subtracting the dose measured with the PSD from the dose measured with the ion chamber to obtain a difference, increasing the relative uncertainty. Both the ion chamber and the PSD measured dose with high precision, but this subtraction resulted in a quantity that was both smaller and noisier than the dose measured by either the PSD or the ion chamber. This made obtaining highly precise results difficult and limited the effects that could be observed. For example, if more precise results were obtained, one might expect to see a small but definite increase in ionization quenching for increasing SOBP widths. Nonetheless, the uncertainty in the results obtained was generally $\pm 1\%$, which is adequate for dosimetry.

The possibility of direct calibration in the proton beam should also be considered. Ionization quenching would be directly accounted for in the calibration, and because the variation in quenching for different energies is slight, a calibration at one energy may be appropriate for measurements at other nearby energies. A direct calibration would also be expected to have an improved SNR, because the total spectrum rather than the difference between 2 portions of the spectrum would constitute the signal. This is possible because of the minimal contribution of Cerenkov light to the total light output.

One logical extension of this work is entrance dosimetry of scanning beams. Scanned beams deliver dose using a large number of pristine pencil beams. Each distinct energy will have a quenching correction factor associated with it. The results of this study suggest that the correction factor will not change greatly as a function of energy. However, determining an appropriate correction factor for an arbitrary combination of pencil beams used in a treatment plan may present a challenge. Additionally, some treatment plans will incorporate beams of lower energies that were studied in this work for which correction factors will need to be determined. Using PSDs for entrance dosimetry of scanning beams is likely a tractable problem, but would require additional investigation.

Finally, because the PSD has been demonstrated to be a good *in vivo* detector in prior studies and because we have shown here that PSDs can be used for entrance dosimetry for

proton fields without undue difficulty, we believe that PSDs are a good candidate for *in vivo* entrance dosimetry in patients undergoing proton therapy. PSDs are small and water equivalent, so the beam should not be perturbed in a clinically significant manner, and skin dose results would be available immediately following treatment. This may prove helpful in assessing the risk of radiation dermatitis for patients undergoing treatment. PSDs for *in vivo* entrance dosimetry would also be capable of detecting gross errors during dose delivery. Unfortunately, other treatment parameters such as beam range could not be verified with such a system. Nonetheless, we believe that PSDs could serve as a useful tool to perform *in vivo* entrance dosimetry.

V. Conclusion

It has been demonstrated that a PSD calibrated in a photon beam can be used to measure entrance dose in a proton beam accurately, with the application of quenching correction factors. The contribution of Cerenkov radiation has been shown to be minimal, permitting a direct dose to light calibration. As expected, PSDs exhibit ionization quenching when measuring entrance dose for proton beams, and the magnitude of this effect varies as the energy of the beam changes. We found that ionization quenching resulted in approximately 7% PSD under-response relative to ion chamber measurements in a 250 MeV beam, and 10% under-response in a 140 MeV beam. Varying the SOBP width had a minimal effect on the magnitude of quenching, despite decreasing the average proton energy at the surface. The PSD was able to measure proton beam profiles at high and low energies with good precision and accuracy. The SNR of the detector decreased from 400 to 300 between 100 MU irradiation of 225 MeV and 140 MeV beams, owing to the loss of signal caused by quenching. Finally, we demonstrated that Cerenkov radiation correction methods such as chromatic removal can safely be ignored for our setup without introducing more than 1% error into the measured dose.

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Figure 1.

Diagram of the setup with the ion chamber and plastic scintillation detector, side view (A) and beams-eye view (B). The phantom consisted of acrylic blocks. The ion chamber was placed in a custom milled cavity (dotted line in figure) that placed the chamber entrance flush with the phantom surface. The center of the ion chamber was placed on the beams central axis. The PSD was placed adjacent to the ion chamber so as not to affect the dose measured by the ion chamber.

Figure 2.

Plastic scintillation detector under-response relative to the dose measured with a plane-parallel ion chamber at the surface of an acrylic block. The under-response increased from 7% at 250 MeV to 10% at 140 MeV and was fairly constant for energies above 200 MeV and below 180 MeV. Error bars indicate 1 standard deviation.

Figure 3.

Plastic scintillation detector (PSD) under-response relative to a plane-parallel ion chamber for a variety of spread out Bragg peak (SOBP) widths. No meaningful change was observed in the PSD response for the 225 MeV beam. For the 140 MeV beam, the under-response was consistently 10% for all but the 10-cm SOBP, for which it increased to 11%. However, the uncertainty in the measurements precludes definitively concluding that this effect is real.

Figure 4.

Percent change in the blue and green channel output and overall light output when approximately 3 times as much fiber is irradiated (20 cm vs 6 cm). Although the total increase in light output doubled between the 140 MeV and 225 MeV beams, the increase was small in both cases (2% and 1%), indicating that although Cerenkov radiation was present, it contributed very little to the total light signal.

Figure 5.

Error introduced into dose measurements by ignoring Cerenkov radiation. A simple total light to dose calibration was performed at 140 MeV and retroactively applied to dose measurements at higher energies. This introduced less than 1% error to the measured dose.

Figure 6.

Film and plastic scintillation detector (PSD) measurements of the lateral beam profile acquired at 225 MeV and 140 MeV. Note that the plots share the same x-axis values. Horizontal error bars represent a ± 1 mm uncertainty in the positioning of the PSD. Vertical error bars are 1 standard deviation of the PSD measurements. The film measurements agree to within the uncertainty of the PSD measurements.

Figure 7. Dose deposition curves for a hypothetical SOBP and its constituent pristine Bragg peaks plotted side by side (a) and stacked from most distal to most proximal (b). It can be seen that the most distal Bragg peak contributes disproportionately more entrance dose than other beams (left side of the plot), and that the contribution to entrance dose by each increasingly proximal Bragg peak diminishes.