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Determination of the quenching correction factors for plastic scintillation detectors in therapeutic high-energy proton beams

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Abstract

The plastic scintillation detectors (PSD) have many advantages over other detectors in small field dosimetry due to its high spatial resolution, excellent water equivalence and instantaneous readout. However, in proton beams, the PSDs will undergo a quenching effect which makes the signal level reduced significantly when the detector is close to Bragg peak where the linear energy transfer (LET) for protons is very high. This study measures the quenching correction factor (QCF) for a PSD in clinical passive-scattering proton beams and investigates the feasibility of using PSDs in depth-dose measurements in proton beams. A polystyrene based PSD (BCF-12, $\phi 0.5\text{mm} \times 4\text{mm}$) was used to measure the depth-dose curves in a water phantom for monoenergetic unmodulated proton beams of nominal energies 100, 180 and 250 MeV. A Markus plane-parallel ion chamber was also used to get the dose distributions for the same proton beams. From these results, the QCF as a function of depth was derived for these proton beams. Next, the LET depth distributions for these proton beams were calculated by using the MCNPX Monte Carlo code, based on the experimentally validated nozzle models for these passive-scattering proton beams. Then the relationship between the QCF and the proton LET could be derived as an empirical formula. Finally, the obtained empirical formula was applied to the PSD measurements to get the corrected depth-dose curves and they were compared to the ion chamber measurements. A linear relationship between QCF and LET, i.e. Birks' formula, was obtained for the proton beams studied. The result is in agreement with the literature. The PSD measurements after the quenching corrections agree with ion chamber measurements within 5%. PSDs are good dosimeters for proton beam measurement if the quenching effect is corrected appropriately.

Keywords

plastic scintillation detectors; proton beam; quenching; LET; Monte Carlo simulations

1. Introduction

Proton therapy has become increasingly popular nowadays (Bonnett 1993) due mainly to the presence of the Bragg peak (BP) in the depth dose distributions of the radiation beam. There is essentially no radiation energy deposition beyond the depth of BP and this makes proton beams very helpful in treating tumor targets where critical organs or tissues exist in close proximity. Because the range of a proton beam is very sensitive to the density and composition of the materials it traverses, water equivalence and high spatial resolution are important in proton beam dosimetry. Scintillation detectors have many advantages over other radiation detectors including their excellent water equivalence, high spatial resolution, and instantaneous readout, etc (Beddar et al. 1992b, c). Plastic scintillator detectors (PSD) are made of a polymerized solution containing scintillation molecules and have been shown extremely useful for small field dosimetry (Klein et al. 2010, Gagnon et al. 2012, Morin et

al. *in press*). Proton beams, and other heavy ion particle beams, have variable linear energy transfer (LET) ranging from few MeV/cm to tens of MeV/cm. The main problem of employing PSD for proton beams is the *quenching* effect (Torrissi 2000, Archambault et al. 2008), which refers to the situation where the light production efficiency for PSD is degraded because of the high ionization density caused by particles of high LET. Close to the depth of BP and beyond, the energy of protons is lowered so that the radiation beams exhibits high LET values. Thus, if a PSD is used to measure the depth dose curve, the measured dose would be substantially under-estimated at depths close to and beyond the BP.

Torrissi (2000) studied the quenching effect for a polyvinyltoluene based PSD in air irradiated by proton beams of energy up to 60 MeV. The amount of the quenching effect for PSD is directly related to the LET of radiation particles (Birks 1964, Torrissi 2000). Assuming dY/dx is the luminescence yield per unit length for the PSD given in 1/cm, S is the light production efficiency for the PSD given in 1/MeV, and dE/dx is the proton stopping power in MeV/cm, then the Birk's empirical formula gives (Birks 1964, Torrissi 2000)

$$\frac{dY}{dx} = \frac{S \cdot \frac{dE}{dx}}{1 + kB \cdot \frac{dE}{dx}} \quad (1)$$

where kB is the quenching factor for the PSD and its unit is the inverse of dE/dx units, making the denominator of (1) dimensionless. If kB is 0, then no quenching effect is present and the luminescence yield per unit length is directly proportional to the proton stopping power. A better experimental fit can be obtained by including the second order approximation (Craun and Smith 1970) for low energy proton beams when LET is very large,

$$\frac{dY}{dx} = \frac{S \cdot \frac{dE}{dx}}{1 + kB \cdot \frac{dE}{dx} + C \cdot \left(\frac{dE}{dx}\right)^2} \quad (2)$$

where C is a second order fitting parameter, in unit of inverse of $(dE/dx)^2$. Equation (1) or (2) says that the optical light signal from a PSD will be degraded by a quenching correction factor (QCF), which is given by,

$$QCF = 1 + kB \cdot \frac{dE}{dx} \quad (3)$$

based on equation (1), or,

$$QCF = 1 + kB \cdot \frac{dE}{dx} + C \cdot \left(\frac{dE}{dx}\right)^2 \quad (4)$$

based on equation (2). In other words, to get the dose distributions in proton beams from the PSD luminescence measurements, one has to multiply the measured signal by the QCF to account for the quenching effect. QCF can be experimentally determined by taking the ratio of measured signal from an ion chamber to that from a PSD.

In this study, we measured the depth-dose distributions in a water phantom using a polystyrene based PSD for the passive scattering unmodulated monoenergetic proton beams

at the Proton Therapy Center at Houston (PTCH). The results were compared to the ion chamber measurements. The LET distributions along depth were calculated by Monte Carlo simulations for different proton nominal energies. The QCF was thus empirically determined as a function of LET.

2. Methods

We first measured the depth-dose curves of proton beams by using both a plane-parallel ion chamber and a PSD. From these results, the QCF as a function of depth was derived for a few proton beams. Next we calculated the proton LET as a function of depth. Then we were able to relate the quenching effect to the proton LET and compared it to the published results in literature. Finally the quenching-LET relationship obtained was applied to the PSD measurements to obtain the corrected proton depth-dose curves.

2.1. Measurements of the depth-dose curves

The measurements of the proton depth-dose curves by using an ion chamber and a PSD were performed in a PTW rectangular water phantom irradiated by the passive scattering proton beam at the PTCH. Proton beams of nominal energies of 100 MeV and 180 MeV were incident at 0° gantry angle to the water phantom; and a proton beam of nominal energy 250 MeV was incident at 270° gantry angle to the water phantom through the side wall. The proton range of 250 MeV in water is larger than the depth of the phantom, and because the phantom we used is rectangular-shaped we switched to the other configuration, beam at 270°. While for the setup at 0° gantry angle we were able to make measurements at shallow depths (< 2 cm) for the setup at 270° we had to account for the 2 cm acrylic wall thickness and a small distance for which the detector cannot reach. The acrylic wall thickness was then converted into water thickness and added to the total water depth. The field size is 10×10 cm² at a source-surface distance of 270 cm. A Markus (PTW TN 23343) plane-parallel ion chamber was used to perform the continuous scanning of the depth-dose curve in the PTW water phantom. A thimble chamber (TN 31010) was used as a reference chamber to account for any possible proton beam intensity fluctuations. The chamber measurements were corrected for the water/air stopping power ratio to get the depth-dose curve by using the stopping power ratio data published by Medin and Andreo (1997), although the corrections turned out to be unnecessary, i.e. there is no significant difference between the depth-ionization curve and the depth-dose curve for proton beams. The polystyrene based PSD used in the depth-dose measurements is a BCF-12 PSD (Saint-Gobain Crystals, Nemours, France) and has a sensitive region of 0.5 mm in diameter and 4 mm in length. The scintillator is protected/shielded by a black polyethylene jacket; and one end face of the scintillator is shielded by black adhesive and the other end is glued to a plastic-core (PMMA, also 0.5 mm diameter) optical fiber (Super Eska GH2001, Mitsubishi Rayon Co, Tokyo, Japan) of about 20 meters long. A scintillator/fiber holder was made to fix the PSD on the scanning arm. At the distal end of the optical fiber, the optical light was collected into a CCD camera (Luca S 658M EMCCD, Andor Technology, Belfast, Ireland). The light signal collected by the camera appears as a bright spot on the acquired image. The 14 bits analogue-to-digital converter gives a maximum pixel value of 16384. The major merit of using a CCD camera rather than photo-multiplier tubes for the optical light detection is because a single CCD camera can process many PSD signals simultaneously (Archambault et al. 2006). The PSD was positioned at various depths in the water phantom and the CCD images were acquired during the delivery of 50 MU proton beams, which corresponds to roughly 99 to 144 cGy of radiation dose at BP for the three passive scattering proton beams. Background images were also acquired with the same amount of exposure time. The pixel values in the background images were around 500. The amount of the needed MU for the PSD measurement was determined by having the maximum pixel value lying somewhere between 5000 and 10000 in order to have good enough signal to noise

ratio and also to prevent saturation. The background image was subtracted from the signal and the summation of all the pixel values of a spot gave the intensity of the incident light from the PSD corresponding to that spot. The region of interest (ROI) for summing up the pixel values is a square enclosing the light spot on the image.

One major problem for the PSD based dosimetry system for photon and electron beams is the Cherenkov light generated by relativistic electrons in the optical fibers attached to the PSDs (Beddar et al. 1992a, Clift et al. 2002, Frelin et al. 2005, Archambault et al. 2006). For therapeutic proton beams, the Cherenkov light is proven to be negligible or non-existent (Safai et al. 2004, Archambault et al. 2008). Another possible noise source is luminescence produced in optical fiber in radiation field, and it was found that luminescence is present in optical fibers irradiated by proton beams (Safai et al. 2004). In this study, we estimated the contribution from the luminescence to the PSD signals. In doing so, we used a 200 MeV passive-scattering proton beam of $10 \times 10 \text{ cm}^2$ field size to irradiate a phantom made of acrylic slabs. A PSD was positioned at a depth close to the BP on the central axis of the proton field so that roughly 5 cm of the optical fiber was exposed in the proton beam. A dummy fiber (i.e. an optical fiber without PSD) was put at the same depth to monitor the signal level of the luminescence. A total of 200 cm of the dummy fiber was exposed to the radiation field by rolling the fiber to several circles of diameter smaller than the field size. It was found that a length of 200 cm fiber exposure in the radiation field gives a signal level of 10% of the light signal from the PSD. Then for a typical 5 cm exposure of optical fiber in a $10 \times 10 \text{ cm}^2$ field, the signal level for the luminescence would be only 0.2% of the signal from the PSD. So the luminescence in the optical fiber in proton beams can be safely neglected since its relative contribution is much less than the combined uncertainty of 2% of determining absorbed dose to water in proton beams by using ion chambers (IAEA 2000).

2.2. Calculations of the LET and depth-dose distributions

Since the quenching effect is directly related to the LET of radiation particles (Birks 1964, Torrisi 2000), to account it correctly, the information about the LET distribution in a phantom for protons is necessary. There is a method of calculating the LET distributions analytically for proton beams (Wilkens and Oelfke 2003) but the accuracy of the calculations needs more verification. Ideally, it would be great if one can accurately measure the LET for proton beams. Although there are experimental techniques to determine the LET of proton beams (Sawakuchi et al. 2010), for the purpose of this study, the LET distributions along depth were calculated by using Monte Carlo simulations. The Monte Carlo code used is the MCNPX 2.6.0 code (Pelowitz 2008), on which a validated nozzle model for the passive-scattering proton beam at the PTCH was used (Titt et al. 2008). Note that the terms “LET” and “stopping power” will be used interchangeably here as they are equivalent for proton beams at the energy regime studied. To calculate the LET directly for a particular proton in a track in Monte Carlo simulation, one may evaluate the proton stopping power dE/dx after each step dx with an energy deposition of dE . One other way of calculating LET is to compute the average proton LET in a small volume by using the relationship between the dose D , the mean fluence Φ in the volume and the mass stopping power $(dE/dx)/\rho$, i.e. $D = \Phi (dE/dx)/\rho$. With dose given in MeV/g, fluence in cm^{-2} and mass stopping power in $\text{MeV cm}^2/\text{g}$. Because this study was conducted in water and its density (ρ) is 1 g/cm^3 the ratio of dose and fluence is the stopping power in unit of MeV/cm. This is the approach we used in this study to calculate the LET for proton beams.

Since we are studying the quenching effect of a PSD in proton beams, it is necessary to simulate or model the PSD in the MCNPX code and calculate the average LET in the sensitive region of the PSD. A computational model of a PSD investigated here is schematically shown in Figure 1. The sensitive region of the PSD is a cylinder (diameter 0.5

mm and length 4 mm) made of polystyrene and it is wrapped around by a polyethylene shielding jacket of diameter 2 mm. Figure 2 shows the calculated depth dose and depth LET distributions for a passive-scattering proton beam of nominal energy 100 MeV. This figure also demonstrates the excellent water equivalence of the PSD in proton beams. In Figure 2(b), the calculated average LET in the sensitive region of the simulated PSD is compared to the average LET calculated in a voxel ($10 \times 10 \text{ mm}^2$, 0.4 mm thickness) in pure water with the center of the voxel positioned at the point of measurement. The data points are overlapped with each other for the two scoring methods. Basically that means the proton fluence spectrum is almost the same in the two scoring regions. Since the volume of the water voxel is about 50 times larger than the sensitive volume of the PSD, the calculation time for water voxel could be 50 times shorter to get the results with similar statistical uncertainty. So we used the water voxel for all the LET distribution calculations in this study. Figure 2(a) shows the comparison of the depth dose curve in pure water to those from the simulations of dose deposition to the sensitive region of the PSDs *with* and *without* the jacket around the sensitive region. There is no significant difference between these curves which means the replacement of water by the polyethylene jacket ($\sim 0.75 \text{ mm}$ thickness) has no effect on the point of measurement of the PSD.

A question pertinent to the LET calculations is how much the calculated LET value at Bragg peak changes versus a slight change in the position of the BP, or the energy of the incident proton beam. Figure 3 shows the calculated depth dose curves for the proton beams of slightly different mean energies around 100 MeV. Three proton beams of energy 98, 100, and 102 MeV, having a spectrum width of 0.30 MeV FWHM, and one proton beam of energy 100 MeV with a spectrum width of 0.67 MeV FWHM are included in the comparison. The calculated depth of BP and the calculated LET at the BP for these proton beams are listed in table 1. It is seen that a 2 MeV energy difference may cause at least 2 mm proton range difference for the 100 MeV proton beam, but the spectrum width of either 0.30 or 0.67 MeV has no effect on the proton range. The difference of LET at BP for the 100 and 98 MeV beam is about 9%. This would be the maximum uncertainty of the calculated LET at BP due to the uncertainty of the modeling of the PTCH nozzle for the passive-scattering proton beam of energy 100 MeV (Titt et al. 2008). The depth of BP is determined by looking for the maximum point on a curve of a polynomial fit to the discrete calculation points close to BP. The estimated uncertainty for the calculated depth of the BP for the 100 MeV proton beam is about 0.2~0.3 mm. Thus, considering the gradient of LET at BP is about 19 (MeV/cm)/mm (Figure 2(b)), the relative uncertainty of LET due to the uncertainty of determining the BP position would be 10 % at most. Note that, in reality, proton energy can never change as much as 2 MeV. The variation of proton energy assumed here is purely fictitious and only for the purpose of determining the uncertainty of calculating the LET at BP with the simulated nozzle.

Figure 4 shows the calculated average LET vs depth in the water phantom for the passive-scattering proton beams at PTCH of nominal energies 100, 180, and 250 MeV. The calculated depth of BP, the average LET at the BP, and the gradient of LET at BP for these proton beams are listed in table 2. Note the uncertainties of LET in the table are the calculation statistics only. Because of the high gradient of LET near BP, another source of uncertainty of LET is related to the uncertainty of derivation of the exact depth of BP from the calculations. The calculation grid of depth at BP for 100, 180, and 250 MeV beams is 0.5, 1, and 1 mm, respectively; thus the estimated precision of determining the depth of BP from calculations is 0.25, 0.5, and 0.5mm (i.e. half of the grid size), which gives a relative uncertainty of LET at BP of 8.4 %, 6.5 %, and 3.3 % for the 100, 180, and 250 MeV proton beams, respectively. The data shown in Figure 4 was used to derive the relationship between the quenching effect and the LET.

3. Results and Discussion

3.1. The quenching correction factor (QCF)

The measured depth-dose curves for the 3 proton beams are shown in Figure 5. The depth-dose curves are normalized at depths of 1, 2, and 10 cm for the 100, 180, and 250 MeV beams, respectively. Close to BP, the signal level for PSDs is substantially lower than that of the ion chamber, clearly indicating the quenching effect to the PSDs. Assuming the ion chamber measurement represents the true dose distribution, the QCF as a function of depth can be determined by taking the ratio of the normalized depth-dose curve measured by an ion chamber to that measured by a PSD. In doing so, for each depth of PSD, the ion chamber reading at that depth (or, in most cases, the linear interpolation value of two adjacent data points) is divided by the PSD reading at that depth. However, at the distal fall-off region of BP, some data points have an equal or even higher PSD signal level than that of the ion chamber. The reason for this is because of the positioning uncertainties, which is about 1 mm due to placing the detectors (both chamber and PSD) at a depth in the water phantom. To account for this uncertainty and also to study the sensitivity of the correction factors to the positioning of the detectors, the nominal depths of the PSD were shifted mathematically upstream or downstream by a small amount before calculating the QCF. The resulted QCF vs depth for the 250 MeV proton beam for different shifts are shown in Figure 6(a) as an example (the same procedure is performed for other 2 proton beams but the results are not shown). It is seen there is a huge variation for QCF beyond BP when the position of the PSD is changed slightly. With measured QCF depth dependency, and the calculated LET depth distributions, the QCF as a function of LET can be derived. For each depth of PSD measurement, the QCF was found as mentioned above; and, the LET at that depth was found by linear interpolation from the two adjacent calculation grid points from the LET-depth curve. The results are shown in Figure 6(b) where QCF is shown as a function of LET for a variety of shifts made to PSD depth.

To find out quantitatively the necessary amount of shift for the relative position of the PSD and the ion chamber, one may start from Figure 6(b) where QCF vs LET is shown. The proton energies studied here (nominal 100 to 250 MeV, actual 73 to 230 MeV) are higher than those investigated by Torrisi (2000) (5 to 62 MeV). The quenching effect in this work was assumed to be a linear relationship as described by equation (3) in agreement with previous studies for high energy protons (Badhwar et al. 1967). Therefore, if one performs linear regression for all the curves of different shifts as shown, e.g. in Figure 6(b), and then calculates the root mean square (RMS) error for the linear fit of the QCF-vs-LET relationship for different shifts, one arrives at results shown in Figure 7. The RMS error reaches minimum when the shift of the PSD is -0.95, -0.90, and -1.05 mm for proton beams of energy 100, 180, and 250 MeV, respectively. The QCF as a function of depth was calculated as the ratio of the normalized depth-dose curve measured by the ion chamber to that measured by the PSD after the depths of PSD are corrected for the shifts just determined.

Figure 8 shows the obtained QCF versus LET for the passive-scattering proton beams of nominal energies 100, 180, and 250 MeV at PTCH. Originally, these QCF are normalized at 1, 2, and 10 cm depths for the respective proton beams; but here, all of them are re-normalized at LET = 15 MeV/cm, this is not influential because the correction factors are relative quantities and QCF should be the same for the same LET value. The horizontal error bars in the high LET region were obtained based on the studies in Section 2.2. The three sets of data are very close on the same straight line. A linear regression for all the data from the three proton beams leads to the solid line in the figure, which is expressed as an empirical formula,

$$QCF = 0.881 + 0.00796 \cdot LET \quad (5)$$

where LET is in the unit of MeV/cm. The measure of the goodness-of-fit for the linear regression is indicated by R^2 which has a value of $R^2 = 0.981$. A very good linear relation is obtained here because the proton energies studied are high with nominal values from 100 to 250 MeV. Torrasi (2000) needed a second order term to best fit his data as the proton energies were very low, from 5 to 62 MeV, roughly corresponding LET values from 100 to 700 MeV/cm. Figure 8 also shows in dashed line Torrasi's second-order fitted curve after renormalization at LET = 15 MeV/cm. It is seen that in this extrapolated low LET regime, the curve also approximately exhibits linear behavior.

Table 3 shows the comparison of the measured kB parameter, as defined in (1), to those found in the literature. The measured kB parameter in this study, which is the smallest as shown in table 3, is obtained by taking the ratio of the slope to the intercept in (5). The difference between the values of kB measured may be attributed to the difference of the materials used for the PSD. Another possible cause of the difference in measured kB is that the range of LET used in the study may affect the outcome of the linear regression; e.g. higher LET may give rise to a QCF larger than that predicted by a linear relation, which will lead to a larger slope when doing a linear regression among the data.

3.2. Applying the QCF to measured curves

The QCF value given by equation (5) can be employed to make corrections to the measured depth-dose curves by PSDs. For the 3 proton beams (100, 180, and 250 MeV) investigated in this study, the relationship of LET vs depth is known from the Monte Carlo simulations. For each depth of PSD measurement, the LET at that depth can be found by table look-up, and then equation (5) is used to find the QCF needed. After applying the QCF at all depths of measurement, a renormalization is done for the depth-dose curves at 1, 2, and 10 cm depths for the 100, 180, and 250 MeV proton beams, respectively. Figure 9(a) shows the depth-dose curves measured by the PSD after applying the QCF calculated by equation (5). Figure 9(b) shows the ratios of the relative dose values of ion chamber to the PSD. The maximum deviation for all 3 proton beams is within $\pm 5\%$. It is important to remind that the QCF function used to correct the PSD readings in Figure 9(a) includes the necessary shifts discussed in the previous section, and that without such correction the distal edge and the peak positions could not be determined accurately.

Obviously, however, there is a requirement when applying the QCF to correct for the PSD measurement of the depth-dose curves in proton beams; namely, the depth distribution of LET for a particular proton beam of interest must be known before any corrections can be made. For unmodulated monoenergetic proton beams, the LET distributions can be calculated easily and tabulated for various proton energies and depths so that the QCF can be correctly applied. Things become more complicated when one has to deal with a proton beam of spread out Bragg peak (SOBP) which is generally a weighted superposition of a series of unmodulated monoenergetic proton beams. Although there is a way of analytically calculating LET for general proton beams (Wilkins and Oelfke 2003), whether it is applicable to all kinds of proton beams at different facilities remains unknown. Additional work needs to be done to obtain the LET depth distributions accurately and conveniently for any, including SOBP, proton beams.

4. Conclusions

In this study, proton beam depth-dose distributions in a water phantom were measured by both a plastic scintillation detector (PSD) and a plane-parallel ion chamber. The LET

distributions along depth for these proton beams were calculated by Monte Carlo simulations. The quenching correction factor (QCF) was obtained from the comparison of the measured depth-dose curves. A linear relationship between QCF and LET, i.e. Birks' formula (Birks 1964), was obtained for the proton beams studied and it agreed with the published results in literature (Titt et al. 2008). The obtained empirical formula for QCF was used to correct the PSD measurements based on the known LET distribution of these proton beams. The agreement between the PSD measurements after the quenching corrections and the ion chamber measurements is within 5%. PSDs could be good dosimeters for proton beam depth-dose measurement if the quenching effect is accounted for appropriately. However, before reaching that goal, additional work needs to be done to find the LET distributions easily for all the clinical proton beams.

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Figure 1. Computational model of a plastic scintillation detector (PSD). The sensitive region is designated by the shaded area. All measures are in millimeters (figure not drawn in scale).

Figure 2.

Calculated (a) depth dose curves and, (b) average LET at depths for the passive-scattering proton beam of nominal energy 100 MeV. Calculations are performed at various depths both in pure water and in the sensitive region of the PSD that is positioned at the same depth in the water phantom. The gradient of the LET curve at the Bragg peak (BP) is about 19 (MeV/cm)/mm for the 100 MeV beam. A.U. stands for arbitrary unit.

Figure 3.

Calculated depth dose curves for the passive-scattering proton beams of slightly different mean energies at around 100 MeV, and having a spectrum width of 0.30 MeV FWHM for the incident proton beams. Also shown is the depth dose curve for the 100 MeV beam with a wider spectrum width (0.67 MeV FWHM) for the incident proton. A.U. stands for arbitrary unit.

Figure 4.

Calculated average LET vs depth in a water phantom for the passive-scattering proton beams of nominal energies 100, 180, and 250 MeV. The gradient of the LET curves at the Bragg peak (indicated by arrows) is about 19, 5, and 2 (MeV/cm)/mm for the 100, 180, and 250 MeV beams, respectively.

Figure 5. Measured depth-dose curves for the passive scattering proton beams of 3 nominal energies. The measurements are done by a Markus plane-parallel chamber and a plastic scintillation detector (PSD). The depth-dose curves are normalized at depths of 1, 2, and 10 cm for 100, 180, and 250 MeV beams, respectively. A.U. stands for arbitrary unit and IC for ion chamber.

Figure 6.

(a) The quenching correction factor (QCF) as a function of depth for the 250 MeV proton beam near BP. The nominal position of the PSD in water was shifted by a small amount (from -0.5 to -1.5 mm) to see how sensitive the QCF is on the detector positioning uncertainty. QCF is found by taking the ratio of the ion chamber reading to that of the PSD. (b) Corresponding QCF as a function of LET.

Figure 7. The root mean square (RMS) errors calculated from the linear fits of the QCF-vs-LET curves (as in Figure 6(b)) for different shifts of the nominal depth of PSD in the 3 proton beams. The negative value of shift means it is shifted toward the incident source or phantom surface.

Figure 8.

The measured quenching correction factors (QCF) for the polystyrene based PSD are shown (symbols) as a function of LET in a water phantom for passive-scattering proton beams of nominal energies 100, 180, and 250 MeV. The QCF are normalized to 1 at LET = 15 (MeV/cm). A linear fit is made for all three proton energies. Torrissi's measurement (Torrissi 2000) for a polyvinyltoluene based PSD is shown in the dashed line, after re-normalizing at LET = 15 (MeV/cm).

Figure 9.

(a) Comparison of the depth-dose curves measured by a PSD after making quenching corrections to those measured by a Markus ion chamber (IC). Dose values are in arbitrary unit and are normalized at 1, 2, 10 cm depths for 100, 180, 250 MeV proton beams, respectively. (b) The ratios of the dose values of ion chamber to PSD.

Table 1

Calculated average LET at Bragg peak (BP) for the passive-scattering proton beams of slightly different mean energy at around 100 MeV. The initial proton spectrum width used in the nozzle model is 0.30 MeV FWHM. A wider spectrum (0.67 MeV) is also used for the 100 MeV beam.

Proton nominal energy (MeV)	100	100	98	102
Proton spectrum width (MeV, FWHM)	0.30	0.67	0.30	0.30
Calculated depth of BP (cm)	4.35	4.35	4.10	4.64
Average LET at BP (MeV/cm)	56.8 ± 0.5	56.6 ± 0.5	61.8 ± 0.6	59.5 ± 0.6

Table 2

Calculated average LET and the gradient of the LET vs depth at Bragg peak (BP) for the passive-scattering proton beams of nominal energies at 100, 180, and 250 MeV. The field size for all the beams is $10 \times 10 \text{ cm}^2$. The proton energy data shown in bracket are the actual or effective proton mean energy just before entering the water phantom.

Proton nominal energy (and effective energy) (MeV)	100 (73.5)	180 (153.0)	250 (212.8)
Calculated depth of BP (cm)	4.35	16.05	28.35
Calculated LET at BP (MeV/cm)	56.8 ± 0.5	38.2 ± 0.6	29.9 ± 0.5
Gradient of LET vs depth at BP (MeV/cm)/mm)	19	5	2

Table 3

Comparison of the measured kB parameter, as in equation (1), in this study to those published in literature. The first order kB data were taken from table 3 in Torrasi (2000).

	Energy (MeV)	LET (MeV/cm)	kB (g/MeV cm ²)
Torrasi	5–62	100 – 700	0.0207
Gooding et al.	28 – 148	55 – 200	0.0132
Badhwar et al.	36 – 220	42 – 123	0.0126
This study	73 – 230 ^a	5 – 70	0.0094

^a actual proton mean energy just before entering the water phantom, the nominal energies are 100 MeV and 250 MeV