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Patient-Specific QA of Spot-Scanning Proton Beams Using Radiochromic Film

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Abstract

Radiochromic film for spot-scanning QA provides high spatial resolution and efficiency gains from one-shot irradiation for multiple depths. However, calibration can be a tedious procedure which may limit widespread use. Moreover, since there may be an energy dependence, which manifests as a depth dependence, this may require additional measurements for each patient. We present a one-scan protocol to simplify the procedure. A calibration using an EBT3 film, exposed by a 6-level step-wedge plan on a Proteus®PLUS proton system (IBA, Belgium), was performed at depths of 18, 20, 24 cm using Plastic Water® (CIRS, Norfolk, VA). The calibration doses ranged from 65 - 250 cGy (RBE) (relative biological effectiveness) for proton energies of 170 - 200 MeV. A clinical prostate + nodes plan was used for validation. The planar doses at selected depths were measured with EBT3 films and analyzed using one-scan protocol (one-scan digitization of QA film and at least one film exposed to a known dose). The gamma passing rates, dose-difference maps, and profiles of 2D planar doses measured with EBT3 film and IBA MatriXX-PT, versus the RayStation TPS calculations were analyzed and compared. The EBT3 film measurement results matched well with the TPS calculation data with an average passing rate of ~95% for 2%/2 mm and slightly lower passing rates were obtained from an ion chamber array detector. We were able to demonstrate that the use of a proton step-wedge provided clinically acceptable results and minimized variations between film-scanner orientation, inter-scan, and scanning conditions. Furthermore, for relative dosimetry (calibration is not done at the time of experiment), it could be derived from no more than two films exposed to known doses (one could be zero) for rescaling the master calibration curve at each depth. The sensitivity of the calibration to depth variations has been explored. One-scan protocol results appear to be comparable to that of the ion chamber array detector. The use of a proton step-wedge for calibration of EBT3 film potentially increases efficiency in patient-specific QA of proton beams.

Keywords

Proton Therapy, Patient-Specific QA, Gaf Chromic EBT3, Film Dosimetry

1. Introduction

Owing to its dosimetric characteristics, particularly finite range, proton therapy provides a potentially favorable treatment option for many cancer patients [1] [2]. Protons show an increasing energy deposition with penetration distance leading to a maximum dose (the Bragg peak) near the end of range of the proton beam. A weighted sum of individual Bragg peaks of different energies can be used to generate a uniform dose plateau or spread-out Bragg peak (SOBP), which in turn, can be overlaid over the target during treatment planning. The SOBP is characterized by its range and width, or modulation [3]. Delivery of an SOBP has used different techniques including most commonly passive scattering [4] [5] as well as uniform scanning [6] [7].

More recently, spot scanning or pencil beam scanning (PBS) has emerged as a delivery technique [8] [9]. Unlike scattered beams, in which the dose is shaped by a selection of the appropriate range and modulation and shaped with a customized compensator and aperture, in spot scanning, the beam is delivered and shaped by scanning individually weighted spots to a radiological depth. The energy is then changed and the next layer is scanned. Analogous to x-ray treatment planning, scatter beams are forward planned in 3D, whereas spot scanning is inversely planned [10] [11].

The current standard of patient-specific QA for spot scanning proton therapy is to perform measurements using a chamber array at different depths followed by a 2D or 3D gamma analysis [12] [13]. Radiochromic film for spot scanning QA provides high spatial resolution and efficiency gains from one-shot irradiation at multiple depths. The use of radiochromic film for protons has been reported in a variety of investigations [14]-[22]. However, calibration can be a tedious procedure that may reduce widespread use. Moreover, since there may be an energy dependence, which manifests as a depth dependence, this may require additional measurements for each patient [23]. We applied the one-scan protocol [24] to simplify the procedure. Briefly, this approach requires only a single calibration exposure to a known dose of one film and a single scan of the QA film thereby vastly simplifying what the previous approach of irradiating multiple films for calibration each time. This study aims to investigate the effectiveness of one-scan protocol on proton dosimetry, focusing attention on its application to spot scanning patient-specific QA.

2. Materials and Methods

Irradiations were performed using a spot scanning beam delivery on a Proteus®PLUS proton system (IBA, Belgium) at the ProCure Proton Therapy Center in Somerset, NJ. Typical energy ranges from the nozzle vary from ~100 to

230 MeV, however, much lower effective energies can be obtained for treating superficial depths using a range shifter. The details of the beam delivery system are described in a separate study [25].

The EBT3 films (lot 02181401, Ashland, Bridgewater, NJ) were irradiated in Plastic Water® (CIRS, Norfolk, VA) at depths of 18, 20, and 23 cm by a 6-level step-wedge plan. Each film sheet was sandwiched between Plastic Water slabs perpendicular to the beam direction. The step-wedge plan consists of 17 different spot energy layers (145 - 198 MeV) and a different number of spots and weights (**Table 1**).

The goal of selecting calibration doses is to equilibrate uncertainty in high and low dose areas. The equi-color dose scheme ensures the high and low dose regions are equally well approximated for EBT3 film. The calibration doses of 65, 91, 128, 179, and 250 cGy(RBE) (relative biological effectiveness) were based on such scheme. All treatment plans were generated in the RayStation (RaySearch Laboratories, Sweden) including the calibration step-wedge plan (**Figure 1**). Dose distributions measured with EBT3 film were also compared with those obtained with MatriXX-PT (IBA Dosimetry, Germany). The responses of the exposed films were evaluated by a flatbed Epson 10000XL scanner at 72 dpi resolution.

A clinical treatment plan for prostate with seminal-vesicles and pelvis-nodal

Table 1. The proton energy layers for the calibration. The films were placed at 18, 20, 23 cm depth Plastic Water®. Only protons with energy >160 MeV deposited dose to the films.

No.	Energy [MeV]	Relative Weight [%]	Number of Spots	Spot Weight [MU/fx]	
				Min	Max
1	197.81	33.96	3452	0.0875	1.7864
2	194.37	11.73	3404	0.0224	1.1532
3	190.97	9.01	3640	0.0226	1.0941
4	187.56	6.56	3589	0.0225	0.6605
5	184.17	5.58	3476	0.0222	0.8894
6	180.77	4.70	3415	0.0223	0.6062
7	177.40	4.03	3371	0.0224	0.5153
8	174.06	3.41	3159	0.0222	0.4507
9	170.76	2.92	2834	0.0225	0.4004
10	167.46	2.62	2609	0.0226	0.3700
11	164.17	2.25	2369	0.0225	0.2678
12	160.87	2.61	2069	0.0231	0.5404
13	157.59	2.20	2023	0.0230	0.4947
14	154.34	1.96	1923	0.0229	0.4417
15	151.16	1.82	1776	0.0230	0.2653
16	148.03	1.44	1259	0.0230	0.4709
17	144.99	3.20	3583	0.0246	0.0461

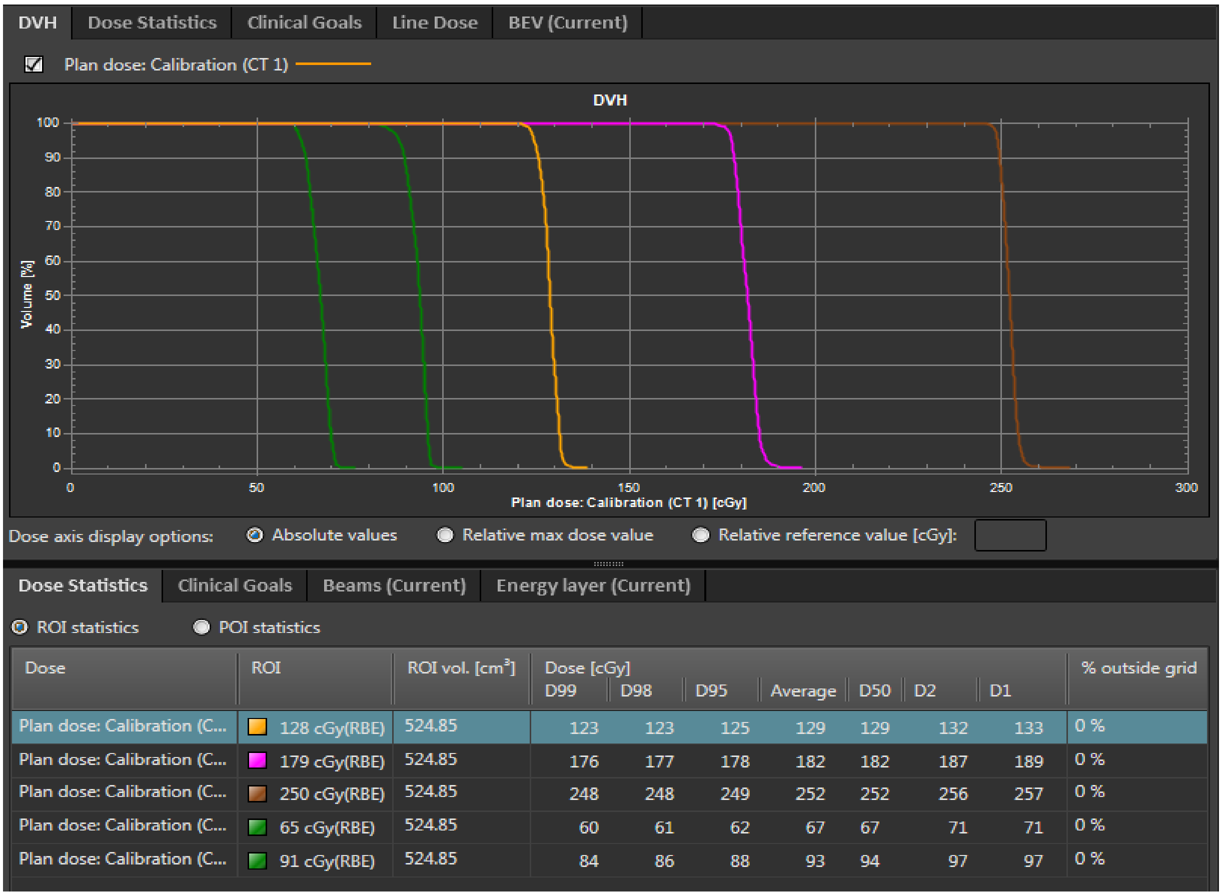


Figure 1. Screenshot of the treatment plan of the step-wedge calibration.

involvement was used for testing (Figure 2). The planar doses at different depths were measured with EBT3 film and the MatriXX-PT. Calibration films were irradiated at 18, 20, and 23 cm while the chamber array was irradiated at nearly identical depths of 18, 20 and 24 cm. The LET dependence of radiochromic films has been thoroughly investigated [6] [18] [22] [26]-[33] and it has been established that the effect is highest for lower (<11 MeV) proton energies [28]. However, for spot scanning beams, there may be a larger distribution of energies used to irradiate the PTV which could make accounting for LET corrections quite variable. To assess the depth (energy) dependence, we performed gamma analysis using calibration films at different depths. The films were analyzed using One-scan protocol (one-scan digitization of QA film and at least one film exposed to a known dose). We used the 180 cGy(RBE) calibration dose and the zero dose to rescale the dose response of the patient film. This is analogous to the absolute dose calibration for diode array or ion chamber array detectors before the patient-specific QA takes place. The gamma passing rates, dose-difference maps, and profiles of 2D planar doses measured with EBT3 film and IBA MatriXX-PT, versus the RayStation TPS calculations were analyzed and compared.

3. Results

The dose-response data could be fit to a set of related rational functions leading

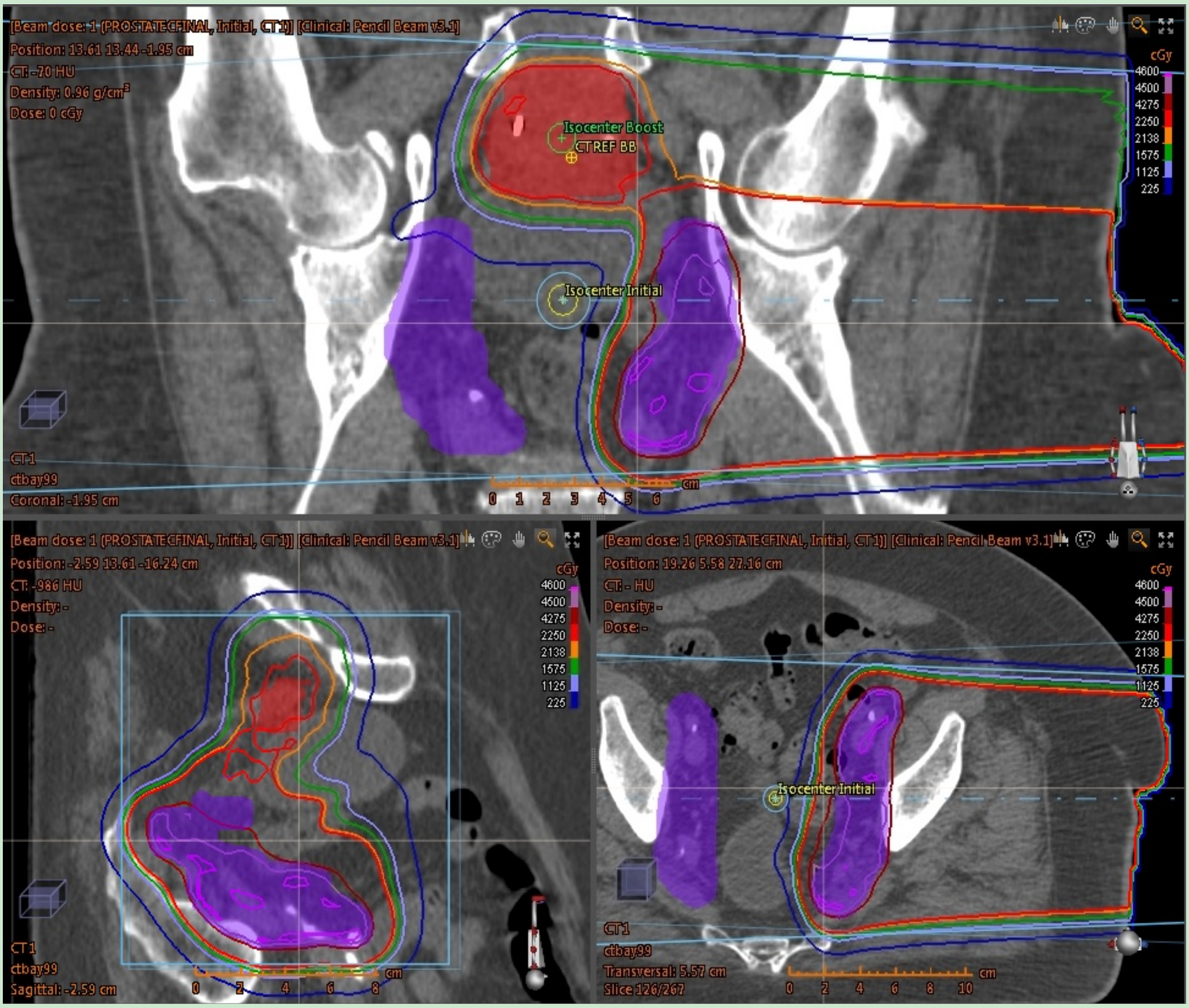


Figure 2. Three orthogonal dose distributions with target doses of 90 cGy(RBE) (red), 180 cGy(RBE) (purple) treated laterally; coronal view (upper center), sagittal view (lower left), transverse view (lower right).

to the description of a generic calibration curve for a given film lot [34]. One generic calibration curve was generated using the scanned step-wedge film at each depth (**Figure 3**). For comparison of MatriXX-PT, a similar dose map and step-level were used. The dose-response data for a specific film lot, scanner, and scanning conditions could be derived from two films exposed to known doses including zero dose. For relative dosimetry when the calibration is not done at the time of patient QA, two-point rescaling could be applied to rebuild the master calibration curve at each depth. Again, the selection of the two-point doses (one of them could be zero) depends on the maximum dose level on the plane of patient QA film. These calibration films must be exposed at the same time as the QA film in order to be compliant with the One-scan protocol. Each QA film was scanned together with an exposed reference film (irradiated within minutes of the QA films) and a piece of unexposed film.

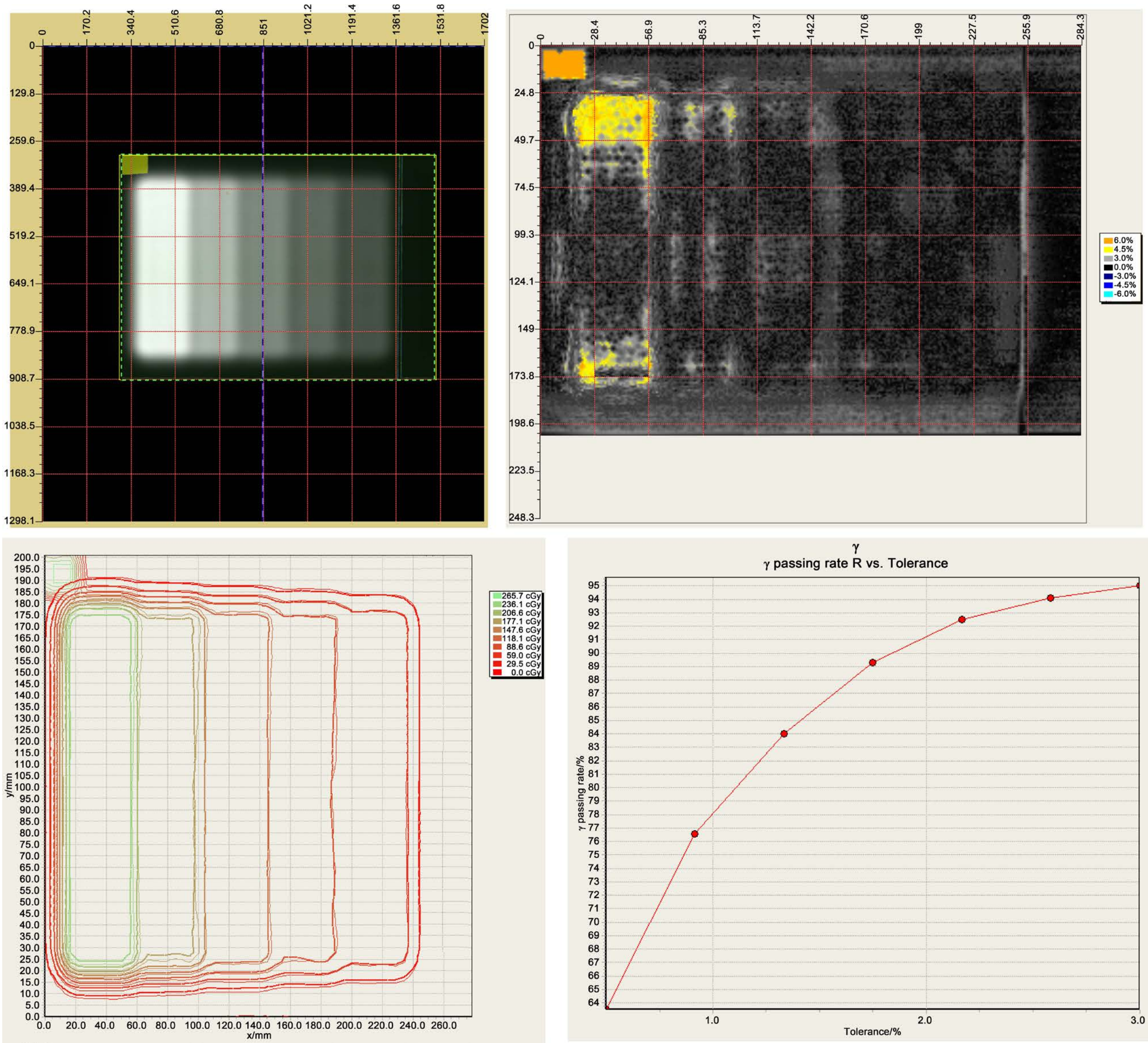
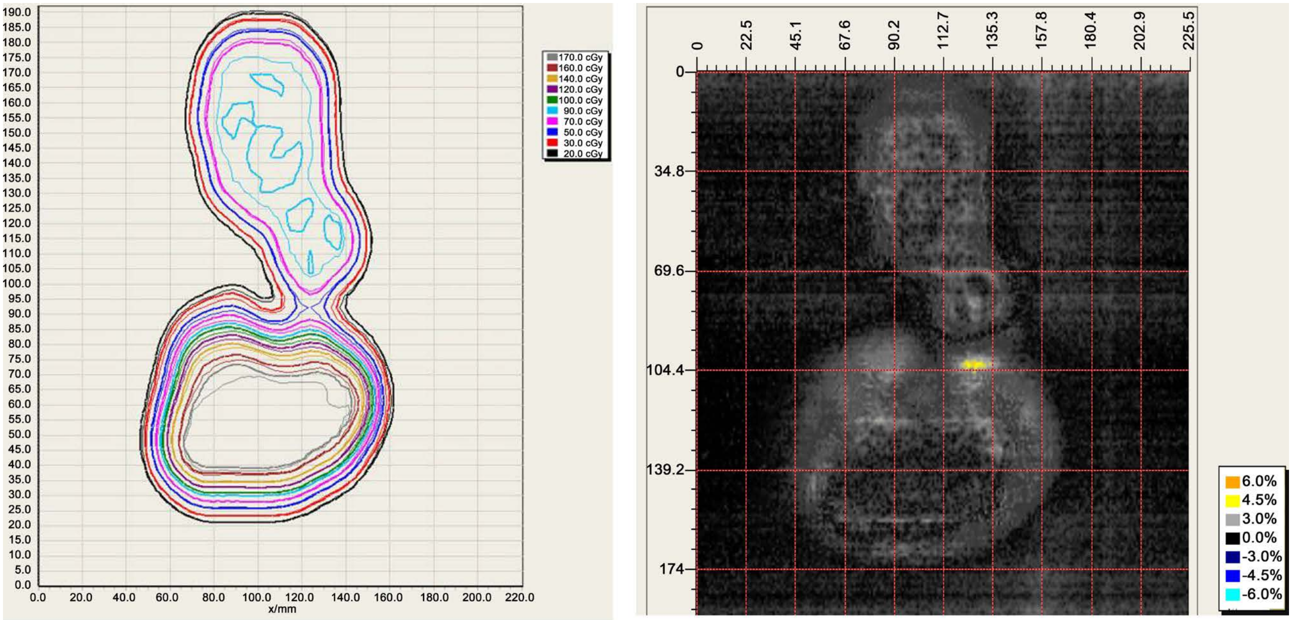


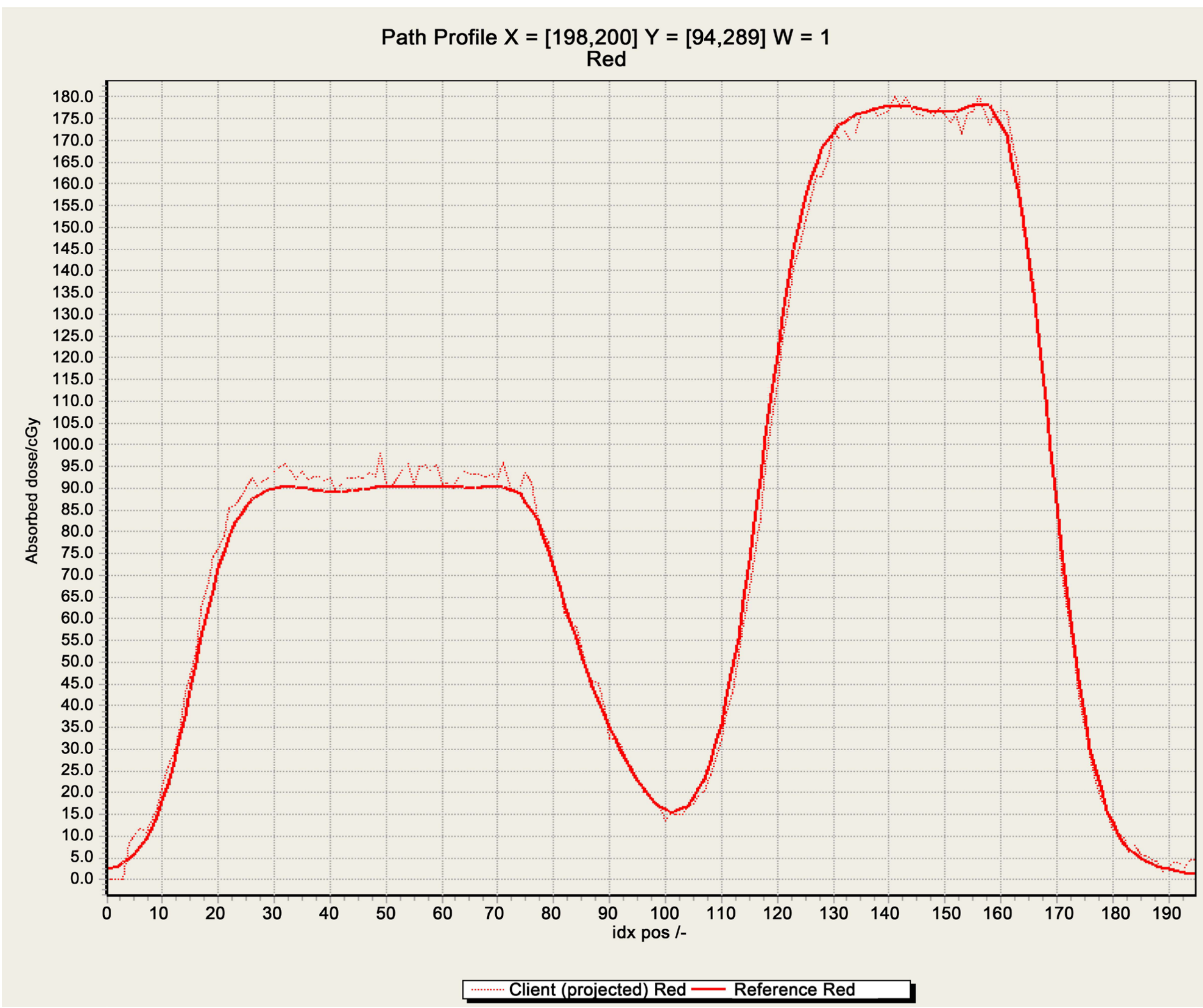
Figure 3. Screenshots of scanned step-wedge film in FilmQA Pro: scanned film image (upper left); isodose lines (lower left); dose difference map (upper right); passing rates as function of gamma (lower right).

Using the gamma test criteria of 3%/3 mm, 3%/2 mm, 2%/2 mm to evaluate the digital image consisting of the patient film, one calibration film, and one unexposed film for calculation and analysis, similar passing rates were obtained between EBT3 film and MatriXX-PT except for the largest discrepancy with the 2%/2 mm criteria at the shallowest depth (d = 18 cm) in the prostate case. Figure 4(a), Figure 4(b) show the isodoses overlay and dose difference map of film and TPS data. Figure 5(a) shows the vertical dose profile of the sagittal view of dose distribution of the prostate plan. Figure 5(b) shows the gamma passing rate as a function of dose difference (DD) and distance-to-agreement (DTA). The EBT3 film measurement results matched well with the TPS calculation data with an average passing rate of ~95% for 2%/2 mm and slightly lower passing rates were obtained from an ion chamber array detector (Table 2).

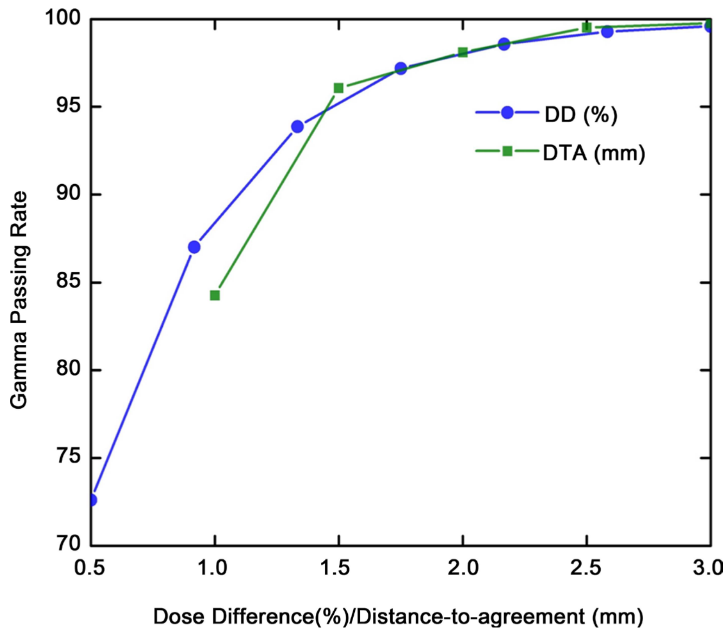


(a) (b)

Figure 4. (a) Sagittal plane isodoses overlay; (b) Dose difference map.



(a)



(b)

Figure 5. (a) Vertical dose profile of the sagittal distribution; (b) Gamma passing rate as a function of dose.

Table 2. Gamma passing rates of dose comparison between film/TPS and MatriXX/TPS.

Proton Beam	Depth (cm)	Criteria of Gamma Evaluation					
		3%, 3 mm DTA		3%, 2 mm DTA		2%, 2 mm DTA	
		EBT3	MatriXX	EBT3	MatriXX	EBT3	MatriXX
Prostate + SV + Pelvis Nodes	18	99.2%	98.7%	98.6%	96.1%	94.3%	89.5%
	20	98.5%	99.1%	98.4%	97.4%	96.1%	93.5%
	23	97.9%	99.5%	97.5%	98.4%	96.7%	95.9%

Note: The MatriXX-PT was taken at 24 cm instead of 23 cm.

Table 3. Highest passing rate with the corresponding calibration curve at each depth.

Passing Rate (3%, 3 mm DTA)	Calibration (d = 18 cm)	Calibration (d = 20 cm)	Calibration (d = 23 cm)
QA Film (d = 18 cm)	**99.2%**	96.0%	92.8%
QA Film (d = 20 cm)	95.5%	**98.5%**	97.3%
QA Film (d = 23 cm)	90.0%	94.9%	**97.9%**

To explore the depth dependence, we have applied different combinations of calibration curves and patient QA films at 3 different depths to assess the effect. Table 3 demonstrates the highest passing rate occurred when using calibration and QA film at the same depth; therefore it suggests having a different calibration function at a different depth.

4. Discussion

Radiochromic film dosimetry in low-energy proton or ion beams requires a correction of the LET dependent film response [35] [36]. Radiochromic film can be used as a reference dosimeter for biomedical experiments with low-energy proton beams if appropriate LET corrections are applied [36]. There are numerous researchers reported that under-response of radiochromic film in the presence of proton SOBPs which could be defined as "quenching effect" of the dosimeter in the region [26]-[33] [35] [36] [37]. "Quenching" is said to occur when, for a given physical dose, a dosimeter not limited to radiochromic film gives a lower output reading for radiation with high LET than for the same dose of low LET radiation. The effects are particularly noticeable for measurements made at the Bragg peak in proton treatments [38]. Quenching of dosimeter response is a major issue in the measurement of the radiation dose from proton and other ion beams. The quenching effect of EBT3 film is the highest at the lowest initial energy of the clinical beams, a phenomenon related to the corresponding higher LET in the film sensitive layer [35]. A possible reason for this is attributed to the shape and arrangement of the monomer particles being different in the active components of EBT. It is suggested that the polymer yield factor is the dominant factor causing the LET quenching effect [29].

Table 3 demonstrates the depth dependence of the calibration film. There is clearly dependence and for optimal results, a calibration film should be generated at the same depth as the measurement. This finding is in agreement with previous studies for depth calibration [39] [40] or at the center of the SOBP [6] [17] [19]. However, the dependence for different ranges and modulations requires further investigation.

Another alternative method reported for calibration rather than multiple measurements at different depths were reported by Vadrucci *et al.* The film is positioned at the entrance of a 5 MeV proton beam with the film data acquired from a readout system, taking average data over a region of interest of uniform dose at the beam center for each film and plot against the known dose [30]. The particle energy of proton beam is variable with depth and could be losing energy continuously (lowest at Bragg peak and highest effect in depth dependence). The energy response is also dependent on the position of the Bragg peak [6].

The film orientation relative to the proton beam direction also plays an important role in dosimetry due to radiation interaction's causing polymerization in radiochromic film [7]. The parallel orientation was found to be superior as one can get an entire 2D data set from one single film. When using a single film piece positioned parallel to the proton beam axis, it is recommended to tilt the film plane at different degrees (1˚ - 5˚) from the proton beam axis or the film can be kept in water [6] [18]. The film had sufficient width so that water in the film would not cause additional perturbation. In our work, we have positioned the EBT3 film perpendicular to the beam axis, calibrated the step-wedge film with the mixed proton energies at each depth, used one-scan protocol for film analysis to eliminate the inter-scan variability and corrected for post-exposure density growth. The film results are comparable with the ion chamber array measurements as respect to the TPS calculations.

5. Conclusion

The use of a proton step-wedge for calibration of EBT3 film appears to increase the efficiency. The sensitivity of the calibration to depth variations has been explored. However, the step-wedge approach should be limited to film dosimetry at the range which is not at the distal edge of SOBP. The LET dependence of EBT3 needs to be incorporated in the process to improve the accuracy of film dosimetry at lower proton energies or when the film is parallel to the beam axis.

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