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Dose verification of proton beam therapy using the Gafchromic EBT film

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ABSTRACT

In proton beam therapy, dosimetric verification is important because proton beams are stopped within targets, and almost no dose proceeds beyond those targets. Patient-specific quality assurance (QA) checks the beam-delivery system using passive-scattering techniques, including portal calibrations and verification of beam-shaping devices, because there are many components to be checked, such as the range shifter, the aperture, and the compensator, in the beam-delivery system. Although the conventional measurement of dose distribution by scanning the ion chamber gives an accurate estimate of the dose, it requires considerable time and effort. While a mechanical check is useful to physically check the milling condition of the compensator, this capability is limited with respect to the investigation of the dose distribution. We investigated the usefulness of EBT films for their applications in the area of high-precision clinical QA of proton beams. Proton beams were delivered to films in a transverse (in solid water) or a longitudinal (in water) direction, with respect to the beam axis, and information about the aperture and the compensator shapes was obtained from the dose distributions measured with either film orientation. Quantitative comparisons between the treatment planning system (TPS) and the EBT film data were carried out using both distance-to-agreement and gamma index procedures. The percentage of points exceeding the acceptance criterion of the gamma index (i.e. 3%, 3 mm) was, on average, 2.4% and 8.3% in films oriented transversely and longitudinally to the beam axis, respectively. The results of transverse irradiations of EBT films were in good agreement with those of the TPS, although consistent disagreements in longitudinal irradiation were observed near the distal edge of the spread-out Bragg peak (SOBP), presumably due to differences in sensitivity in the linear energy transfer (LET). In addition to range, uncertainty (~3 mm) caused by the non-water-equivalence of the EBT film was observed in longitudinal irradiation. The under-response of the EBT film in the high-LET region improved remarkably after we corrected the SOBP of the EBT film, using a weight function based on the Bragg peaks. Although our correction data obtained using the EBT film did not match the result of the chamber after the distal fall-off region, the EBT film could be a useful QA tool for both dose and range verification of aperture and compensator, after careful correction.

1. Introduction

In proton therapy, a reliable dosimetry system for quality assurance (QA) is required for yielding practical measurements of both beam energy (depth) and modulation (width). For proton beams, diamond detectors, ionization chambers, and thermoluminescent dosimeters (TLDs) can be employed for depth–dose measurements, using the single Bragg peak (Bichsel, 1995). Similarly, diodes and films are valuable for profile measurements and penumbra characterization (Chu et al., 1993; Vatnitsky et al., 1995). However, ionization chambers, diamond detectors, and diodes do not rapidly provide a quantitative pattern of radiation distribution over the target volume. Moreover, the sensitive volume of TLDs is relatively large for resolving high-dose gradients at the distal edges of the beams, as compared to that of films for proton beams. Therefore, the radiochromic film is an attractive dosimetry modality for small field sizes (less than 5 mm) and an efficient dose verification method in proton therapy

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(Vatnitsky et al., 1999). In particular, the Gafchromic EBT (EBT) film provides excellent spatial resolution, tissue equivalency, and low energy dependency to an external beam. This film is convenient to handle because of its self-developing property and its insensitivity to ambient light (Butson et al., 1998). However, as the proton linear energy transfer (LET) increases, energy is deposited in relatively small volumes, and the local dose approaches the saturation region of the EBT film response.

In this study, we carried out dose verification using an EBT film and evaluated the feasibility of applying such a film to high-precision clinical QA procedures of the proton beam, for both transverse (film perpendicular to beam direction) and longitudinal (parallel) film orientations, with respect to the beam axis. In general, there is a quenching effect of the EBT film in a proton beam near the end of the spread-out Bragg peak (SOBP) region. In order to correct the under-response of the EBT film, data correction was performed using the Bragg peaks of the EBT film, and results were compared with those of an ionization chamber, in order to investigate whether the EBT film could be a useful QA tool for proton beams.

2. Materials and methods

2.1. Proton beam and treatment planning system (TPS)

Proton beam irradiation was performed at the National Cancer Center of Korea (NCC), using an ion beam application proton beam therapy system (IBA S.A.; Louvain-la-Neuve, Belgium); it provided energy in the range of 70–230 MeV. The Eclipse proton beam planning system (Varian Medical Systems, Inc.; Palo Alto, CA) was used for planning. With the beam directed along the AP (anterior-posterior) axis, nine differently shaped fields were used for both transverse and longitudinal irradiations. We selected nine patients with brain and prostate tumors, whose ranges and SOBP widths ranged from 90 to 190 g/cm^2 and from 50 to 100 g/cm^2, respectively. The air-gap between the beam-delivery snout and the patient was 20 mm. The prescribed dose was 60 Cobalt Gray Equivalent (CGE) in 25 fractions for the brain and 60 CGE, in either 20 or 33 fractions, for the prostate.

2.2. Setup and film calibration

Gafchromic EBT films (ISP Corporation; Wayne, NJ) were used for verifying dose distributions. They consist of two active layers separated by a surface layer coated onto a polyester base. In order to facilitate the setup, solid water phantom (30 $\times$ 30 $\times$ 30 cm^3; Nuclear Associates Division of Victoreen, NY) was used for the transverse proton beam irradiation. The EBT films were placed in plastic water phantoms for proton irradiation at the middle depth of the SOBP (mid-SOBP), where the relative biological effectiveness (RBE) was close to 1.1, as previously shown (Paganetti, 2003).

In all nine patients, for the longitudinal proton beam irradiation, the EBT film was submerged in water, instead of the solid phantom, to prevent any air-gaps between the film and the phantom, and was aligned to the water surface for QA. We modified the setup to reduce uncertainty factors, such as setup error and water surface tension. Thus, we hung a poise to fix the position of the EBT film and to make the EBT film stand upright in water. We also inserted a Styrofoam block between the beam-delivery snout and the water surface, and attached the EBT film to the Styrofoam block, in order to remove the uncertainty of the water surface position due to surface tension and setup error. We converted the range of Styrofoam into the water equivalent range (WER), based on the scanning data of the chamber. We selected R80 (i.e. the range at 80% dose) as the reference point that was not influenced by the momentum band (Thomas and Hanne, 2007), and compared the data of the EBT film with those of the chamber.

We explored dose verification in both the longitudinal and transverse directions for each field. The calibration of proton beams was performed at the mid-SOBP depth (50 g/cm^2), using radiation of 30–700 cGy, for investigating the effect of the EBT film on proton beams. The analysis of the radiochromic film was delayed for 24 h, in order to minimize the effects of post-irradiation coloration (Cheung et al., 2005; Niroomand-Rad et al., 1998). The film response as a function of the dose was measured using the Epson 1680 film scanner (a 48-bit scanner; Epson; Sydney, Australia). Films were scanned after several successive warm-up scans conducted at the beginning of the measurement. The EBT films were aligned on the scanner bed in the same position, and the scan was performed while maintaining the same orientation of films on the scanner bed, because scanner values varied with the scanning direction of the EBT film (Lynch et al., 2006; Butson et al., 2006). We calibrated two directions using each lot (Lot# 36306-0011) in order to reduce the calibration errors. Films were analyzed with FilmQA and the in-built software.

2.3. Dose verification and depth–dose profiles

The depth–dose profile measured using the EBT film was compared with measurements using a PTW Markus chamber whose dose distributions were normalized to the plateau region at the Bragg peak and mid-SOBP at the SOBP. Dose verifications were carried out using both the DTA approach, proposed by Harms et al. (1998), and the gamma evaluation method, proposed by Low et al. (1998).

In order to investigate the feasibility of corrections in EBT films, proton beams were irradiated in the longitudinal direction under six different Bragg peaks, with ranges of 51, 99, 135, 164, 196, and 204 g/cm^2, respectively. The weight function acquired from the relationship of Bragg peaks between the chamber and the film was used as a correction factor in the EBT film, for patient-specific QA.

3. Results and discussion

3.1. Dose verification of the treatment plan with film

In transverse irradiation, the dose distributions of EBT films at mid-SOBP showed good agreement (3%, 3 mm) with the calculated dose distributions (TPS). Fig. 1 shows examples of gamma index maps for transverse [(a) and (b)] and longitudinal [(c) and (d)] irradiation of the proton beam. On average, the points with a gamma index <1 were 97.6% and 91.7%, for the nine cases oriented transversely and longitudinally, respectively. Most values of the gamma index passed the criteria (3%, 3 mm) in the transverse direction; however, a few points failed in the longitudinal direction. For the longitudinal proton beam, the gamma index values exceeding the acceptance criteria were locally distributed near the edge of the SOBP, because of the under-response of the EBT film, as shown in Fig. 1(c) and (d). However, the under-response of the EBT film in the high-LET region seemed to be improved, and was slightly lower than that of the previous film model (i.e. the MD-55 film). This might be attributed to the differences in the response of the detector for proton beams, perhaps due to differences in either the crystal structure or the effective Z number of active layers. It has been demonstrated that differences in the crystal structure may be responsible for the difference in dosimetric behavior. The monomer crystals used in the MD-55 film are sand-like, whereas the monomer crystals within the EBT film are stick-like structures (Alexandra et al.,