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Commissioning of applicator-guided stereotactic body radiation therapy boost with high-dose-rate brachytherapy for advanced cervical cancer using radiochromic film dosimetry

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ABSTRACT

PURPOSE: To describe an EBT3 GAFCHROMIC film-based dosimetry method to be used in commissioning of a combined HDR brachytherapy (HDRB) and stereotactic body radiation therapy (SBRT) boost for treatment of advanced cervical cancer involving extensive residual disease after external beam treatment.

METHODS AND MATERIALS: A cube phantom was designed to firmly fit an intrauterine tandem applicator and EBT3 radiochromic film pieces. A high-risk clinical target volume ($CTV_{HR,\ Total}$) was contoured with an extended arm at one side. The HDRB treatment was planned to cover the proximal $CTV_{HR,\ Total}$ with 7 Gy and the distal volume, referred to as $CTV_{HR,\ Distal}$, was planned by SBRT for dose augmentation. After HDRB treatment delivery, SBRT treatment was delivered within 1 hour by image guidance using the applicator geometry. Intentional 1D and 2D misalignments were introduced to evaluate the effect on target volumes. In addition, effect of film reirradiation at different time gaps and dose levels was evaluated.

RESULTS: Film dosimetric accuracy, with up to 2 hours gap between irradiations, was shown to be unaffected. A 2%/2 mm gamma analysis between measured and planned doses showed agreement of >99%. Misalignments of more than 2 mm between applicator and SBRT isocenter resulted in suboptimal dose-volume histogram affecting mostly D98% and D90% of $CTV_{HR,\ Distal}$.

CONCLUSIONS: Visualizing how target dose-volume metrics are affected by minor misalignments between SBRT and HDRB dose gradients, in light of achievable phantom-based experimental quality assurance level, encourages the clinical applicability of this technique. Radiochromic film was shown to be a valuable tool to commission procedures combining two different treatment planning systems and modalities with varying dose rates and energy ranges.

Keywords: HDR brachytherapy; SBRT; Radiochromic film dosimetry; Cervical cancer

Introduction

There is emerging evidence that dose escalation to high-risk clinical target volume (CTV_{HR}) leads to improved clinical outcome in patients with cervical cancer (1–5). For patients with large residual disease at the time of brachytherapy or with unfavorable topography of parametrial spread, options include external beam parametrial boost which lacks precision (6), the addition of interstitial needles which requires a specialized brachytherapy program and is invasive procedure (7), or recent novel techniques such as directional modulation brachytherapy (8). The option of adding a stereotactic body radiation

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therapy (SBRT) boost was introduced earlier for extensive residual disease that is not properly covered by intracavitary and interstitial brachytherapy (9, 10). It was further explored as a viable alternative for centers lacking interstitial brachytherapy (11).

Image-guided brachytherapy based on 3D-imaging has become a worldwide standard mainly because of its widespread availability in radiation oncology departments (12–14). Combining image-guided high-dose-rate brachytherapy (HDRB) with SBRT per fraction for the boost treatment introduces certain complexities. These are dose calculation accuracy (requiring commissioning of the combined system), selection of dosimeters for quality assurance (QA), and radiation delivery. Summing calculated doses from two different treatment planning systems (TPSs) questions the accuracy of the combined dose distribution delivery. For the selection of dosimeters, this complexity stems from the involvement of different photon beam qualities, dose rates, and dynamic dose ranges in these treatments. During radiation delivery, complexity lies in the quality of achievable image-registration based on the applicator.

Radiochromic film offers a unique solution for such heterogeneous irradiation given its low profile and 2D high-resolution nature (15, 16), dynamic dose range (17), dose rate independence (18), energy independence in clinical radiotherapy beam qualities down to effective energy of 100 kV for EBT1, EBT2, and earlier EBT3 models (19, 20) and down to 40 kV for newer EBT3 film models with improved active layer (21), making it possible to be used for in vivo measurements (22–25) of cumulative doses. The active layer of the film polymerizes when exposed to ionizing radiation which causes film color darkening, constituting the origin of film signal. The first phase of polymerization is fast and then converts into a slow-phase (18, 26) where changes in film absorption properties are proportional to logarithm of elapsed time. This was shown for EBT1 (27) and EBT2 (28) film models and is expected to be the same for EBT3 because the sensitive layer is similar to EBT2 as shown by Ref (29). Although one may expect the active components to polymerize at the same rate when reirradiated after a certain time gap, any possible changes in the rate of polymerization question the dosimetric accuracy of the radiochromic film dosimetry system. This questioning stems from the fact that the rate of polymerization is not linear during and after exposure to radiation (27).

The purpose of this work is to introduce and evaluate an EBT3 GAFCHROMIC film dosimetry method to be used in the commissioning of a combined HDRB and SBRT boost. Film reirradiation effect, planning process, and dose delivery will be described in detail, followed by a detailed uncertainty budget on calculated and measured doses. Finally, the effect of positional inaccuracies on overall dosimetric outcome will be studied to reflect on the achievable accuracy level in light of QA results.

Methods and materials

Radiochromic film

EBT3 GAFCHROMIC film model (Ashland Inc, Wayne, NJ) from lot#07221301 was used in this study. The film structure contains a 30 μm active layer sandwiched between two 125 μm matte polyester layers. Silica particles were added between the active layer and the polyester layers to frustrate the creation of Newton rings. The active layer of the film was made of C (58.4%), O (28.4%), H (9.7%), Cl (1.1%), Li (0.9%), Br (0.8%), Na (0.4%), S (0.2%), N (0.1%) (21). In newer film batches (including the one used in this study), the Cl and Br were replaced by Al (7%) to improve energy response of the film in kilovoltage range (21) which is advantageous for the dosimetry of heterogeneous energy photon beams.

Phantoms for film calibration and reirradiation tests

Output measurements

A 10 MV photon beam from a Varian TrueBeam linear accelerator (Varian, Palo Alto, CA) was used for film calibration. The beam output was calibrated using a reference 0.6 cc PTW Farmer ion chamber type 30013 with a UNIDOS E electrometer (PTW Freiburg, Germany) in accordance to IAEA TRS398 Code of Practice (30). This chamber was positioned at 10 cm depth in a $30 \times 30 \times 30$ cm^3 Solid Water phantom, and the field size was 10×10 cm^2 at 100 cm source-to-surface distance (SSD). At the same time, output was monitored by a similar ion chamber positioned 10 cm beneath.

Film calibration

To generate the calibration curve, film pieces (5.08 cm × 10.16 cm in size) were irradiated at the same phantom and conditions described in section *Output measurements* except that the film was positioned at 10 cm depth in place of the reference ion chamber, where exact doses to film were reported from the monitor chamber. Doses of up to 41 Gy were delivered to different calibration film pieces and the choice of high-calibration dose was made because high accumulated doses were anticipated during film reirradiation tests (section *Reirradiation tests*) and also as a precaution because high doses are expected near the HDRB source.

Reirradiation tests

Different tests were designed to evaluate the ability of film to accurately measure accumulated doses from two irradiations at different dose levels, time gaps, and dose rates. The film irradiation setup was the same as described in section *Film calibration*, however, this time film was used as an absolute dosimeter, and its reading was compared with reference dose acquired from the monitor chamber reading. For practicality, films were scanned after 24 hours of a time "between" the two exposures (the base dose and the added