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Original paper

On the use of a novel Ferrous Xylenol-orange gelatin dosimeter for HDR brachytherapy commissioning and quality assurance testing

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ABSTRACT

Purpose: To evaluate a commercially available Ferrous-Xylenol Orange-Gel (FXG) dosimeter (TrueView™) coupled with Optical-Computed Tomography (OCT) read out, for 3D dose verification in an Ir-192 superficial brachytherapy application.

Methods: Two identical polyethylene containers filled with gel from the same batch were used. One was irradiated with an 18 MeV electron field to examine the dose-response linearity and obtain a calibration curve. A flap surface applicator was attached to the other to simulate treatment of a skin lesion. The dose distribution in the experimental set up was calculated with the TG-43 and the model based dose calculation (MBCA) algorithms of a commercial treatment planning system (TPS), as well as Monte Carlo (MC) simulation using the MCNP code. Measured and calculated dose distributions were spatially registered and compared.

Results: Apart from a region close to the container's neck, where gel measurements exhibited an over-response relative to MC calculations (probably due to stray light perturbation), an excellent agreement was observed between measurements and simulations. More than 97% of points within the 10% isodose line (80 cGy) met the gamma index criteria established from uncertainty analysis (5%/2 mm). The corresponding passing rates for the comparison of experiment to calculations using the TG-43 and MBDCA options of the TPS were 57% and 92%, respectively.

Conclusion: TrueView™ is suitable for the quality assurance of demanding radiotherapy applications. Experimental results of this work confirm the advantage of the studied MBDCA over TG-43, expected from the improved account of scatter radiation in the treatment geometry.

1. Introduction

Model based dose calculation algorithms (MBDCAs) have been recently introduced in Ir-192 HDR brachytherapy [1,2] as an improvement over standard algorithms based on the TG-43 formalism [3]. In contrast to TG-43 based algorithms which rely on pre-calculated data derived using homogeneous water phantoms of standard geometry, MBDCAs account for tissue inhomogeneities and scatter conditions in the patient geometry. Despite its inherent limitations, the TG-43 formalism provides the community with an intrinsic consistency in dose calculation and thus the implementation of MBDCAs must be subjected to independent experimental and/or computational verification for clinical cases and situations where non-isotropic scatter conditions and/or material heterogeneities may affect dose distributions [1]. Monte Carlo (MC) simulation has been repeatedly used for MBDCA benchmarking in such applications [2,4–9]. On the contrary, experimental verification studies in geometries simulating clinical scenarios (termed Level-2 experimental commissioning in Beaulieu et al. [1]) are scarce [10,11].

Three dimensional (3D) gel dosimeters contain a small amount of reporter molecules which undergo radiation induced change to a degree which can be correlated with absorbed dose. These dosimeters have specific advantages relative to conventional dosimeters (point dosimeters, such as ionization chamber and TLDs, and two dimensional dosimeters such as films), for quality assurance and dosimetry verification in radiotherapy applications where steep dose gradients exist, such as brachytherapy [12]. Ferrous-Xylenol Orange-Gel (FXG) dosimeters in conjunction with optical computed tomography (OCT) read out can perform this task combining speed and ease of implementation, providing accurate 3D dose distribution measurements with high

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spatial resolution (< 1mm) [13–16]. TrueView™ (Modus Medical Devices, Inc., London, ON, Canada) is a FXG composition commercially available for dose verification purposes in radiotherapy applications [17]. This gel exhibits characteristics that render it a good candidate for quality assurance (QA) in Ir-192 brachytherapy applications. It consists of low scatter gelatin facilitating OCT cone-beam scanning, its dose response is linear up to 20 Gy, and its chemical composition (H = 10.96%, C = 2.15%, N = 0.78%, O = 85.99%, S = 0.11%, Na < 0.01%, Fe < 0.01%) and physical density (1.002 g/cm^3) imply that it can be considered water equivalent.

In this work TrueView™ radiochromic gel was utilized in conjunction with OCT read out to determine its suitability for 3D dosimetry verification of an Ir-192 brachytherapy application using a flap applicator for superficial irradiation. An independent characterization of dose response linearity and water equivalence, as well as an uncertainty analysis of dosimetry using the TrueView™ gel, were performed. The potential of the method for 3D dose verification in demanding applications was evaluated through comparison with corresponding MC calculations. Given that MC is a well established computational dosimetry method and that a benchmarked methodology was used in this work [18], comparison of experiment and MC is useful in picking up undetected systematic uncertainties such as poorly characterized absorbed dose sensitivity dependencies on influence factors or spatial registration inaccuracies. The experimental set-up employed in this work is also appropriate as a benchmarking test of MBDCAs in terms of their ability to accurately predict scatter conditions when sources are positioned close to the edge of a bounded geometry, and 3D dose measurements were also compared with corresponding treatment planning system (TPS) calculations using both the TG-43 based algorithm and the Advanced Collapsed-cone Engine (ACE) MBDCA options included in Oncentra Brachy v4.5 (Nucletron BV, Veenendaal, The Netherlands). This comparison serves to evaluate whether the experimental method employed is sensitive enough to verify the differences reported in the literature between the three computational dosimetry methods [2,9,19,20]. To the best of our knowledge, this is the first study to investigate the use of the TrueView™ for dose verification in a radiotherapy application.

2. Materials and methods

2.1. Dosimeters

Two standard polyethylene terephthalate (PETE) containers filled with TrueView™ FXG from the same batch were used. The cylindrical containers (approximate dimensions: 9.6 cm diameter, 16 cm height) and the accompanying lids were fully compatible with the Vista^{TM} (Modus Medical Devices Inc, London, ON, Canada) cone beam CCD-based optical scanner [21]. One dosimeter was used for dose response characterization (see Section 2.2) and the other was subjected to an irradiation mimicking a brachytherapy treatment of a superficial skin malignancy (see Section 2.3).

2.2. Dose response characterization

In the absence of relevant literature, the TrueView™ dosimeter was evaluated in terms of its suitability for use in dose verification of HDR brachytherapy. One of the two 1L PETE TrueView™ FXG containers used in this work was irradiated to verify dose-response linearity, determine the dosimeter's sensitivity and obtain a calibration curve. A maximum dose of 12 Gy was delivered to the gel by a single 18 MeV electron field of 5 cm in diameter, with the container lid removed (Fig. 1(a)). The gel was OCT scanned and the resulting Optical Density (OD) change was correlated with dose to water as determined by corresponding measurements following the IAEA TRS-398 protocol [22]. This approach is commonly adopted in the literature [16,23,24]. Custom routines were developed to calculate the mean OD change over a region of interest of 2.5 × 2.5 mm^2 around the central beam axis on every slice. The OD results obtained were fitted to corresponding electron depth-dose measurements to yield the TrueView™ dosimeter dose response calibration and sensitivity.

2.3. Brachytherapy treatment planning and irradiation

A CT compatible surface applicator flap, used for the treatment of superficial skin malignancies, was attached to the second PETE TrueView™ FXG container to facilitate dose delivery. In particular, the flap comprises 18 parallel plastic catheters embedded into a 0.8 cm thick, rectangular (18 × 22.5 cm^2) piece of bolus material (Fig. 1(b)) with a Hounsfield Unit (HU) of approximately 290. The flap is flexible and therefore easy to fix around the container (Fig. 1(c)) but relatively incompressible. The flap was fixed in such a way that it was level with the container base with the catheters' tips lying closer to the container's base, providing a reproducible position with respect to the container's central axis. Five pen markers (OCT compatible) determined the flap's edges on the container during irradiation to facilitate the spatial registration of data from different imaging modalities, X-ray CT used for treatment planning and optical CT used for dosimeter read out.

An irradiation plan simulating a superficial skin lesion treatment was prepared. The gel container with applicator flap attached underwent X-ray CT scanning with a reconstructed voxel size of 0.3633 × 0.3633 × 1 mm^3 (512 × 512×177 DICOM CT images). The CT image series was imported into the Oncentra Brachy v. 4.5 TPS which includes a MBDCA option besides the standard TG-43 based algorithm. Using the TPS-embedded tools a structure set was generated including the external contour, the flap and a planning target volume (PTV) mimicking a 0.7 cm thick skin lesion of area 7 × 4 cm^2 (Fig. 2). A plan was prepared using the microSelectron v.2 Ir-192 HDR source. The catheters were reconstructed and reference dose points were created within the PTV at a distance of 1 cm from the six central catheters. Geometrical optimization was applied and dose was normalized to the reference dose points. Dose coverage goals included 100% of the prescribed dose covering at least 90% of the PTV. A prescribed dose of 8 Gy to the 100% isodose was chosen to optimize dose delivery to the dosimeter according to its calibration dose range. The resulting plan consisted of 56 active source dwell positions in the 8 central catheters and a total reference air kerma (TRAK) of 3282 cGy × cm^2 (Fig. 2).

2.4. Experimental dosimetry protocol

The protocol for the measurement of radiation induced OD changes involved a pre- and a post- irradiation cone-beam OCT scan at 589 nm, consisting of 512 projections (i.e., a rotation step of 0.7032°) and one dark field image. A minimum warm up time of three hours was allowed for light source stabilization prior to OCT scans [13]. During image acquisitions, the gel container was immersed into a tank filled with a refractive index matching water solution of 11 wt% propylene glycol [21]. The FXG containers were transported in a large water container to allow for temperature stability. Both the refractive index matching tank and transportation container were left to equilibrate to room temperature. This ensured temperature control within less than 1.5 °C between the OCT scans and the irradiations.

All scanning, handling, storage and transportation conditions and parameters were the same for both the calibration gel and the gel used for the brachytherapy application, in order to achieve maximum conformance between them [13] and the same auto-oxidation effects [16]. In specific, the two gels were transported together in the same water container, irradiations were carried out at approximately the same temperature and specific care was taken in performing all scans for both containers at closely matched time conditions [13]. Accuracy demands in the latter aspect of the followed protocol are relaxed by the fact that the radiation-induced signal is stable within a time window of 60–90 min post-irradiation, according to the manufacturer. Light