How feasible is remote 3D dosimetry for MR guided Radiation Therapy (MRgRT)?

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Abstract. To develop and apply a remote dosimetry protocol with PRESAGE® radiochromic plastic and optical-CT readout in the validation of MRI guided radiation therapy (MRgRT) treatments (MRIdian® by ViewRay®). Through multi-institutional collaboration we performed PRESAGE® dosimetry studies in 4ml cuvettes to investigate dose-response linearity, MR-compatibility, and energy-independence. An open calibration field and symmetrical 3-field plans were delivered to 10cm diameter PRESAGE® to examine percent depth dose and response uniformity under a magnetic field. Evidence of non-linear dose response led to a large volume PRESAGE® study where small corrections were developed for temporally- and spatially-dependent behaviors observed between irradiation and delayed readout. TG-119 plans were created in the MRIdian® TPS and then delivered to 14.5cm 2kg PRESAGE® dosimeters. Through the domestic investigation of an off-site MRgRT system, a refined 3D remote dosimetry protocol is presented capable of validation of advanced MRgRT radiation treatments.

1. Introduction

⁶⁰Co IMRT subject to a 0.35T lateral magnetic field was recently commissioned at Siteman Cancer Center at Barnes-Jewish Hospital and Washington University School of Medicine in St. Louis (Missouri, USA) following AAPM’s TG-119 recommendations [1]. Dosimetric challenges arise with the introduction of an MR field into radiotherapy i.e. electron return effect (ERE), ferromagnetic incompatibility during quality assurance (QA), etc. [2]. Our unique approach to MRgRT dosimetry affords high-resolution 3D measurements [3] using PRESAGE® radiochromic plastics and optical-CT. Previous works qualitatively demonstrated remote dosimetry feasibility and dose-response linearity in 1kg volume PRESAGE® over 48hrs [4, 5]. Until now, remote dosimetry studies have been limited to this small field-of-view (FOV) dosimeter (8x10cm), insufficient in size for routine clinical plans. Here, we investigate the large-FOV (2kg) PRESAGE® (10x14.5cm), dose-response stability in remote dosimetry settings with a quantitative approach, to identify and model temporal and spatial behaviors over time.
2. Materials and Methods

2.1 The PRESAGE®/Optical-CT System

High resolution 3D Dosimetry was performed with the PRESAGE® dosimeter (Heuris Inc.), a radiochromic plastic, and the Duke Large Optical-CT Scanner (DLOS), an in-house bi-telecentric optical-CT scanner [6]. The linear dose-response using PRESAGE is well documented in the literature [7-9]. Formulation details are displayed in Table I. DLOS data acquisition was performed in two phases, pre- and post-irradiation, to yield change in optical density (ΔOD) post-reconstruction of 720 dosimeter projections at 0.5° increments (360° rotation). Reconstruction at 1mm isotropic resolution was performed in a MATLAB-based GUI developed in-house using filtered back-projection and a RamLak filter. ΔOD reconstructions were imported into A Computational Environment for Radiotherapy Research (CERR), a MATLAB software developed at Washington University, registered to the corresponding treatment plan, and scaled to the point of prescription dose (relative dosimetry).

Table 1. PRESAGE® formulation (DEA-1.5) and composition. Percentages are given by weight.

| Component                | % Make-up |
|--------------------------|-----------|
| Smooth-On Crystal Clear® | 91.50%    |
| Ethyl Acetate            | 5.00%     |
| DMSO                     | 2.00%     |
| 2-methoxy-DEA LMG        | 1.50%     |
| Carbon Tetrabromide      | 0.50%     |

2.2 Small Volume Characterization

Prior to the 3D TG-119 MRgRT study, PRESAGE® sensitivity (dose-response) was tested in 4ml cuvettes to verify three key factors: linearity, MR-compatibility, and energy-independence in remote dosimetry use. Eight cuvettes from a single batch of PRESAGE® material were separated into two irradiation groups: ⁶⁰Co with 0.35 T MRgRT (200cGy/min), and 6 MV linac RT (600cGy/min). Four cuvettes were uniformly irradiated to 0, 5, 10, and 15Gy on both systems under the following dosimetric conditions: 10×10 cm field, 5 cm buildup, 10cm backscatter. Absorption measurements were taken and optical density was calculated prior to and after (t=48hr) irradiation using a Spectronic Genesys 20 spectrophotometer (Thermo Electron Scientific Instruments Corp., Madison, WI).

2.3 Large Volume Characterization

A detailed study of PRESAGE® dosimeters (2kg) was conducted to investigate the temporal and spatial stability of radiation induced optical density change (ΔOD) over one week. Dose-response linearity was investigated on three dosimeters irradiated with four equally-spaced square (4cm2) 6MV fields delivering doses between 10cGy and 300cGy. Spatial uniformity of ΔOD response was investigated on three separate dosimeters irradiated uniformly with 15MV extended-SSD fields with doses of 15cGy, 30cGy and 60cGy. Data from temporal and spatial stability studies were compiled, analyzed, and modeled using CERR and MATLAB’s Curve Fitting tool-box. Derivation of the temporal correction for scan-time t’=48hrs (Cₜ) involved normalizing ΔOD reconstructions from t=48hr (delayed) by ΔOD reconstructions at t=1hr (immediate). Derivation of the spatial correction for scan-time t’=48hrs (Cᵣ) involved the subtraction of registered ΔOD reconstructions for time-stamp t=1hr from t’=48hrs as a function of radial distance from dosimeter core. The final corrected optical density measurement ΔOD_{t=1hr} is displayed in the equation 1 below:

$$\Delta OD_{t=1hr} = \Delta OD_{t=48hrs} \left( C_T - \frac{C_R}{100} \right)$$

(1)
Application of equation 1 involves correcting each element within a scan taken at t’=48hrs, the typical post-irradiation scan-time in a remote dosimetry study, back to t=1hr.

2.4 MRgRT Study
TG-119 plans were created in the MRIdian®’s (by ViewRay®) TPS located at Washington University in preparation for an IMRT evaluation study [10]. 2x1kg and 4x2kg PRESAGE® dosimeters were scanned, pre-irradiation, at Duke and shipped. For preliminary large volume testing, we delivered an open calibration (AP) beam and a symmetrical 3-field plan (BANDS) with three adjacent regions of varying dose (3Gy, 6Gy, 9Gy) using 10cm diameter PRESAGE®. Percent depth dose and dose-response uniformity within the dosimeter under a magnetic field were analyzed. After initial testing, the remainder of TG-119 plans were delivered to 14cm 2kg PRESAGE® dosimeters. Dosimeters were returned to Duke within t=48hrs post-irradiation for dose readout. All treatment deliveries were validated with absolute dose measurements using an IBA CC01 ion chamber and Washington University’s standard patient-specific QA methods for MRgRT systems.

3. Results
3.1 Formulation Characterization
In small volume (4ml), PRESAGE® responds linearly to ⁶⁰Co irradiation, in the presence of a 0.35T magnetic field. The sensitivity was measured at (0.0305±0.003)cm⁻¹Gy⁻¹, R²=0.9996) This value is within 1% of a 6MV non-MR linac irradiation (0.0302±0.003)cm⁻¹Gy⁻¹, R²=0.9991). In the large volume study (2kg), consistent intra-batch sensitivity (0.0930±0.002 ΔODcm⁻¹Gy⁻¹) and linearity (R²=0.9996) was observed at t=1hr. However, all dosimeters were observed to gradually darken with time (<5% per day globally) and exhibited a non-linear dose-response at later scan times (>1hr). Relative depth dose distributions are displayed in Figure 1.a for scans with time stamps t=1hr and t=4hrs for the four 4cm² fields: A, B, C, and D with Rx doses of 300cGy, 130cGy, 75cGy and 30cGy, respectively. A spatially uniform dose-response was observed at scan-time t=1hr. In delayed scans (>1hr), a small radially-dependent dose-response (<3% globally) was observed Figure 1.b. These results are currently under further scrutiny, but initial hypothesis attributes the phenomena to curing thermodynamics during manufacture. The refined remote dosimetry protocol (including polynomial correction terms for temporal and spatial effects, C_T and C_R) was then applied to independent dosimeters irradiated with MRgRT treatments (Figure 1.c-e).

3.2 TG-119 for MRgRT in 3D
Analysis of TG-119 clinical plans using 3D-gamma (3%/3mm, 10% threshold) give passing rates of: AP 99.3%, bands 99.6%, H&N 99.1%, prostate 98.0%, C-shape 90.8%, and multi-target 98.5%. The average 3D-gamma passing rate for the same criteria was 97.5%± 3.37%.

4. Conclusion
The presence of strong magnetic fields in MRgRT introduces new challenges and constraints to the already difficult task of complex treatment verification. The PRESAGE®/Optical-CT dosimetry system has some useful features in this context, remaining functionally unaffected by magnetic fields, and able to yield dosimetry information in high resolution in 3D. Here we demonstrate a novel 3D remote dosimetry protocol which can provide uniquely comprehensive verification data to enhance commissioning and treatment plan verification for MRgRT. The protocol uses 2kg radiochromic plastic dosimeters read-out by optical-CT within a week of treatment. Small correction factors (~5%) are required to account for spatial and temporal changes that occur in the dosimeter during the delayed readout period of one-week post-irradiation.
Figure 1. (a) Relative depth dose distribution measurements for four fields (A-300cGy, B-130cGy, C-75cGy and D-30cGy) at time-stamp t=1hr and t=48hrs, revealing non-linear increase in OD in delayed read-out. (b) Normalized radial dose-response between t=1hr and t=48hrs of uniformly irradiated dosimeters at 60cGy). (c) Temporal (relative ratio) and (d) spatial (%Δ) corrections. (e) 3D TG-119 remote dosimetry using PRESAGE® for ViewRay®. Left to right: TPS calculated dose, measured dose, and 3D-gamma (3%/3mm, 10% threshold) for Multi-target (98.5% passing rate for 3%/3mm, 10% threshold criteria).
5. References

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