Characterization of a reusable PRESAGE® 3D dosimeter

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Abstract. This study investigates a reusable PRESAGE® 3D dosimeter (Presage-RU), which would improve cost-effectiveness and facilitate wider implementation of comprehensive, high resolution 3D dosimetry. Small (1x1x4.5 cm) and large (8 cm diameter, 4.5 cm length) sample dosimeters were irradiated multiple times to characterize dose response (i.e. radiation-induced change in optical density (ΔOD)), optical clearing rate, and dose distribution stability. Presage-RU exhibited an initial dose response sensitivity of 0.0119 ΔOD/(cm∙Gy), a reduction in response with subsequent irradiations, and a small, permanent ΔOD (~1-6% of initial signal) following each irradiation. Dosimeters optically cleared at an exponential rate (average T½ = 24.8±3.6 h), and were effectively cleared after ~5-8 days. 3D gamma analysis (3%/3mm, 10% dose threshold) of a 4-field box plan applied to the large dosimeter showed good agreement following initial irradiation (96.6% passing), but a reduction in passing rate (89.1% passing) with subsequent irradiation. Further study is warranted to fully assess and quantify the performance of Presage-RU for repeat irradiations.

1. Introduction
PRESAGE® is a radiochromic plastic which has demonstrated strong potential in high resolution 3D dosimetry [1-5]. Permanent radiochromic response has limited current PRESAGE® dosimeters to single use, and while optical clearing has been noted in several earlier PRESAGE® formulations [6-8], there has not yet been an extensive study to determine the feasibility of putting potentially reusable 3D PRESAGE® dosimeters into clinical use. A new PRESAGE® formulation (Presage-RU, Table 1) exhibits a reversible response that optically clears post-irradiation and allows for reirradiation, which opens up the potential for reusability. This would have the practical benefit of improving cost-effectiveness and facilitating the wider implementation of comprehensive, high resolution 3D dosimetry.

This study investigates the feasibility of Presage-RU for reusability by studying dose response, optical clearing rate, and the stability of relative dose distributions for repeat irradiations.

2. Methods
Multiple irradiation experiments were performed on Presage-RU samples of both small and large volumes to allow exploration of any volume effect. All irradiations (doses and details below) were performed at 6 MV and 600 MU/min on a clinical linac. All measurements were tracked for 14 days following each irradiation, and dosimeters were allowed to completely optically clear at room temperature in a dark room between irradiations.
Table 1. Comparison of the components in a standard, single-use PRESAGE® formulation and the new Presage-RU formulation.

| Formulation   | Polyurethane          | Leuco Dye          | Initiator     | Other Components | Shore Hardness |
|---------------|-----------------------|-------------------|---------------|------------------|---------------|
| Single Use    | 91.10% Smooth-On      | 1.5% o-MeO-DEA LMG | 0.40% CBr4   | 2.0% DMSO, 5.0%  | 80D           |
| PRESAGE®      | Crystal Clear® 206    |                   |               | C6H12O2          |               |
| Presage-RU    | 46.25% Heuris Inc.   | 1.7% o-MeO-DEA LMG | 0.40% CBr4   | 2.0% DMSO, 3.4%  | 30-50A        |
|               | FC30                  |                   |               | solvents         |               |
|               | FC50                  |                   |               |                  |               |

2.1. Small volume measurements
Small volume dosimeter samples were made in optical cuvettes (1x1x4.5 cm). Characterization of dose response and optical clearing rates was performed on the small volume dosimeter samples, which were irradiated to known doses from 0-8 Gy. Subsequent change in optical density (ΔOD) was determined by measuring absorption before and after irradiation using a Spectronic Genesys 20 spectrophotometer, then subtracting the preirradiation value from the postirradiation value. Measurements of an unirradiated control sample were used to correct for systematic error at each time point. All samples were subject to 5 irradiations total, with the same dose delivered to each sample with each subsequent irradiation.

2.2. Large volume measurements
A large volume sample was made as a cylindrical dosimeter (8 cm diameter, 4.5 cm length). The cylindrical dosimeter was irradiated with a 4-field box plan (parallel opposed pairs of 4x4 cm² AP-PA beams and 4x2 cm² lateral beams) to a central dose of 20 Gy. High resolution (1 mm isotropic) 3D dose distributions were obtained through optical-CT imaging with the Duke Mid-sized Optical-CT Scanner (DMOS) [2, 4, 9, 10] at multiple time-points. Measured relative dose distributions were compared to the corresponding calculated dose distribution from a commissioned treatment planning system (Eclipse, Varian Medical Systems). The Presage-RU dose was normalized to the central high dose region of the calculated distribution. Presage-RU’s suitability for reusable dosimetry was evaluated with 3D gamma passing rates (3%/3mm criteria, 10% dose threshold) calculated for both the initial irradiation and one subsequent reirradiation. 3D gamma calculations and dose registrations were performed in CERR (Washington University).

Tracking measurements in the dosimeter (average ΔOD within the 98% isodose region) were also compared against the dose response and optical clearing rate determined from the small volume dosimeters.

3. Results

3.1. Dose Response
The initial irradiation yielded a change in optical density in small volumes of Presage-RU of 0.0119 ΔOD/(cm·Gy), followed by reduced responses in subsequent irradiations (figure 1), Table 2). A strong linearity of response (R²≥0.993) was observed for all irradiations.

3.2. Optical Clearing
Optical clearing in small volume Presage-RU samples was observed to be an exponential decay over time (figure 2). A summary of decay constants and half-life values (determined over 96 h and averaged across doses for each irradiation) can be found in Table 3. Presage-RU samples were effectively cleared after ~5-7 days. A small, permanent post-irradiation change in optical density (0.0001-0.0039 ΔOD/cm, ~1-6% of initial signal) was observed to persist after clearing. This does not
affect subsequent measurements as pre-irradiation measurements are used to determine ∆OD after irradiation.

Measurement tracking in the larger dosimeter similarly demonstrated a drop in response with re-irradiation and exponential decay in optical density (figure 3). Half-lives were 24.8 h (initial irradiation) and 27.7 h (re-irradiation), with effective dosimeter clearing after ~5-8 days.

Table 2. Dose response sensitivity and linearity determined from multiple irradiations of PRESAGE-RU.

| Irradiation | Dose Response (Iteration #) | Fit Linearity |
|-------------|-----------------------------|---------------|
| #1          | 0.0119                      | 0.9996        |
| #2          | 0.0087                      | 0.9966        |
| #3          | 0.0087                      | 0.9960        |
| #4          | 0.0083                      | 0.9930        |
| #5          | 0.0070                      | 0.9943        |

Figure 1. Change in optical density in small volume cuvettes following initial and subsequent irradiations. Fit values are summarized in table 1.

Figure 2. Optical clearing of small volume Presage-RU samples following initial irradiation.

Table 3. Optical clearing decay constants and half-lives.

| Irradiation Iteration # | Average λ (h⁻¹) | St Dev λ (h⁻¹) | Average T₁/₂ (h) | St Dev T₁/₂ (h) |
|-------------------------|-----------------|----------------|------------------|-----------------|
| 1                       | 0.033           | 0.002          | 21.2             | 1.4             |
| 2                       | 0.035           | 0.013          | 21.7             | 6.5             |
| 3                       | 0.025           | 0.002          | 27.5             | 1.9             |
| 4                       | 0.024           | 0.002          | 29.6             | 2.3             |
| 5                       | 0.029           | 0.002          | 24.2             | 1.9             |
| Average                 | 0.029           |                 | 24.8             |                 |
| St Dev                  | 0.004           |                 | 3.6              |                 |
3.3. Relative Dosimetry
The 3D gamma passing rates were 96.6% for the initial irradiation and 89.1% for the subsequent irradiation. Gamma maps (figure 4) and line profiles showed that the passing rate decrease in the reirradiated distribution was primarily due to dose underestimation in the anterior portion of the dosimeter and dose overestimation in the lateral regions outside of the high-dose box.

Figure 3. Optical clearing in a dosimeter as represented by average dose response over time in the 98% isodose region of the 4-field box distribution.

Figure 4. 3D gamma passing maps of initial dosimeter irradiation and subsequent reirradiation.

4. Conclusions
This preliminary study introduced Presage-RU, a potentially reusable radiochromic 3D dosimeter that can be imaged with high resolution optical-CT. Presage-RU demonstrated strong dose linearity and an average optical clearing half-life of 24.8±3.6 h over 5 irradiations. The dose response between the small and large volume Presage-RU dosimeters differed by 5.5% for the initial irradiation and 3.6% for a subsequent irradiation, but yielded similar optical clearing characteristics. A small permanent change in optical density (0.0001-0.0039 ∆OD/cm, ~1-6% of initial response) persists following each irradiation. Good agreement was seen between measured relative dose and calculated dose distributions upon initial irradiation, but further study is warranted to quantify the accuracy of Presage-RU for relative dosimetry following subsequent re-irradiations.
5. Acknowledgements
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6. References
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