Preliminary investigation of a reusable radiochromic sheet for radiation dosimetry

Cielle Collins[1], Jacob Kodra[1], Suk Whan Yoon[1], Robert Coakley[2], John Adamovics[2], and Mark Oldham[1]

(1) Duke University, Durham, North Carolina, USA (2) Rider University, Lawrenceville, New Jersey, USA.

cielle.collins@duke.edu & mark.oldham@duke.edu

Abstract. This work investigates a novel reusable radiochromic sheet developed as an economic film substitute and also, potentially, as a radiochromic bolus. The radiation-induced optical density (OD) change of the sheet is read-out with a commercial flat-bed optical scanner. An optimized readout procedure was developed including an optimal scan-time window. Fundamental radiochromic properties of the sheets were characterized including temporal decay of OD, dose sensitivity and consistency through repeated irradiations, and temperature sensitivity. The radiation induced OD change in the sheets was found to decay to baseline within ~24 hours, after which the sheet could be reused. The sensitivity of subsequent re-irradiations was found to be consistent within ±5% (coefficient of variation of 4.5%) for 6 irradiations. Importantly, the sheets were not observed to carry any detectable memory of previous irradiations within measurement uncertainty. In conclusion, the Presage sheets show promise as an economic multi-purpose alternative for film applications and potentially as a radiochromic bolus. Further work is required to test the sheet in diverse clinical applications, and to develop a softer material for bolus applications.

1. Introduction

Presage is a well-established dosimetric material composed of a transparent polyurethane matrix, containing a leuco dye with a radiochromic response when exposed to ionizing radiation [1-5]. The radiation induced optical density (OD) change can be imaged and used to measure radiation dose distributions. Permanent radiochromic response has typically limited Presage dosimeters to one-time use [1]. In this work, we characterize a new reusable formulation of Presage and evaluate its potential for use primarily as an economic radiochromic film alternative and secondarily as a radiochromic bolus. In this formulation, the Presage is cast in sheets for 2D evaluation and readout with a flatbed scanner. Extension to reusable 3D dosimetry may be possible, but has not been explored here. Bolus has been used for many years, with recent improvements including the capability for 3D printed bolus [6-8]. This work extends these efforts by developing a bolus that is radiochromic, reusable, and can aid in treatment verification. Reusable Presage is suitable for manufacturing into sheets of variable thickness (1-10mm) and variable stiffness for bolus applications.

2. Methods

The reusable Presage sheets are manufactured by Heuris, INC. The sheets use 2% cumin-LMG-DEA (see figure 1) with varied plasticizer (25% by weight), depending on applications. The sheets consist of a uniform active layer with no coatings or substrates, which differentiates them from traditional films. The active leuco dye molecules are uniformly distributed throughout the sheet leading to a nominal uniform response. The consistency of thickness of sheets is confirmed using an electronic caliper. The current investigations were performed with a standard reusable Presage formulation and sheet thickness of 5 mm.

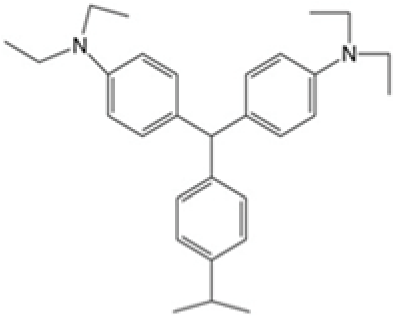

Figure 1: Structural formula of leuco dye cumin-LMG-DEA.

All Presage sheets were scanned without enhancements using an Epson Expression 10000XL flatbed scanner and subsequently analyzed to yield change in OD measurements, which are proportional to delivered dose. To avoid air bubbles, each sheet was pressed into a 1 cm diameter drop of mineral optical fluid, applied to the scanner bed. The scanner was set to 48-bit color, resolution 50 dpi, document size 5x5 in. Each scanned image had a 0.5 mm resolution. As in EBT film analysis, the red channel of the RBG image from the scanner was selected for image analysis [9]. A pre-scan was taken before each irradiation and a readout scan was taken soon after. Sheets were then removed from the scanner and stored in an opaque dark bag at room temperature until needed for the next irradiation. The OD change was calculated by taking the log of the pre-scan divided by the post-scan. As the change in OD radiochromic response of reusable Presage is linear with dose, these images are dose maps.

The temporal decay of the radiation induced change in OD in the sheets was studied by irradiating four 0.5 cm thick 6 cm^2 sheets to 6, 4, 2, and 1 Gy. They were irradiated at dmax (depth of maximum dose) in a solid water phantom stack with 6 cm solid water beneath the sheets and 1.5 cm above. Before the irradiation the sheets were pre-scanned and then after the irradiation they were scanned every 10 minutes for an hour and every hour for 9 hours, with a final readout taken at 26 hours post-irradiation.

To assess the Presage reusability, two experiments were conducted. The first experiment was a repeat pyramidal experiment where each of a series of four concentric square irradiations (at dmax, solid water phantom stack) were delivered on consecutive days to the same 0.5 cm thick, 12 cm^2 sheet with the field size increasing every day. This created pyramidal steps of cumulative dose, with time for the signal to fade-out between each irradiation. Each field was delivered centered on the sheet with a dose of 4.5 Gy. The Presage was pre-scanned before irradiation and scanned for readout 8 minutes after each irradiation. For analysis, a 5 mm median filter was applied to the readout scans to minimize the effect of sheet imperfections. After each irradiation in the series, a line profile through the center of the sheet, crossing each concentric square field, was analyzed, quantified, and plotted against each line profile from the previous layered irradiations.

The second experiment was a repeat irradiation series with the same field overlaid each day, for a greater number of irradiations. A 0.5 cm thick, 6 cm^2 Presage sheet was irradiated at dmax in a solid water phantom stack with a 4x4 cm 4.5 Gy field once a day. The sheet was pre-scanned once before each irradiation and post-scanned 10 minutes after each irradiation. The change in OD at 10 minutes was quantified and compared each day.

3. Results and Discussion

Figure 2 presents the decay of the reusable Presage radiation induced color change with time. A final readout scan was taken 26 hours after irradiation. This scan demonstrated cleared signal for all doses, with less than 2% of signal remaining. Temporal decay curves were created for 6 Gy, 4 Gy, 2 Gy, and 1 Gy irradiations and the control sheet. The decay constants for the curves were 6.5 $hours^{-1}$ for 6 Gy, 5.7 $hours^{-1}$ for the 4 Gy data, 5.6 $hours^{-1}$ for the 1 Gy and 2 Gy data, and a constant change in OD (within scanner error range) along the zero ΔOD line for the control sheet.

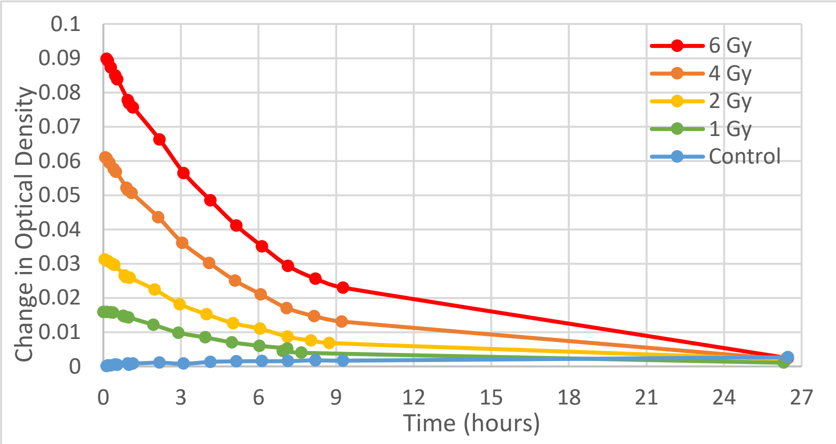

Figure 2: Temporal decay of reusable Presage signal in a 26 hour period. Five different sheets were irradiated to four doses: 1 Gy (green), 2 Gy (yellow), 4 Gy (orange), 6 Gy (red), and an un-irradiated control (blue). The sheets were scanned together periodically for 26 hours.

This data was used to find a clinical scanning time window. Fifteen minutes post irradiation was determined to be a clinically feasible scan time. Using the 6 Gy data, which has the steepest decay, a suggested readout window of 1-24 minutes post irradiation for doses less than or equal to 6 Gy was developed. This was based on the elapsed time before and after 15 minutes when the change in OD had diverged by less than ±3% from the change in OD at 15 minutes.

The pyramid style test was used to determine whether the reusable Presage sheets carried any memory effects from prior irradiations. In figure 3, the illustration explains the irradiation pattern used in the pyramid test. Figure 4 presents the results from this experiment. In this figure, each line profile is a smooth straight line across the irradiated section and each line reaches up to about the same change in OD value, with a 3.5% percent difference between the centers of the two most different line profiles and a 1.52% coefficient of variation. In an analysis of the scanner error and known machine error from calibration standards, an overall expected error range of ±5 % was determined. The error found in this analysis falls well within this ±5% expected error range. The overall finding that each line profile in figure 4 falls within 3.5% of every other profile with no evidence of reduction in signal in the regions of the profile where previous irradiations occurred indicates that the sheets do not carry a memory of previous irradiations.

Figure 3: Graphic of the pyramid test experimental setup where a series of four concentric 4.5 Gy irradiations was delivered consecutively to the same sheet, with the field size increasing every day, to create pyramidal steps of cumulative dose. Signal was allowed 24+ hours to clear after each irradiation. The yellow bar in each diagram of figure 2 marks the line profiles collected 10 minutes after irradiation.

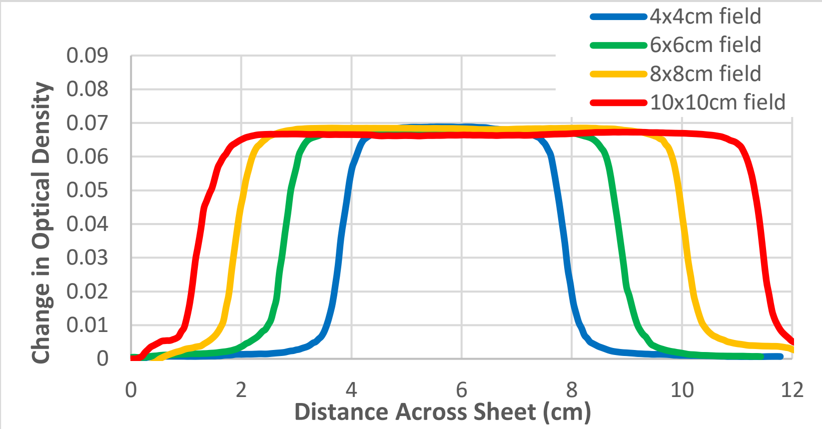

Figure 4: Pyramid style reusability test. The plot presents line profiles from the center axis of the reusable Presage sheet after each irradiation. Each irradiation delivered 4.5 Gy to the sheet with the first filling a 4x4 cm field (blue), second a 6x6 cm field (green), third an 8x8 cm field (yellow) and fourth a 10x10 cm field (red).

To investigate the extended reusability of the Presage sheets, one sheet was irradiated to the same dose with the same field on six different days. This process was also repeated 3 times on a different sheet with a 2 Gy dose instead of 4.5 Gy. For the six 4.5 Gy irradiations, there was a standard deviation of 7.4×10^{-4} and a coefficient of variation of 4.5% (figure 5). The 2 Gy repeated irradiation dataset had a standard deviation of 2.9×10^{-4} and a coefficient of variation of 1.95% (figure 5). These percentages were considered in reference to the same ±5 % expected error range from scanner error and known machine error from calibration standards.

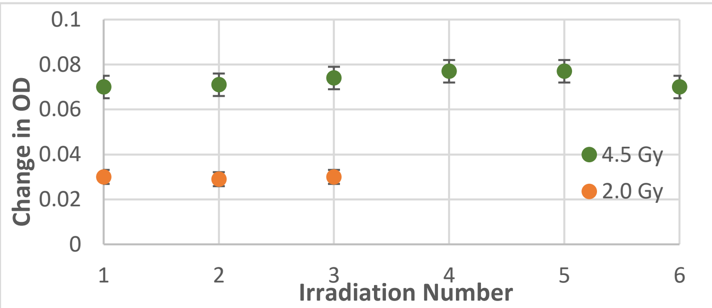

Figure 5: Repeatability of radiation induced color change upon repeated use. The same reusable Presage sheets were irradiated with a 4 cm^2 field to 4.5 Gy on six different days (green) and a different sheet to 2 Gy on three different days (orange). Sheets were scanned at 10 minutes post-irradiation and all change in OD values fell within the established machine and scanner error range (±5 %).

4. Conclusion

Reusable Presage shows promise as an economic multi-purpose alternative for film applications and as a radiochromic bolus. The results of this work correspond to sheets of 5 mm thickness. This may be an optimal thickness for many applications considering that the sensitivity and stiffness decreases with thinner sheets. To date studies have been limited to 6 re-irradiations, and have shown that repeat dose sensitivity is consistent within ±5%. Some uniform background increase in OD was observed which may limit the number of repeat irradiations, however further modifications to the formulation may reduce this limitation. Future work will investigate reusable Presage applications in QA practices and as a radiochromic bolus.

5. References

[1] Guo P, *et al.* 2006. *Med Phys*. **33**(5): 1338–1345.
[2] Palmer AL, *et al.* 2013. *Medical Physics,* **40** (6).
[3] Guo P, *et al.* 2005 *Int J Radiat Oncol, Biol, Phys* **63**:S206–S206. 32.
[4] Adamovics J, *et al.* 2003. *Med Phys* **30**:1349–1349.
[5] Sakhalkar HS, *et al.* 2008. *Medical Physics,* **36** (1).
[6] Pugh R, *et al.* 2017. *Journal of Radiotherapy in Practice,* **16** (3).
[7] Yang K, *et al.* 2017. *Radiotherapy and Oncology,* **123**(1) S636-S637.
[8] Fujimoto K, *et al.* 2017. *European Journal of Medical Physics,* **38** 1-9.
[9] Fiandra C, *et al.* 2006. *Medical Physics,* **33** (11).