On the feasibility of comprehensive high-resolution 3D remote dosimetry

Titania Juang

*Medical Physics Graduate Program, Duke University Medical Center, Durham, North Carolina 27705 and
Department of Radiation Oncology Physics, Duke University Medical Center, Durham, North Carolina 27710*

Ryan Grant

*The Graduate School of Biomedical Sciences, University of Texas Health Science Center, Houston, Texas 77030
and Department of Radiation Physics, University of Texas MD Anderson Cancer Center, Houston, Texas 77030*

John Adamovics

Department of Chemistry and Biology, Rider University, Lawrenceville, New Jersey, 08648

Geoffrey Ibbott

Department of Radiation Physics, University of Texas MD Anderson Cancer Center, Houston, Texas 77030

Mark Oldham^{a)}

Department of Radiation Oncology Physics, Duke University Medical Center, Durham, North Carolina 27710

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Purpose: This study investigates the feasibility of remote high-resolution 3D dosimetry with the PRESAGE®/Optical-CT system. In remote dosimetry, dosimeters are shipped out from a central base institution to a remote institution for irradiation, then shipped back to the base institution for subsequent readout and analysis.

Methods: Two nominally identical optical-CT scanners for 3D dosimetry were constructed and placed at the base (Duke University) and remote (Radiological Physics Center) institutions. Two formulations of PRESAGE® (SS1, SS2) radiochromic dosimeters were investigated. Higher sensitivity was expected in SS1, which had higher initiator content (0.25% bromotrichloromethane), while greater temporal stability was expected in SS2. Four unirradiated PRESAGE® dosimeters (two per formulation, cylindrical dimensions 11 cm diameter, 8.5–9.5 cm length) were imaged at the base institution, then shipped to the remote institution for planning and irradiation. Each dosimeter was irradiated with the same simple treatment plan: an isocentric 3-field “cross” arrangement of 4 × 4 cm open 6 MV beams configured as parallel opposed laterals with an anterior beam. This simple plan was amenable to accurate and repeatable setup, as well as accurate dose modeling by a commissioned treatment planning system (Pinnacle). After irradiation and subsequent (within 1 h) optical-CT readout at the remote institution, the dosimeters were shipped back to the base institution for remote dosimetry readout 3 days postirradiation. Measured on-site and remote relative 3D dose distributions were registered to the Pinnacle dose calculation, which served as the reference distribution for 3D gamma calculations with passing criteria of 5%/2 mm, 3%/3 mm, and 3%/2 mm with a 10% dose threshold. Gamma passing rates, dose profiles, and color-maps were all used to assess and compare the performance of both PRESAGE® formulations for remote dosimetry.

Results: The best agreements between the Pinnacle plan and dosimeter readout were observed in PRESAGE® formulation SS2. Under 3%/3 mm 3D gamma passing criteria, passing rates were 91.5% ± 3.6% (SS1) and 97.4% ± 2.2% (SS2) for immediate on-site dosimetry, 96.7% ± 2.4% (SS1) and 97.6% ± 0.6% (SS2) for remote dosimetry. These passing rates are well within TG119 recommendations (88%–90% passing). Under the more stringent criteria of 3%/2 mm, there is a pronounced difference [8.0 percentage points (pp)] between SS1 formulation passing rates for immediate and remote dosimetry while the SS2 formulation maintains both higher passing rates and consistency between immediate and remote results (differences ≤ 1.2 pp) at all metrics. Both PRESAGE® formulations under study maintained high linearity of dose response ($R^2 > 0.996$) for 1–8 Gy over 14 days with response slope consistency within 4.9% (SS1) and 6.6% (SS2), and a relative dose distribution that remained stable over time was demonstrated in the SS2 dosimeters.

Conclusions: Remote 3D dosimetry was shown to be feasible with a PRESAGE® dosimeter formulation (SS2) that exhibited relative temporal stability and high accuracy when read off-site 3 days postirradiation. Characterization of the SS2 dose response demonstrated linearity ($R^2 > 0.998$) over 14 days and suggests accurate readout over longer periods of time would be possible. This result provides a foundation for future investigations using remote dosimetry to study the accuracy of

advanced radiation treatments. Further work is planned to characterize dosimeter reproducibility and dose response over longer periods of time. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4884018>]

Key words: Remote dosimetry, 3D dosimetry, optical-CT, PRESAGE®, quality assurance

1. INTRODUCTION

Remote dosimetry is practiced by the Radiological Physics Center (RPC) in assessing radiation therapy programs for consistency and accuracy in radiation dose delivery and for credentialing institutions for advanced radiotherapy technologies.^{1,2} In remote dosimetry, dosimeters are shipped from a central base institution (e.g., the RPC) to a remote institution for irradiation, and then shipped back to the base institution for readout and analysis. The RPC's remote dosimetry tests for intensity-modulated radiation therapy (IMRT), where participating institutions plan and deliver treatment to an anthropomorphic phantom, currently rely on data provided by point dose measurements (TLDs) and 2D dosimetry (film) in selected planes.^{3,4} Despite this limited dosimetric sampling of the treatment volume, it has been reported that a substantial percentage of participating institutions do not pass credentialing.^{1,2} For instance, in irradiations of the IMRT head and neck (H&N) phantom between 2001 and 2011, 18.4% failed to meet the credentialing requirements of delivered doses within 7% or 4 mm of the treatment plan. Furthermore, when a more stringent criteria of 5%/4 mm is applied, the failure percentage increases to 31%.¹ Given that this high failure rate is seen even with generous passing criteria and limited dose sampling, it is reasonable to assume that greater errors would be seen if evaluations were performed with more sensitive metrics and comprehensive 3D dosimetry.

3D dosimetry with PRESAGE® dosimeters imaged via optical computed tomography (optical-CT) has been studied in the context of IMRT QA (Refs. 5 and 6) and has demonstrated potential for use in remote dosimetry applications.^{7,8} A previously published study⁷ demonstrated the feasibility of using PRESAGE®/Optical-CT for relative 3D dosimetry in the credentialing tests with the RPC IMRT H&N phantom. In this study, the RPC H&N phantom was taken through the entire credentialing treatment planning and delivery procedure both with the standard RPC insert (containing 3 pieces of radiochromic EBT film and 8 TLDs) and with PRESAGE® in lieu of the standard insert. PRESAGE® dosimetry results were on par with the current film standard with a 98% 2D gamma passing rate (4%/3 mm) in comparison with the EBT film distribution. PRESAGE® dosimetry also provided a full 3D distribution for analysis against the calculated treatment planning dose distribution. In a comprehensive, slice-by-slice gamma comparison (4%/3 mm) between PRESAGE® and Eclipse dose distributions, good agreement was seen with a 94% passing rate. The PRESAGE®/Optical-CT system's performance in the context of IMRT QA was also demonstrated in recent work with base-of-skull IMRT treatments,⁶ where close agreements between measured and calculated dose distributions were observed across 6 cases

with a mean 3D gamma passing rate (3%/2 mm) of 94.9%. Similarly, PRESAGE®/Optical-CT measurements of a complex volumetric modulated arc therapy (VMAT) plan independently delivered to four dosimeters⁹ demonstrated both excellent agreement with a 3D gamma passing rate of 98.0% (3%/2 mm) and consistency with a dose standard deviation of <3% across all dosimeters. The dosimetry in all of these earlier studies, however, was performed on-site and immediately (within 1 h) postirradiation. Extending the remote RPC credentialing procedure to include 3D dosimetry requires that the accuracy of PRESAGE®/Optical-CT holds up when subjected to the shipping stresses and time delays that occur with remote dosimetry.

The primary objective of this study was to extend these efforts by investigating the feasibility of remote 3D dosimetry with the PRESAGE®/Optical-CT system. Identical optical-CT systems installed at two institutions (Duke University and the RPC) allowed for study of dosimeter stability with direct comparisons between immediate dosimetry results taken on-site after irradiation versus delayed dosimetry results taken after shipping from a remote institution.

2. MATERIALS AND METHODS

2.A. PRESAGE®

PRESAGE® (Heuris Inc., Skillman, NJ) is a polyurethane-based 3D dosimeter with a radiochromic response facilitated by a triarylmethane leuco dye and a trihalomethane initiator.^{8,10} PRESAGE® has been previously studied^{8,10,11} and continually developed for improved dosimetry characteristics. Given the time delay between dosimeter irradiation and read-out in remote dosimetry, a characteristic of particular importance for this application is temporal stability. An earlier PRESAGE® formulation⁸ demonstrated relative temporal stability with a radiochromic dose response that increased with time, but remained linear with respect to time at all dose levels. This particular formulation, however, had an effective atomic number of $Z_{\text{eff}} = 8.34$, with a 12.3% difference from water ($Z_{\text{eff}} = 7.42$). The two formulations of PRESAGE® (SS1 and SS2) undergoing study in the current work have improved water equivalence with lower Z_{eff} values of 8.08 (SS1) and 7.86 (SS2). The compositions of both of these PRESAGE® formulations under study, as well as that of the earlier formulation from Sakhalkar *et al.*^{7,8} are shown in Table I. PRESAGE® formulations SS1 and SS2 differ from each other only in initiator content and percentage. PRESAGE® formulation SS1 includes an additional trihalomethane initiator (bromotrichloromethane), which increased the total initiator content from 0.50% to 0.75%. The higher initiator content in SS1 was expected to increase dose response sensitivity,¹² while lower initiator content in SS2

TABLE I. PRESAGE® formulations and composition. Percentages are by weight.

Component	Formulation		
	SS1	SS2	Sakhalkar 2009
Polyurethane Resin (Smooth-On Crystal Clear® 206)	90.25%	90.50%	93.28%
Cyclohexanone	7.00%	7.00%	-
Leucomalachite Green (leuco dye)	2.00%	2.00%	2.00%
Carbon Tetrabromide (initiator)	0.50%	0.50%	0.75%
Bromotrichloromethane (initiator)	0.25%	-	-
Carbon Tetrachloride (initiator/solvent)	-	-	3.97%

allowed for better water equivalence and was expected to yield greater temporal stability.

Two cylindrical dosimeters (11 cm diameter, 8.5–9.5 cm length) each of PRESAGE® formulations SS1 and SS2 were used in the remote dosimetry portion of this study. Dosimeter size and shape are comparable to that of the standard dosimetry insert used in the RPC H&N credentialing phantom.

2.B. Dosimeter image acquisition and reconstruction

Dosimeters were read out with the Duke Mid-sized Optical-CT Scanner (DMOS), a telecentric optical-CT scanner developed by the Duke 3D Dosimetry and Optical Bio-Imaging Lab. The instrumentation and operating procedures for the DMOS are analogous to that of the DLOS (Duke Large field-of-view Optical-CT Scanner), details of which have been previously published.¹⁰ The primary difference between the DMOS and the DLOS is that components of the DMOS have been scaled down for easier system portability. This system uses a telecentric light source (3 W red LED, glass diffuser, 632.8 ± 10 nm filter, telecentric lens with $<0.08^\circ$ telecentricity) in conjunction with a telecentric imaging lens ($<0.08^\circ$ telecentricity) and Basler A102f CCD camera (Basler AG, Ahrensburg, Germany). Dosimeters are docked to a rotating stage in a tank located between the light source and camera lenses. This tank is filled with room-temperature fluid matched to the refractive index of the dosimeter to minimize diffraction and edge artifacts. The docking mechanism between the dosimeter and the rotating stage provides reproducible spatial registration between multiple scans of the same dosimeter. Projections taken with the DMOS have a native resolution of $\sim 106 \mu\text{m}/\text{px}$, which represents the highest resolution the system is capable of, and are typically scaled down to 1–2 mm/px in reconstruction to match treatment planning system dose calculations.

In-house DMOS systems with identical instrumentation were installed at the Duke University and the Radiological Physics Center (RPC) and were used in this study. (A comparison of readouts between the two systems can be found in Sec. 3.B.2.a.) Dosimeters were imaged with 360 projections over 360° , which were then smoothed with a 5×5 pixel median filter and downsized to a 2 mm/px resolution prior to filtered backprojection reconstruction using the MAT-

FIG. 1. Spectrophotometer ΔOD readings from small volume samples of the SS1 PRESAGE® formulation irradiated to a dose of 3 Gy and then stored at either 3°C or -15°C . Error bars depict standard deviation of 2 measurements per point. After 18 days, the samples stored at 3°C exhibited a 66% optical density increase versus a 23% increase for the samples stored at -15°C .

LAB (The Mathworks, Inc., Natick, MA) iradon function with a Ram-Lak filter. Scans were taken both before and after irradiation. Preirradiation data were used to correct postirradiation data in the reconstruction process to yield the net change in optical density (ΔOD) in the dosimeter from irradiation.

2.C. PRESAGE® characterization

PRESAGE® dose response sensitivity was characterized for both formulations using standard techniques.¹⁰ Small volume optical cuvettes ($1 \times 1 \times 4$ cm) of PRESAGE® material were irradiated on a 6 MV linac at 600 MU/min to known doses (0, 1.0, 2.5, 5.0, and 8.0 Gy) at 100 cm SSD and 5.5 cm depth in a block of solid water. Change in optical density was measured with a Spectronic Genesys 20 spectrophotometer (Thermo Electron Scientific Instruments Corp., Madison, WI) at the LMG peak absorption wavelength of 633 nm and determined by subtracting the preirradiation absorption values from the postirradiation absorption values.

Dose sensitivity was tracked in these cuvettes for 14 days to characterize change in dose response over time. Cuvettes were stored in the dark at approximately -15°C between measurements and allowed to come to room temperature prior to measurement. The postirradiation storage temperature of -15°C was selected based on data demonstrating that storage at lower temperatures improves postirradiation stability (Fig. 1).

2.D. Remote dosimetry evaluation

The feasibility of remote dosimetry was tested by shipping the cylindrical dosimeters from Duke to the RPC, which served as the remote institution where planning, irradiation, and on-site dosimetry took place. The dosimeters were then shipped back to Duke for remote readout. Dosimeters were stored at low temperatures (approximately 3°C – 5°C prior to irradiation and -15°C post irradiation) while on site and

FIG. 2. Flow chart and timeline for the remote dosimetry evaluation.

shipped in insulated containers to minimize temporal changes in dose response.¹³ Dosimeters were allowed to thermally equilibrate to room temperature prior to irradiation and scanning. Because identical optical-CT scanners were available at both institutions, changes in the dosimeter over time were observed with a comparison between dose distributions obtained immediately after irradiation (the current procedure for on-site dosimetry) and at the later remote dosimetry time point. The remote dosimetry results obtained at Duke comprise the primary dataset used to determine remote dosimetry feasibility.

The procedure and timeline for the remote dosimetry trial is summarized by the timeline flow chart shown in Fig. 2.

2.D.1. Treatment plan and delivery

The treatment plan consisted of a simple 3-field box created with 2 lateral and 1 AP 4×4 cm fields with a maximum dose of 4.42 Gy (Fig. 3). This plan was selected specifically because it would provide known dose distributions from a commissioned treatment planning system that would be suit-

able as a gold-standard for comparison to a measured distribution. The 3-field box plan also creates a distinct buildup region as well as regions of distinctly different dose levels for analysis. The simplicity of the plan was also practical for accurate, reproducible setup for all four dosimeters.

Planning was performed in Pinnacle v9.0 (Philips, Amsterdam, Netherlands) at the RPC using a Duke-provided CT dataset of a representative dosimeter. Doses were calculated on a 2 mm grid using the collapsed cone convolution superposition algorithm. Irradiations were carried out on a Clinac 2100 linear accelerator (Varian Medical Systems) subject to routine QA and performing within clinical specifications.

For treatment delivery, dosimeters at room temperature were situated upright on the treatment table [as pictured in Figs. 3(a) and 3(b)] and aligned to crosshairs marked at identical locations on each dosimeter. The AP beam was aligned centrally on the anterior dosimeter surface and set to a SSD of 95.5 cm (isocenter at 4.5 cm depth). Lateral beams were positioned by rotating the gantry to 90° and 270° . Beams were delivered to the dosimeters at 6 MV and 400 MU/min.

2.D.2. Analysis methods

Optical-CT dose distributions measured at the RPC and Duke were manually registered to the Pinnacle-calculated plan in CERR (Washington University, St Louis, MO). As previously published, sensitivity differences have been observed between measurements in small volume optical cuvettes versus larger dosimeters.^{7,10} Consequently, calibration curves derived from small volume cuvettes have been found to result in dose discrepancies of 4%–7% when applied to large volume dosimeters. Thus, measured dose distributions were calibrated with corresponding cuvette-based calibrations, then normalized to the central high dose region. In this simple geometry and arrangement, the commissioned planning system is known to accurately calculate this dose. For a more complex treatment plan, an independent absolute dose measurement would be needed, as demonstrated by Oldham *et al.*⁶

Dosimeter dose distributions were uniformly cropped to a length of 8.5 cm from the anterior surface to control for slight differences between dosimeter lengths. About 2–3 mm of data from the edges of the dosimeter distributions were additionally excluded from analysis to remove imaging artifacts.

3D gamma passing rates were calculated in CERR against the Pinnacle-calculated treatment plan, which served as the reference dose. Calculations were performed under three sets

FIG. 3. (a) Transverse, (b) sagittal, and (c) coronal views of the 3-field box treatment plan (1 AP beam, 2 lateral beams) delivered to all dosimeters.

of gamma criteria with a 10% maximum dose threshold: 5%/2 mm, 3%/3 mm, and 3%/2 mm. The criteria of 3%/3 mm with a 10% maximum dose threshold were chosen for consistency with the recommendations of TG119.¹⁴ These 3D gamma passing rates were used as the basis of comparison between immediate and remote readings and to assess remote dosimetry performance.

3. RESULTS AND DISCUSSION

3.A. PRESAGE® characterization

Dose responses as determined with small volume optical cuvettes are displayed in Figs. 4(a) and 4(b). As expected, higher sensitivity values were seen in the formulation with a greater percentage of initiator content. In the calibration curves determined immediately postirradiation [Fig. 4(a)], the sensitivities were 0.0225 $\Delta OD/(cm \cdot Gy)$ for PRESAGE® formulation SS1 (0.75% initiator content) and 0.0213 $\Delta OD/(cm \cdot Gy)$ for formulation SS2 (0.50% initiator content). Higher dose sensitivity with greater initiator content

was also observed 14 days postirradiation [Fig. 4(b)] with an increase to 0.0232 $\Delta OD/(cm \cdot Gy)$ for SS1 while a decrease to 0.0199 $\Delta OD/(cm \cdot Gy)$ was observed for SS2. Dose responses with high linearity ($R^2 > 0.996$) were maintained for both formulations and across all time points.

SS2 was found to be more stable over time: change in sensitivity remained within 4.9% for SS1 and within 6.6% for SS2 over a period of 14 days [Fig. 4(c)]. The temporal changes of increased sensitivity for SS1 and decreased sensitivity for SS2 over time generally persisted through the 14 day tracking period, as illustrated by the percentage change in sensitivity for both formulations in Fig. 4(c).

These small volume calibration curves confirm dose response linearity in both formulations and characterize trends in temporal stability.

3.B. Evaluation of PRESAGE® for remote dosimetry

The efficacy of PRESAGE® for remote dosimetry was evaluated by comparing the agreement of measured

FIG. 4. Dose response for PRESAGE® formulations SS1 and SS2. (a) Immediate postirradiation dose response. (b) Dose response 14 days postirradiation. (c) Percent change in PRESAGE® formulation dose sensitivities over 14 days.

TABLE II. 3D gamma passing rates for immediate and remote readings for all dosimeters.

Dosimeter	5%/2 mm		3%/3 mm		3%/2 mm	
	Immediate	Remote	Immediate	Remote	Immediate	Remote
SS1-A	96.7%	98.0%	94.0%	98.4%	82.9%	90.7%
SS1-B	96.1%	98.1%	88.9%	95.0%	79.2%	87.6%
Average	96.4% ± 0.4%	98.0% ± 0.1%	91.5% ± 3.6%	96.7% ± 2.4%	81.1% ± 2.6%	89.1% ± 2.1%
SS2-C	97.4%	97.6%	99.0%	98.0%	92.1%	90.1%
SS2-D	95.5%	96.3%	95.9%	97.1%	84.4%	88.7%
Average	96.4% ± 1.4%	96.9% ± 0.9%	97.4% ± 2.2%	97.6% ± 0.6%	88.2% ± 5.4%	89.4% ± 1.0%

distributions with the reference distribution (from the commissioned Pinnacle planning system) for the simple plan shown in Fig. 3. Comparison was performed using 3D gamma analyses. Measurements were made at both base and remote institutions to check for any change in measured dose distribution. Key assumptions in this approach are: (1) The dose calculation from Pinnacle is accurate for this plan, and there-

fore comparisons of line profiles, 2D dose maps, and 3D gamma passing rates with the TPS distribution are indicative of dosimeter measurement accuracy. (2) The optical-CT scanners installed at each institution are identical, and therefore any discrepancies between the immediate local readings and the delayed remote readings are attributable to changes in the dosimeter. (3) While dose response in the dosimeter

FIG. 5. Transverse cross sections of representative dose distributions and gamma passing maps for both PRESAGE® formulations (SS1 and SS2) studied. All gamma values ≥ 1 are displayed as the same color to aid visualization of failing regions. Small variations in gamma passing values may arise from minor registration or setup errors.

FIG. 6. Sagittal cross sections of representative dose distributions and gamma passing maps for both PRESAGE® formulations (SS1 and SS2) studied. All gamma values ≥ 1 are displayed as the same color to aid visualization of failing regions.

may change over time [Fig. 4(c)], the relative dose distribution remains constant [Figs. 4(a) and 4(b)]. We now describe the results, but return to comment on the validity of these assumptions in Sec. 3.B.2.

Evaluation of both PRESAGE® formulations took into consideration the 3D gamma passing performance under each set of gamma criteria and variation between immediate and remote passing rates.

3.B.1. 3D gamma comparisons

Comprehensive 3D gamma passing rates are tabulated in Table II. Gamma maps of representative cases for both PRESAGE® formulations (dosimeters SS1-A and SS2-C as labeled in Table II) in the central transverse, sagittal, and coronal planes are displayed in Figs. 5–7.

At 3%/3mm and 5%/2 mm, both PRESAGE® formulations yielded high 3D gamma passing rates ($>96\%$ passing) for remote dosimetry. The gamma criteria of 3%/3 mm with a 10% maximum dose threshold is of particular interest in

that it is both the TG119-recommended criteria for IMRT commissioning¹⁴ and, according to a 2007 survey of IMRT QA, the most commonly used clinical QA standard.¹⁵ Although the TG119 gamma criteria and passing parameters were originally determined for 2D planar dose distributions, these criteria have been applied to measurements made with both 3D dosimeters^{6,10} and 3D array systems,^{16,17} and thus provide a useful standard metric when extended to 3D dose measurements. Under the TG119-suggested action levels of 88%–90% passing for composite irradiations,¹⁴ both sets of dosimeters pass readily. In other words, remote dosimetry measurements by both PRESAGE® formulations reflect treatment accuracy within the criteria and action threshold deemed acceptable by TG119.

Recent studies, however, have shown that the TG119 gamma criteria of 3%/3 mm can be insufficient for detecting systematic errors that would be identifiable with more sensitive criteria.¹⁸ In light of this, dosimetry results were also evaluated under more stringent 3%/2 mm criteria. The 3%/2 mm criteria highlighted one shortcoming of the SS1

FIG. 7. Coronal cross sections of representative dose distributions and gamma passing maps for both PRESAGE® formulations (SS1 and SS2) studied. All gamma values ≥ 1 are displayed as the same color to aid visualization of failing regions.

formulation: increasingly sensitive gamma criteria correspond to increasingly large differences between immediate and remote passing rates. At 3%/2 mm, the difference between average immediate and remote SS1 passing rates is 8.0 percentage points (pp). A review of the gamma passing rates for the SS2 formulation, meanwhile, shows that the average passing rates between the immediate and remote readings vary by only 1.2 pp at 3%/2 mm and ≤ 0.5 pp for the other two gamma metrics.

Gamma maps (Figs. 5–7) indicate that the regions of failure for both formulations largely occur in the lower dose regions of the AP beam. The narrow region of gamma failure adjacent to the anterior dosimeter surface (seen in Figs. 5–7, columns 2–4) is due to higher values in the dosimeter and may be an effect of light refraction due to the curved surface. Regions of failure or near-failure also occur in the relatively lower dose regions lateral beams toward the edges of the dosimeter. While the specific cause of the higher differences in immediate and remote passing rates for the SS1 formulation is unknown, lower passing rates for the immedi-

ate readings are primarily due to dose underestimation in the buildup region and dose overestimation in the tail relative to the Pinnacle calculation.

Applying the more sensitive gamma criteria of 3%/2 mm successfully and sufficiently differentiates the performance of the two PRESAGE® formulations to show that SS2 is the recommended choice based on comparable immediate and remote dosimetry results and reasonable average gamma passing rates at three metrics of varying sensitivity. Further study, however, is still required to address the differences in passing rate between the two SS2 dosimeters, which is more pronounced ($\sigma = \pm 5.4\%$) relative to other cases for immediate dosimetry at 3%/2 mm.

3.B.2. Uncertainties in measurement

The 3D gamma passing rates provide a metric for quantifying the dosimeter performance of each PRESAGE® formulation, and also clearly identify a promising formulation (SS2) for remote dosimetry. Because the SS1 formulation

FIG. 8. A comparison of (a) preirradiation and (b) postirradiation projection images taken of a single dosimeter at both local and remote locations, and (c) their resulting ΔOD . Although a number of variables can contribute to differences in projection images between individual scanners, these differences are largely corrected out when the difference between pre- and post-irradiation images is taken in determining ΔOD . This is further discussed in Sec. 3.B.2.b and illustrated in Fig. 9.

has been removed from consideration for remote dosimetry, discussion in this section will focus only on results from the SS2 formulation. One unexpected result was the finding that average passing rates at all gamma criteria for the remote readings were higher than that of the immediate readings, albeit only for a small margin (0.2–1.2 pp). This might be due to on-site imaging occurring prior to full completion of the radiochromic response, or perhaps to minor differences between readout scanners. While the average differences between immediate and remote readings were minimal, we examined our procedure for variables that may have contributed to uncertainties in measurement.

3.B.2.a. Differences in optical-CT scanner readout. Although the optical-CT scanners at both institutions are identical in instrumentation, there are still a number of variables that can contribute to differences in the projection images acquired, including the refractive index match between the fluid in the scanner tank and the dosimeter, light output, and alignment of the light source relative to the camera.

A comparison of a representative projection image taken both preirradiation [Fig. 8(a)] and postirradiation [Fig. 8(b)] by both scanners is shown in Fig. 8, along with the resulting calculated ΔOD . Images taken at Duke (Fig. 8, bottom row) are standard. The projections taken by the optical-CT scanner at the RPC (Fig. 8, top row), however, show an uncharacteristic darkened appearance with bright bands at the top and bottom of the dosimeter, which suggest a slight vertical misalignment between the light source and the camera. Because this effect is consistent between pre- and post-irradiation scans and the difference between these scans is taken in determining ΔOD , however, these differences are largely corrected out in the dose recon-

struction. This is illustrated by the similarity of the ΔOD images [Fig. 8(c)] and normalized line profiles from the reconstructed distributions [Fig. 9(b)] despite the visible differences in the projections from each scanner. The differences between the immediate and remote readings seen in the ΔOD line profiles are thereby expected to be the result of changes in the dosimeter over time. This is further discussed in Sec. 3.B.2.b.

3.B.2.b. Relative temporal stability in dosimeters. From characterization of PRESAGE® formulation SS2 with small volume cuvette measurements (Sec. 3.A), it is expected that although dose response will change over time, it should remain linear with respect to dose and hence maintain a temporally stable relative dose distribution. It has been noted in previous studies that there exists a volume effect where sensitivity and response over time may differ subtly based on the volume of the dosimeter.^{7,10} An in depth examination of these volume effects is beyond the scope of this work, but as shown in Fig. 9 and discussed below, linear response over time was confirmed for the large volume cylindrical dosimeters for this study.

Figure 9(a) shows the $\Delta OD/\text{pixel}$ for central lateral and AP line profiles for both immediate and remote reconstructions of a representative dosimeter (SS2-C). Line profiles were chosen to clearly illustrate response at distinctly different dose levels. Although a slightly lower response is noted in the buildup region of the immediate AP profile, the immediate and remote plots for both profiles are otherwise essentially identical when normalized to the high dose region [Fig. 9(b)], indicating that the relative dose response is temporally stable across the time frame for this study. Given the similarity to the radiochromic response over time observed in an earlier study,⁸ it is

FIG. 9. (a) Lateral and AP line profiles ($\Delta OD/px$) across both immediate and remote reconstructed dose distributions of a representative formulation SS2 dosimeter. Profile locations are indicated by the white dotted lines. (b) When $\Delta OD/px$ is normalized to the central high dose region for the same line profiles, they are essentially identical, indicating that relative dose distributions remained stable between measurements.

reasonable to conclude that the difference between the two readings is primarily the result of actual changes within the dosimeter rather than an effect of scanner variables. This also rules out the likelihood of dose-dependent OD changes as a contributor to measurement error, and supports the conclusion that the SS2 formulation is suitable for performing relative remote dosimetry.

It should also be noted that the temporal creep in ΔOD for the SS2 formulation over the 3 days between on-site and remote measurements is an increase of 4.5%. This is a substantial improvement in overall response stability versus the earlier PRESAGE® formulation,⁸ which also demonstrated relative temporal stability but exhibited a ΔOD increase of $\sim 33\%$ over a similar period of time.

3.C. Considerations for future work

From the results of this study, PRESAGE® formulation SS2 has been identified as a promising candidate for remote 3D dosimetry. One caveat is that this initial feasibility study represents an ideal remote dosimetry case with careful dosimeter handling (e.g., low temperature storage to minimize changes in response) and a quick turnaround of only 3 days between irradiation and remote readout. Realistically, if 3D remote dosimetry were implemented, the time delays

between irradiation and readout could be much longer, and characterization of this formulation's dose response demonstrating linearity over 14 days suggests that dosimetry over longer periods of time would be feasible. Future work could then be expanded to characterize PRESAGE® dose response over longer periods of time, determine optimal storage and shipping temperatures, include a larger number of dosimeters to evaluate interdosimeter reproducibility, and incorporate ion chamber measurements for calibration to absolute dosimetry.

4. CONCLUSIONS

On-site and remote dosimetry was performed with two PRESAGE® dosimeter formulations in order to test the feasibility of 3D remote dosimetry. Comparison against a known reference distribution using metrics including dose line-profiles, 2D dose maps, and 3D gamma passing rates demonstrated that both formulations perform adequately within TG119-suggested metrics (88%–90% passing at 3%/3 mm) for both immediate and remote readings. However, given that the 3%/3 mm gamma criteria standard is known to be insensitive to detecting some types of systematic error, a more stringent 3D gamma criteria was used to further evaluate efficacy for remote dosimetry and to differentiate between the two PRESAGE® formulations. The SS2 formulation was

found to be optimal in this work with 3D gamma passing rates of $97.6\% \pm 0.6\%$ at 3%/3 mm and $89.4\% \pm 1.0\%$ at 3%/2 mm when compared against a known distribution. A stable relative dose response was maintained over a 3-day time delay for remote readout. The SS2 formulation in combination with optical-CT appears to be a promising foundation for future investigations using remote high resolution 3D remote dosimetry to study the accuracy of advanced radiation treatments. Further work is needed to characterize dosimeter reproducibility and dose response over longer periods of time.

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^{a)} Author to whom correspondence should be addressed. Electronic mail: mark.oldham@duke.edu

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