An Investigation of dosimetric accuracy of a novel PRESAGE radiochromic sheet and its clinical applications

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Abstract. A novel radiochromic PRESAGE sheet (Heuris Inc.) with variable thickness of 1-3 mm has been developed to provide 2D dosimetry. It can also be used for patient surface dosimetry or as a tool for patient-specific QA (PSQA) in 3D dosimetry. Its softness and flexibility to conform with the patient’s skin make this product advantageous for future clinical applications. This study presents a comprehensive investigation into the PRESAGE sheet’s dosimetric accuracy at different scanning times and its potential use for clinical applications. For the characterization of the dosimeter, temporal stability of dose rate, energy dependence, dose linearity, beam profile, and dose distribution measurements were investigated by irradiating a single sheet of PRESAGE with different doses and energies while scanning the sheet with an Epson 11000XL high-resolution scanner at different time intervals following its irradiation. Additionally, two clinical applications, including PSQA and surface dose measurement, were conducted and were compared to dosimeters currently used for clinical applications. For QA measurement, a stack of PRESAGE sheets, with EBT3 films sandwiched in-between, was used to measure the dose distribution of a pancreas SBRT treatment plan at different depths. For surface dose measurement, PRESAGE sheets, EBT3 films, and OSLDs were placed on the surface of an anthropomorphic phantom to measure the skin dose of a modulated treatment fields. When the stack of PRESAGE sheets were scanned within a period of two hours following its irradiation, the dosimeter exhibits a stable linear response to dose with negligible dose rate and energy dependence. In addition to its temporal stability, the dosimeter can provide accurate relative dose measurements comparable to those exhibited by EBT3 films. In the application of PSQA, when compared with EBT3 films using gamma test with a 2%/2 mm criteria, PRESAGE sheets have a passing rate of 99.7% measured at the isocenter and 99.1% in application of surface dose measurements. This study demonstrates the dosimetric characteristics and the potential use of a novel dosimeter, PRESAGE sheets.

1. Introduction
The dosimetric characteristic of PRESAGE polyurethane dosimeters, formulated with a halogenated hydrocarbon free radical initiator and leuco-dye has been investigated thoroughly [1, 2]. The primary advantages of PRESAGE over other types of dosimeters include its linear response to the absorbed dose over a wide doserange, its tissue equivalency over a wide energy range, and its capability to provide 3D dose distribution with high resolution. Additionally, the dosimeter can be fabricated to any size or shape for different purposes.
In 2015, a published study shows the potential use of PRESAGE thin sheets for dosimetry when analyzed using a flatbed scanner [3]. Unlike the conventional PRESAGE dosimeters, PRESAGE sheets don’t require expensive equipment such as optical computed tomography (OCT) [4-6], laser fluorescence confocal microscopy (LFCM) [7] and expert users. However, the sensitivity, signal to noise ratio and temporal stability of the PRESAGE thin sheets in the study were insufficient to be used in clinical applications. Consequently, this work seeks to investigate the dosimetric accuracy of the newly developed radiochromic sheets concerning their temporal stability with regards dose linearity, energy dependence, dose rate dependence, beam profiles, and dose distribution measurements. Additionally, two clinical applications were first conducted using the PRESAGE sheets. First, a stack of PRESAGE sheets was used to perform IMRT patient-specific QA, which provides the dose distribution with high resolution at different depths. Secondly, surface dose measurements were performed by conforming the dosimeter to the contour of an anthropomorphic phantom to investigate its \textit{in-vivo} dosimetric capability. The results of this study provide insight into the dosimetric properties of the PRESAGE sheet for its use in future applications.

2. Materials and Methods

2.1. Dosimetric Characterization

A comprehensive characterization regarding the dosimetric accuracy of the PRESAGE at different scanning times was performed by investigating the dose rate dependence, energy dependence, dose linearity, beam profile, and dose distribution measurements of the dosimeter. As shown in Fig. 1, a single radiochromic sheet with 3.2 mm thickness was irradiated with a 6 MV photon beam using a TrueBeam (Varian Inc.) linear accelerator at six different dose points (1, 3, 5, 8, 10, and 15 Gy) within a 4 x 4 cm² field size to measure the dosimeter’s linearity in its dose response. For dose rate dependence measurements, 5 Gy was delivered to the sheet using dose rates of 100, 300, and 600 MU/min using a 6 MV photon beam. Additionally, 5 Gy was also delivered to the PRESAGE sheet using a 18 MV photon beam to investigate the energy dependence of the dosimeter. Following its irradiation, the PRESAGE sheets were scanned at five different time intervals (0.5, 1, 2, 19, 24 h) using an Epson 11000XL high-resolution scanner to acquire information about the optical density (OD) development and fading of the dosimeter. To further verify the accuracy of dose distribution measurement, the beam profiles of different doses (3, 4, 5, 6 Gy) and the isodose line distributions from the PRESAGE sheets were compared with the measurements taken on the EBT3 films sandwiched in-between the PRESAGE sheets during the irradiation.

![Figure 1. An image of an irradiated radiochromic sheet.](Image)

![Figure 2. An image of a stack of PRESAGE sheets.](Image)

2.2. IMRT QA

A stack of PRESAGE sheets with 3 mm thickness, shown in Fig. 2, was used to perform patient-specific QA of a pancreas SBRT treatment plan using modulated photon fields from a linear accelerator,
TrueBeam (Varian Inc.). EBT3 films with the same area as the PRESAGE sheets were sandwiched in-between the sheets to verify the dose distribution measurements. In addition, to compare the measured distributions with the calculated distributions from the treatment planning system, at each depth, simulated images of the dosimeter were imported into the planning system to perform dose calculation. The passing rates of gamma tests between the dose distributions measured from the EBT3 and PRESAGE sheets, as well as the EBT3 sheets and the treatment planning system, at eight different depths were calculated using DoseLab (Mobius Inc.).

2.3. Surface Dose Measurement
To verify the capability of in-vivo surface dose measurement, as presented in Fig.3, PRESAGE sheets, EBT3 gafchromic films, and OSLDs were placed on the surface of an anthropomorphic phantom to measure the skin dose of a modulated 6 MV photon beam from a Trilogy (Varian Inc.) linear accelerator. Five OSLDs were placed with a 3 cm space separating each OSLD adjacent vertically and 4 cm space separating each adjacent OSLD horizontally to measure the relative doses at five different locations in the field. The results of relative dose measurement from OSLD and PRESAGE sheets were compared with those measured on the EBT3 films.

3. Results
3.1. Dosimetric Characterization
This study examined both the temporal stability and dosimetric accuracy of the PRESAGE dosimeter. With regards to its temporal stability, the results presented in Fig. 4 show that the PRESAGE sheet exhibits a stable linear response to dose, negligible dose rate dependence (error < 1%), and negligible energy dependence (error < 2.5%) when scanned within two hours following its irradiation. There was also an negligible difference in the measured beam profiles and dose distributions in the dosimeters when scanned within a two hour time frame following their irradiation (penumbra difference <1%). However, when scanned after a period greater than two hours, the dosimeter exhibited a nonlinear dose response, energy dependence and significant changes to its penumbra. For dosimetric accuracy, in Fig. 4, beam profiles of doses greater than 4 Gy corresponded to what was measured by the EBT3 film (error <1 %) while a non-uniform color-change was observed when the dose delivered to the dosimeters was below 3 Gy, which contributes to and manifests as a ± 5% noise measured on the top portion of the beam profile. Beyond beam profile comparison,s to quantify the discrepancies between measured dose distributions from PRESAGE sheets and EBT3 films, gamma tests with a criteria of 2%/2mm were performed on the dose distributions of 4 Gy measured by the two dosimeters, which had a passing rate of 99.4%. Fig. 4 shows the isodose lines comparison of the two distributions.
Figure 4. Results of dosimetric characterization. Temporal stability of (a) linear dose response (b) energy dependence (c) dose rate dependence (d) beam profile measurements was investigated. In addition, (e) dose uniformity at different delivered doses and (f) comparison of 2D distributions from EBT3 (red) and PRESAGE (green) were presented.

3.2. IMRT QA
Table 1 shows the passing rates of gamma tests between the dose distributions measured from EBT3 and PRESAGE sheets, and the passing rates of gamma tests between EBT3 and the treatment planning system at eight different depths. The passing rates with a 2%/2 mm criteria between EBT3 and PRESAGE at all depths were greater than 95%, with the maximum passing rate measured to be at 99.8%. On the other hand, dose distributions from the treatment planning system were not close to what from the EBT3 films due to the overmodulation of the fields. Using the 3%/3 mm criteria, the lowest and the highest passing rates were measured to be 85% and 94.8%. Fig. 5 shows the difference of isodose lines at the 6 mm depth from the isocenter.
Table 1. Passing rates of gamma tests at multiple depths

| Depth of the dose plan relative to isocenter | -18 mm | -12 mm | -6 mm | Isocenter | 6 mm | 12 mm | 18 mm |
|---------------------------------------------|--------|--------|-------|-----------|------|-------|-------|
| EBT3 vs. PRESAGE sheets (2%/2mm)            | 95.9%  | 99%    | 96.4% | 99.7%     | 96.1%| 94.6% | 99.8% |
| TPS vs. EBT3 (3%/3mm)                       | 91.3%  | 94.1%  | 94.8% | 90.8%     | 90%  | 92.1% | 90.1% |

3.3. In-vivo Skin Dose Measurement
To evaluate the accuracy of relative dose measurement on the surface, the measured dose distribution of a modulated photon field measured from PRESAGE sheets was compared with the measured dose distribution from the EBT3 film. Gamma test with 2%/2mm criteria shows the passing rate to be at 99.1% (Fig. 6). Additionally, the relative doses at the measured points from both OSLDs and PRESAGE sheets were compared with EBT3 films. To obtain the relative dose, the measured doses at five points from the OSLDs were normalized to the OSLD placed at point 5 as shown in Fig. 7. Table 2 shows that the OSLDs exhibit a larger discrepancy than PRESAGE sheets with its maximum relative dose difference to be at 3.7% and the relative dose differences exhibited by the PRESAGE sheet to be within 1.0%.

Figure 5. Isodose lines comparison of EBT3 film, treatment planning and PRESAGE sheets at 6 mm depth from the isocenter.

Figure 6. Isodose lines comparison of EBT3 film (red) and PRESAGE sheets (green).

Figure 7. Positions of five OSLDs relative to the dose distribution.
Table 2. Relative dose difference of OSLDs and PRESAGE sheets at measured points compared with EBT3 film. The doses at five measured points were normalized to Point 5 to obtain relative dose.

| Dosimeter     | Point 1 | Point 2 | Point 3 | Point 4 |
|---------------|---------|---------|---------|---------|
| OSLD          | 3.70%   | 1.80%   | 2.00%   | 3.50%   |
| PRESAGE Sheet | 0.61%   | 0.73%   | 0.85%   | 0.45%   |

4. Discussion
The results from the preceding section show that there is a negligible change to the dosimetric characteristic of the PRESAGE sheet which includes its linear dose response, dose rate independence, energy independence, and relative dose measurements when the PRESAGE sheet is scanned within a period of two hours following its irradiation. However, when scanned within a period greater than two hours, the scanned results become less accurate due to different rates of OD increase and fading at different doses. Moreover, the fading of the OD in low dose region was observed to occur at a later period than OD in the high dose region. This effect leads to the larger penumbra of the beam profiles when the sheet is scanned within a time frame greater than two hours following its irradiation. For dosimetric accuracy, PRESAGE films can provide an accurate relative dose measurement, comparable to EBT3 film, when scanned within a two hours period and delivered with sufficiently high dose.

For clinical applications, using a stack of PRESAGE sheets, patient-specific QA at different depths can be conducted using a conventional film scanner. The results of gamma tests show that the dose distributions from PRESAGE sheets correspond to what was measured using EBT3 film. In addition, the passing rates of the gamma tests between EBT3 and treatment planning system were observed to change at different depths significantly. Plans that had smoothed distributions exhibited passing rates that were higher than those with modulated fields, which indicates that the conventional IMRT QA at a certain depth could be insufficient to make a proper judgement for the small field and high gradient treatments.

In the third part, in-vivo surface dose measurements of PRESAGE sheets and OSLDs were compared with EBT3 films. From the results, OSLDs exhibit larger discrepancies than PRESAGE sheets due to their comparatively larger statistical and experimental uncertainty in comparison to EBT3 film and the changes in the OSLD response as a function of dose [8, 9]. The greater discrepancy in the relative dose measurements between OSLDs may have been attributed to the uncertainty in the sensitivity of an individual dosimeter as well as the uncertainty in the performance of the reader used to measure the dose extracted from the OSLDs [9]. The difference in sensitivity between OSLDs may be ascribed to the slight differences of the amount of dosimetry material (Al2O3:C) contained in the dosimeter [9]. This difference in sensitivity is manifested as differences in their response when exposed to the same radiation field. Screened OSLDs were reported to have a measurement uncertainty of ~ ± 2% and the uncertainty in the performance of the microstar reader (Landauer Inc.) used to measure the dose from the OSLDs in this experiment is reported to have an uncertainty between 1-2% [9]. Besides, PRESAGE sheets have a comparable resolution as EBT3. Compared to EBT3 film, PRESAGE sheets have the same dosimetric capability as EBT3 and are softer and more flexible to conform to the patient’s skin, which makes it a valuable tool for in-vivo dosimetry.

5. Conclusion
This study shows the dosimetric characteristics and the potential use of a novel dosimeter. When scanned within a two hour time frame following its irradiation, the radiochromic sheets can provide accurate relative dose measurement comparable to EBT3 films. For clinical applications, the PRESAGE sheets can be used effectively in clinics to provide accurate in-vivo dosimetry with less statistical error and higher resolution than OSLDs. Additionally, it can be a valuable and convenient tool for in-vivo dosimetry.
tool for patient-specific QA in 3D to verify the dose distributions at multiple depths. In the future, the sheets could be produced in different thickness for other purposes, such as a replacement of bolus, and the influence of thickness difference on its dosimetric characteristic, and the depth of measurement should be investigated further.

6. References
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