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An investigation of PRESAGE® 3D dosimetry for IMRT and VMAT radiation therapy treatment verification

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Abstract

The purpose of this work was to characterize three formulations of PRESAGE® dosimeters (DEA-1, DEA-2, and DX) and to identify optimal readout timing and procedures for accurate in-house 3D dosimetry. The optimal formulation and procedure was then applied for the verification of an intensity modulated radiation therapy (IMRT) and a volumetric modulated arc therapy (VMAT) treatment technique.

PRESAGE® formulations were studied for their temporal stability postirradiation, sensitivity, and linearity of dose response. Dosimeters were read out using a high-resolution optical-CT scanner. Small volumes of PRESAGE® were irradiated to investigate possible differences in sensitivity for large and small volumes ('volume effect'). The optimal formulation and read-out technique was applied to the verification of two patient treatments: an IMRT plan and a VMAT plan.

A gradual decrease in post-irradiation optical-density was observed in all formulations with DEA-1 exhibiting the best temporal stability with less than 4% variation between 2–22 h post-irradiation. A linear dose response at the 4 h time point was observed for all formulations with an R^2 value >0.99 . A large volume effect was observed for DEA-1 with sensitivity of the large dosimeter being ~63% less than the sensitivity of the cuvettes. For the IMRT and VMAT treatments, the 3D gamma passing rates for 3%/3 mm criteria using absolute measured dose were 99.6 and 94.5% for the IMRT and VMAT treatments, respectively.

In summary, this work shows that accurate 3D dosimetry is possible with all three PRESAGE® formulations. The optimal imaging windows post-irradiation were 3–24 h, 2–6 h, and immediately for the DEA-1, DEA-2, and DX formulations, respectively. Because of the large volume effect, small volume cuvettes are not yet a reliable method for calibration of larger dosimeters to absolute dose. Finally, PRESAGE® is observed to be a useful method of 3D verification when careful consideration is given to the temporal stability and imaging protocols for the specific formulation used.

Keywords

PRESAGE®; 3D dosimetry; IMRT verification; optical-CT

1. Introduction

PRESAGE[®] is a solid polyurethane-based radiochromic material, developed for 3D dosimetry (Adamovics and Maryanski 2006). Thomas *et al* (2011) documented clinical commissioning of PRESAGE[®] with dose readout by a telecentric optical-CT scanner. The dosimetric characteristics of PRESAGE[®] have been evaluated in a number of articles (Guo *et al* 2006, Sakhalkar *et al* 2009a, Monstaar *et al* 2010, Yates *et al* 2011). Juang *et al* (2013) provided the most comprehensive discussion of different PRESAGE[®] formulations to date, including formulations with potential for remote dosimetry and reusability. The basic formulation of PRESAGE[®] has continually evolved in an attempt to further optimize several aspects including: increased dose sensitivity, improved optical transparency of unirradiated dosimeters, improved tissue-equivalence, and controlled temporal stability of optical-density (OD) post irradiation. For temporal stability, two directions of development can be distinguished: dosimeters that are stable post-irradiation and dosimeters that optically clear with time and can be re-used (Pierquet *et al* 2010, Juang *et al* 2014a). Sakhalkar *et al* (2009a) demonstrated an early formulation of PRESAGE[®] that enabled accurate 3D dosimetry; however, the effective atomic number was slightly high (8.3), and an increase in post-irradiation OD over time was observed, denoted as ‘OD creep’. The works outlined above, and further discussion in Oldham *et al* (2014), indicate a need for further investigation of the temporal stability and dosimetry characteristics of current Presage formulations, including any volume effect (see below).

The initial goal of this work was to investigate three new formulations of PRESAGE[®] suitable for in-house 3D dosimetry (i.e. we are not considering remote dosimetry formulations). Post-irradiation OD stability was investigated, as well as dose sensitivity, and dose response linearity. An ideal formulation for this work would allow for scanning immediately or soon after irradiation and exhibit temporal stability for a reasonable amount of time (30 min) to enable optical-CT imaging. The sensitivity of these formulations as well as the linearity of dose response was investigated. A further goal was to investigate any potential ‘volume effect,’ a term we use to refer to variation in dose sensitivity of PRESAGE[®] from the same batch but cast and cured in different volumes (Pierquet *et al* 2010). Prior studies have suggested a volume effect may be present between small volume (~4 g) cuvettes used for calibration and large volume dosimeters (Sakhalkar *et al* 2009, Thomas *et al* 2011b). The final goal was to apply the optimal formulation and read-out procedures to investigate the end-to-end accuracy of IMRT and VMAT treatments.

2. Methods and materials

2.1. PRESAGE[®] formulations and dosimeters

The PRESAGE[®] formulations to be characterized are labeled DEA-1, DEA-2, and DX. The chemical components of these formulations include the polyurethane matrix, the type and concentration of leuco dye (color changing component), the type and concentration of leuco dye solvent, the concentration of initiator, and other components as listed in table 1.

All large dosimeters were cylindrical in shape with diameter of 11 cm and height of 10 cm. Small volumes of the DEA-1 formulation were formed from the same batch as the large dosimeters and placed in $1 \times 1 \times 4$ cm plastic cuvettes for investigation of the volume effect.

2.2. Irradiation geometry

Large cylindrical dosimeters were treated with $5 \times 2 \times 2$ cm fields incident on the upper flat surface with edges separated by 1.25 cm and SSD = 100 cm (see figure 1). A 6 MV beam with a dose rate of 600 MU min^{-1} was used for all irradiations. The dosimeter was irradiated to three dose levels: 3, 6, and 9.5 Gy. These 5 regions of interest (ROI's) were analyzed individually. The monitor units for each beam were calculated so that these dose levels occurred at a depth of 1.5 cm (d_{max}).

2.3. Optical-CT acquisition and reconstruction

The Duke Mid-Sized Optical-CT Scanner (DMOS) (Newton *et al* 2010, Juang *et al* 2014b) and the Duke Large field-of-view Optical-CT Scanner (DLOS) were used for acquisition of data on large dosimeters (Thomas and Oldham 2010, Thomas *et al* 2011b). Both optical-CT scanners were developed in the 3D Dosimetry and Bio-Imaging lab at Duke University, and DMOS is a scaled down version of the DLOS. Both systems are bi-telecentric systems with $<0.1^\circ$ telecentricity with magnification of $0.061\times$ for the DMOS and $0.037\times$ for the DLOS. The camera used is a 1392×1040 Basler with a CCD chip. Bandwidth filters of ± 10 and ± 5 nm for the DMOS and DLOS, respectively, were used to filter the light source centered about 633 nm, thereby reducing spectral artifacts (Thomas *et al* 2011c). Stray light was determined to be negligible for these irradiations (Thomas *et al* 2011a). Standard imaging protocols for all dosimeters called for one projection every 1° for 360 projections. Each projection was averaged 8 times to minimize noise. Flood and dark corrections (400 averaged images) were applied to both the pre-irradiation scan and post-irradiation scan to account for any imperfections of the camera and CCD chip. Post-irradiation flood projections were taken at 0 h, 3 h and before the final scan at 24 h. The 0 and 3 h floods were used for scans between 0–3 h post-irradiation and 3–24 h, respectively, while the 24 h flood was used only for the 24 h scan.

A pre-irradiation and post-irradiation scan is necessary to obtain the change in OD, which is proportional to the absorbed dose due to the linearity of PRESAGE[®] dose response. For evaluating temporal stability data, scans were taken immediately post-irradiation, at 30 min, at one hour and at every subsequent hour up to 6 h. One last scan was taken the next day at 24 h post-irradiation. The dosimeter was not removed from the optical-CT tank between scans for the first 6 h, however it was stored in the refrigerator at 3°C between the 6 and 24 h scan and was allowed to warm to room temperature prior to scanning. Storing the dosimeters in cold temperatures has been shown to stabilize the OD change of the dosimeter post-irradiation (Skyt *et al* 2010). The timing of the post-irradiation scans is important because it was desirable to capture the variation in OD for the first few hours post-irradiation in order to characterize the optimal imaging window for each formulation.

All images were reconstructed with a Matlab-based reconstruction program using filtered backprojection. Images were reconstructed with 2 mm voxel size using a ramp filter in

frequency space. The system has the ability to reconstruct to higher resolution, but 2 mm was chosen as a suitable trade-off between noise and spatial resolution for these purposes.

After each dosimeter was irradiated and scanned with the optical-CT system, an x-ray CT was taken of the dosimeter on a GE Lightspeed CT scanner for dose calculation. Both the calculated dose and measured OD distribution were imported into a 3D analysis tool, Computational Environment for Radiotherapy Research (CERR), where the 3D dose distributions could be compared (Deasy 2010).

2.4. 2D independent verification with film

In order to independently verify the dose distribution, a 2D independent measurement was made with GAFCHROMIC[®] EBT2 film (ISP corporation, NJ). The film was placed on top of 8 cm of solid water to provide good scatter conditions. A transparent template of the 5-field irradiation pattern was placed on top of the EBT2 film to ensure accurate delivery of the plan. Then, 1.5 cm of solid water was placed on top of the film so that the film was located at $d_{\max}$. The 5-field irradiation pattern was then delivered to the film with a 6 MV beam and dose rate of 600 MU min⁻¹. A calibration curve was obtained to convert the OD to absolute dose. All films were read out in an EPSON flatbed scanner using the red channel data for measurements.

2.5. Volume effect

One method of calibration to absolute dose is to irradiate small volumes of PRESAGE[®] from the same batch contained in optically clear cuvettes to known doses. These cuvettes were placed in solid water at a known depth and surrounded by bolus material to ensure good scatter conditions. Six cuvettes (two cuvettes for each dose level) were irradiated to known dose levels of 3, 6, and 9.5 Gy along with two cuvettes as controls that were not irradiated. The cuvettes were scanned before and after irradiation with a spectrophotometer (Genesys 20, ThermoSpectronic) to obtain their change in OD. The OD of the cuvettes of the same dose level was averaged. A linear calibration curve was then be obtained by plotting OD versus the known dose of the cuvettes for each dose level with the slope being the sensitivity. The sensitivity of the cuvettes was compared to the sensitivity of the large dosimeters at the same dose levels in order to assess any volume effect that might be present.

2.6. Application to complex treatment verification

The DEA-1 formulation of PRESAGE[®] was chosen for investigation and demonstration of 3D verification for an IMRT and VMAT treatment because of its promising temporal stability post-irradiation (see data in section 3.1). The PRESAGE[®] cylindrical dosimeter was inserted into a head and neck phantom cast with the same polyurethane as was used in the dosimeter. Two patient plans were selected for evaluation. The first was a 5-field coplanar IMRT treatment of the brain with a prescription dose of 5 Gy per fraction. The second was a brain VMAT plan with two coplanar arcs and prescription dose of 1.80 Gy per fraction. The plans were chosen for maximum field sizes smaller than ~7 cm so that the 50% isodose line would be contained within the dosimeter. Each of the plans was delivered twice: once for 3D relative measurement of the OD distribution within the dosimeter and

then a second time to enable determination of absolute dose at a point. The measurement of absolute dose was determined after optical-CT scanning using a small ion chamber (CC01) inserted into a drilled cavity in the high dose region of a dummy PRESAGE® dosimeter. This method has been shown to provide an accurate method of scaling relative 3D dose to absolute 3D dose (Oldham *et al* 2012). The measured OD distribution could then be scaled to match the TPS calculation in the high dose region for a relative dose comparison or could be scaled according to the ion chamber measurement for an absolute dose comparison. Each dosimeter was imaged on the DLOS system with 360 projections (one projection every 1°) approximately 5 h post-irradiation in order to comply with the temporal stability data shown in section 3.1. In order to avoid dose from the planning CT contributing to the optical-CT measured signal, a CT scan for dose calculation was taken after optical-CT scanning using external isocenter marks as the CT zero.

3. Results and discussion

3.1. Temporal stability and sensitivity in large dosimeters

OD values for each of the 5 ROI's, as described in section 2.2, were obtained by taking line profiles through the center of each ROI at a depth of $d_{\max}$ (1.5 cm). The temporal stability of OD is shown in figure 2 for all dosimeters. The OD values in the left column were normalized to the 3 h time point. The OD values in the right column were normalized to the dose calculated by the TPS. Error bars were estimated in the right column to account for uncertainties in the OD value due to PRESAGE® noise ($\pm 1\%$), Eclipse® leakage modeling ($\pm 0.2\%$), and set-up errors ($\pm 0.0833\%$). These errors were summed in quadrature to obtain a total error estimate of $\pm 1.02\%$.

The DEA-1 formulation (top row) exhibited an initial rapid increase in OD over the first hour followed by excellent stability ($< 2\%$ variation) over the next 5 h. The OD of both 3 Gy ROI's increased by $\sim 10\%$ while the OD of both 9.5 Gy ROI's increased by $\sim 4\%$ in the first 1–2 h post-irradiation. The 6 Gy ROI along the central axis does not exhibit the same rapid OD increase in the first 1–2 h. Four of the five ROI's exhibit stable OD ($\sim 1\%$ variation) for the 22 h scan, however, the OD of the ROI along the central axis (6 Gy) decreased by 3% from the value at 3 h post-irradiation. At the 4 h time point, the DEA-1 formulation shows an average sensitivity of $0.0153 \text{ OD}/(\text{Gy}\cdot\text{cm})$ with a variation of $\pm 3.8\%$. Independent ROI's of the same dose level agreed well with each other. The two 3 Gy ROI's and two 9.5 Gy ROI's exhibited sensitivity differences of 2.5 and 0.3%, respectively. The excellent temporal stability from 3–22 h post-irradiation gives a very wide optimal imaging window, however the accuracy of 3D dosimetry could be limited by the $\pm 3.8\%$ variation in sensitivity between different dose levels.

The DEA-2 formulation (middle row) exhibited a similar rapid change in OD in the first hour, where the values of OD increased by roughly 4–10%. The OD then remained somewhat stable ($< 3\%$ variation) from 3 h until 7 h. The optical densities dropped by 3–11% from 7 h until 24 h. At the 4 h time point, the DEA-2 formulation shows an average sensitivity of $0.0271 \text{ OD}/(\text{Gy}\cdot\text{cm})$ with a variation of $\pm 5.4\%$. The differences between ROI's of equal dose at 24 h post-irradiation were 2.6 and 3.8% for the two 3 and 9.5 Gy dose levels, respectively.

Unlike the DEA-1 and DEA-2 formulations, the DX formulation exhibited no rapid change in OD for any of the 5 ROI's in the first 1–2 h post-irradiation. The OD of the 3 Gy ROI's remain stable between 1 and 6 h post-irradiation with less than 2% variation. The OD of the 6 Gy ROI remained stable between 0 and 5 h post-irradiation with less than 2% variation, and after 5 h the OD value began to decrease. The OD of the 9.5 Gy ROI's decreased continuously (~25%) from immediately after irradiation until the last measurement was taken at 21 h. At the 4 h time point, the DX formulation showed an average sensitivity of $0.0384 \text{ OD}/(\text{Gy}\cdot\text{cm})$ with a variation of $\pm 5.9\%$. However, at the 0 h time point, this formulation showed an average sensitivity of $0.0387 \text{ OD}/(\text{Gy}\cdot\text{cm})$ with a variation of only $\pm 3.2\%$. The differences in sensitivity between independent equal dose levels were 3.9 and 1.3% for the 3 and 9.5 Gy ROI's, respectively. Although this formulation exhibited changes in OD dependent on dose level, it shows promise for accurate 3D dosimetry based on a small variation of sensitivity of all 5 ROI's immediately post-irradiation.

The sensitivity (given by the slope) and linearity of the 0 and 4 h time points are shown for all 3 formulations in figure 3. The DX formulation exhibited the highest sensitivity of all formulations while the DEA-1 formulation exhibited the lowest sensitivity. All three formulations showed excellent linearity with R^2 values for all three formulations being >0.99 . Theoretically, the intercept of each linear regression should be very close to zero, and while the sensitivity curves of each formulation did show small y-intercepts, the cause of the varying intercepts of each sensitivity curve could be attributed to noise at low dose levels.

3.2. Comparison with Eclipse® and film

Informed from the results in section 3.1, the DEA-1 formulation was selected for a detailed analysis of optical-CT image quality (artifacts and noise) and comparison with predicted dose distributions. Axial images with line profiles are shown in figure 4 to illustrate image quality, noise, and agreement with Eclipse®. The optical-CT data is of high quality, exhibiting no noticeable image artifacts in this slice of PRESAGE®, and the dose profiles show little to no noise. The peak dose of each dose level matches well with the Eclipse® calculation ($<1\%$ difference), however the vertical profile shows the high gradient region to be more rounded off in the PRESAGE® distribution than in the Eclipse® distribution. The film measurement serves as an independent verification of the absolute dose and the shape of the penumbra of each beam. The general shape of each field appears to be similar in both film and PRESAGE®, however there seem to be some slight misalignment issues. Since each treatment field was set up independently for both the PRESAGE® and film measurements, this could have led to some compounding misalignments. The maximum dose at the center of each of the beams showed disagreement of up to 2% for all fields except the 9.5 Gy dose level in the horizontal profile. This dose level showed disagreement up to ~4%.

The 5-field irradiation pattern was repeated on the DEA-1 formulation. Gamma maps were generated for both irradiations between the PRESAGE® dose distribution and Eclipse® calculation using criteria of 3%/3 mm as shown in figure 5. The percentage of voxels passing the gamma analysis (voxels <1.0) for the left dosimeter was 98.2%. The voxel

passing rate for the right dosimeter was 99.9%. Most of the regions of failure appear to be in the high-gradient regions at the edges of the fields.

3.3. Cuvette measurements

The sensitivity of the DEA-1 cuvettes was measured to be $0.0289 \text{ OD}/(\text{Gy}\cdot\text{cm})$ with an R^2 value of 0.999 and intercept of $0.0027 \text{ OD}/\text{cm}$.

Since cuvettes can be used for calibration to absolute dose in the large dosimeter, a comparison of the sensitivity of large dosimeter to cuvettes was done (figure 6). The cuvettes and large dosimeter were irradiated to the same dose level of 3, 6, and 9.5 Gy (at a depth of d_{max} for the large dosimeter), so a direct comparison of sensitivity can be made. Ideally, when the sensitivities of the cuvettes and large dosimeter are plotted against one another, the slope of the line should be 1 with an R^2 value of 1 and having an intercept of zero indicating that their sensitivities are equal for all dose levels. This was not the case for this formulation, however. The slope of the curve was 0.3694 indicating that the large dosimeter had less than half the sensitivity of the cuvettes. The curve showed a high degree of linearity with an R^2 value of 0.999 and had a near-zero intercept. It is important to note that the cuvettes were made from the same batch of PRESAGE[®] as the large dosimeter.

3.4. IMRT and VMAT verification

The DEA-1 formulation of PRESAGE[®] was used to verify the delivery of a brain IMRT and a brain VMAT treatment. The absolute dose at a point in the head and neck phantom with PRESAGE[®] insert was measured for both the IMRT and VMAT treatments using an SRS (CC01) ion chamber. The percent difference between the ion chamber and Eclipse[®] calculation at the same point was 2.2% for the IMRT treatment and 3.1% for the VMAT treatment. The percent difference between ion chamber measurement and TPS calculation was larger than expected and could be a result of noise in the planned dose distributions. When the absolute dose measurement is used to scale the PRESAGE[®] OD distribution to dose, noise in the measured distribution is a possible source of error in the gamma analysis. Because of these possible errors, both the relative and absolute dose distributions can be useful in verifying agreement to the planned dose distribution.

Gamma criteria of 3%/3 mm and 3%/2 mm were used to compare the absolute and relative PRESAGE[®] dose distributions to Eclipse[®]. A 10% threshold was applied to the measured distribution so that only points with more than 10% of the maximum dose were included in the analysis. Increased sensitivity was observed in a ring of about 5 mm inside the edge of the dosimeter in the PRESAGE[®] distribution. This caused inaccuracy in the apparent dose around the edge of the dosimeter ($\sim 2 \times$ higher than actual dose). Because of this effect, the edges of the dose distribution are not shown, and the 3D gamma map was calculated after the edges of the dosimeter were cropped off to avoid these erroneously high values. The cause of this edge enhancing effect is not known. The gamma maps below have been windowed so that any failing pixel (value >1.0) appears red, and all other colors represent passing pixels. The percentage of passing pixels for both treatments are shown in table 2 for both relative and absolute dose distributions with criteria of 3%/3 mm and 3%/2 mm.

The comparison of measured and calculated 3D dose distributions for the 5-field IMRT plan is shown in figure 7. The PRESAGE[®] OD distribution was normalized to a point in the high dose region of the Eclipse[®] calculation. The isotropic spatial resolution was 1 mm for both PRESAGE[®] and Eclipse[®]. The average dose difference between PRESAGE[®] and Eclipse[®] in the high dose region for the IMRT treatment was less than 2%. In the high gradient regions, the average distance to agreement was less than 2 mm.

For the dual arc VMAT treatment shown in figure 8, the PRESAGE[®] OD distribution was again normalized to a point in the high dose region of the Eclipse[®] calculation. Line profiles through both the PRESAGE[®] dose distribution and the Eclipse[®] calculation show good agreement in both high dose regions and high gradient regions. The maximum disagreement in the high dose regions was 3%, however the agreement was generally within 2%. The distance to agreement in the high gradient regions was generally within 1–2 mm with a maximum of 3 mm.

4. Conclusions

Although they had different dosimetric characteristics, all three formulations of PRESAGE[®] showed potential for accurate 3D dosimetry. It is recommended that the DEA-1 formulation is scanned between 3 and 24 h post-irradiation, the DEA-2 formulation is scanned between 2–6 h post-irradiation, and the DX formulation is scanned immediately post-irradiation. One area of concern for all formulations studied is the y-intercept of the sensitivity curves. This intercept should be very near zero; however, a small, non-negligible, positive intercept was seen for all formulations.

This work shows that the large dosimeters had sensitivity less than half the sensitivity of small volumes of PRESAGE[®] from the same batch, constituting a substantial volume effect for dose sensitivity. This is observed to be formulation-dependent and possibly related to different hardening of PRESAGE[®] cured in different volumes. Small samples of these PRESAGE[®] formulations cannot therefore be used to calibrate larger volumes. An alternative calibration method is recommended, where the relative 3D dose distribution is normalized to a point of known dose, which is determined by ion chamber in a duplicate dummy dosimeter containing a channel to house the chamber. This method is subject to limitations such as noisy PRESAGE[®] data, which could lead to small (~1–2%) discrepancies.

In summary, this work shows that accurate 3D dosimetry is possible with all three PRESAGE[®] formulations studied, however, it is essential to understand the temporal stability of the formulation and conduct imaging readout accordingly. PRESAGE[®] with optical-CT readout was shown to be a useful high-resolution 3D verification technique for IMRT and VMAT treatments of the brain.

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Figure 1.
(a) Axial slice at 1.5 cm depth of the dosimeter (Eclipse® [Varian Medical System Inc., Palo Alto, CA] calculation). Fields were 2×2 cm with edges separated by 1.25 cm. (b) Coronal slice. Dashed line in (a) shows plane of (b) and vice versa.

Figure 2.

Temporal stability plots for all three formulations of PRESAGE®. Data points were extracted from the central high dose regions indicated in figure 1(a). The left column shows normalized OD to the 3 h time point for DEA-1 (top), DEA-2 (middle), and DX (bottom) formulations. The right column shows sensitivity plotted over time for DEA-1, DEA-2, and DX formulations. Dose estimates were extracted from the TPS.

Figure 3. Sensitivity curves plotted for DEA-1, DEA-2, and DX formulations using 0 and 4 h scans and axial slice at 1.5 cm depth. The slope of each curve gives the sensitivity of the formulation.

Figure 4.

Line dose profile comparison of PRESAGE[®] with Eclipse[®] (top two rows) and film (bottom two rows) through axial slice at 1.5 cm depth. PRESAGE[®] measurement was taken with DEA-1 formulation at 4 h time point.

Figure 5.

Gamma maps for two irradiations of the 5-field pattern on independent dosimeters of DEA-1 formulation. Criteria of 3%/3 mm was used to compare PRESAGE™ to Eclipse® calculation for both dosimeters. The voxel pass rate for left dosimeter was 98.2%. The voxel pass rate for right dosimeter was 99.9%

Figure 6.

Plot A shows OD/cm for each cuvette versus dose (Gy) for DEA-1 formulation cuvettes with slope giving sensitivity. Plot B shows sensitivity of large dosimeter plotted versus sensitivity of cuvettes of same formulation and batch for the same dose levels. The dashed line shows the ideal slope of 1.

IMRT treatment

Figure 7. Comparison of relative PRESAGE[®] dose distribution (left-most column) to Eclipse[®] calculation (2nd column from left) for 5-field IMRT treatment technique. Line dose profiles and 3D gamma analysis (3%/3 mm) are shown in axial (top row), sagittal (middle row) and coronal (bottom row) planes of the head and neck phantom.

Figure 8. Comparison of relative PRESAGE[®] dose distribution (left-most column) to Eclipse[®] calculation (2nd column from left) for dual arc VMAT treatment technique. Line dose profiles and 3D gamma analysis (3%/3 mm) are shown in axial (top row), sagittal (middle row) and coronal (bottom row) planes of the head and neck phantom.

Table 1

Chemical components of three PRESAGE® formulations.

	Polyurethane	Leuco dye	Leuco dye solvent	Initiator	Other components
DEA-1	Smooth-on crystal clear® 206 (90.94%)	o-MeO-LMG-DEA (1.5%)	C ₆ H ₁₂ O ₂ (5.0%)	CBr ₄ (0.4%)	0.16% solvent 2.0% DMSO
DEA-2	Smooth-on crystal clear® 206 (51.44%)	o-MeO-LMG-DEA (1.0%)	C ₆ H ₁₂ O ₂ (5.0%)	CBr ₄ (0.4%)	0.16% solvent 2.0% DMSO 40% plasticizer
DX	Smooth-on crystal clear® 206 (90.25%)	LMG (2.0%)	(CH ₂) ₅ CO (7.0%)	CBr ₄ (0.5%) CBrCl ₃ (0.25%)	—

Table 2

Gamma index (3%/3 mm, 3%/2 mm) passing rates of both relative and absolute PRESAGE[®] dose distributions compared to Eclipse[®] calculations for IMRT and VMAT treatments.

	Relative dose		Absolute dose	
	3%/3 mm	3%/2 mm	3%/3 mm	3%/2 mm
IMRT	99.4%	98.7%	99.6%	97.0%
VMAT	97.9%	93.1%	94.5%	80.6%