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A practical three-dimensional dosimetry system for radiation therapy

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Abstract

There is a pressing need for a practical three-dimensional (3D) dosimetry system, convenient for clinical use, and with the accuracy and resolution to enable comprehensive verification of the complex dose distributions typical of modern radiation therapy. Here we introduce a dosimetry system that can achieve this challenge, consisting of a radiochromic dosimeter (PRESAGE™) and a commercial optical computed tomography (CT) scanning system (OCTOPUS™). PRESAGE™ is a transparent material with compelling properties for dosimetry, including insensitivity of the dose response to atmospheric exposure, a solid texture negating the need for an external container (reducing edge effects), and amenability to accurate optical CT scanning due to radiochromic optical contrast as opposed to light-scattering contrast. An evaluation of the performance and viability of the PRESAGE™/OCTOPUS, combination for routine clinical 3D dosimetry is presented. The performance of the two components (scanner and dosimeter) was investigated separately prior to full system test. The optical CT scanner has a spatial resolution of ≤ 1 mm, geometric accuracy within 1 mm, and high reconstruction linearity (with a R^2 value of 0.9979 and a standard error of estimation of $\sim 1\%$) relative to independent measurement. The overall performance of the PRESAGE™/OCTOPUS system was evaluated with respect to a simple known 3D dose distribution, by comparison with GAFCHROMIC® EBT film and the calculated dose from a commissioned planning system. The “measured” dose distribution in a cylindrical PRESAGE™ dosimeter (16 cm diameter and 11 cm height) was determined by optical-CT, using a filtered backprojection reconstruction algorithm. A three-way Gamma map comparison (4% dose difference and 4 mm distance to agreement), between the PRESAGE™, EBT and calculated dose distributions, showed full agreement in measurable region of PRESAGE™ dosimeter ($\sim 90\%$ of radius). The EBT and PRESAGE™ distributions agreed more closely with each other than with the calculated plan, consistent with penumbral blurring in the planning data which was acquired with an ion chamber. In summary, our results support the conclusion that the PRESAGE™ optical-CT combination represents a significant step forward in 3D dosimetry, and provides a robust, clinically effective and viable high-resolution relative 3D dosimetry system for radiation therapy.

Keywords

3D dosimetry; gel dosimetry; PRESAGE™; optical CT; quality assurance

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I. INTRODUCTION

Present intensity modulated radiotherapy (IMRT) dose verification techniques including ion chambers, film, and MAPCHECK[®] (diode array), are insufficient to provide a truly comprehensive and convenient dose measurement in three dimensions (3D).^{1,2} The need for an accurate and practical 3D dosimeter is becoming ever more critical as modern dose delivery techniques increase in complexity and sophistication. A recent report from the Radiological Physics Center (RPC),³ revealed that 38% of the institutions failed the head-and-neck IMRT phantom credentialing test at the first attempt, despite a generous criteria (7% dose difference and 4 mm distance to agreement). The RPC criteria were applied to thermoluminescent dosimeters (TLD) measurements at six points inside the simulated planning target volume (PTV) and GAFCHROMIC[®] film measurement in a single axial plane through PTV and organ at risk. The question arises—what percentage of institutions would have failed if a more comprehensive 3D measurement had been feasible, rather than measurements restricted to the central film plane and TLD points? This question can only be adequately answered by a comprehensive verification in 3D, and presents a compelling argument for the need for a clinically viable 3D dosimetry system.

An accurate and convenient 3D dosimeter would be useful for commissioning as well as for routine quality assurance (QA) to enhance treatment quality. Recent research has focused on gel dosimetry^{4–11} as a solution to this challenge. In gel dosimetry, a hydrogel records the 3D dose which is then read out by the means of optical computed tomography (CT)^{6,9,12–15} or magnetic resonance imaging (MRI)^{6,8,16–18} depending on the nature of response of the gel to radiation. Other less established readout techniques have been proposed including ultrasound tomography,¹⁹ and x-ray CT.²⁰ Polymer gels and Fricke gels have been the most popular reported in literature^{11,17,21–25} and both have advantages and limitations. In general, polymer gels have good stability postirradiation and can be scanned by both optical CT and MRI, but the dose response is extremely sensitive to atmospheric oxygen, which introduces difficulty during manufacture and usage.^{13,17,26} Also, polymer gels, being translucent, respond to irradiation by generating polymer microparticles that cause optical contrast through light scattering. It is well known that scattered radiation causes artifacts in x-ray CT. Similarly significant scatter artifacts have been demonstrated in optical-CT scanning of polymer gels.^{15,27} Fricke gels are relatively easy to manufacture and use but suffer from poor stability postirradiation due to diffusion.^{21,28} Both the polymer and Fricke gel dosimeters require an external container, and the refractive index differences between the gel, container and matching fluid lead to edge artifacts reducing the useful region of the dosimeter. Although improvements continue in both Fricke and polymer gels,^{29,30} and in artifact correction techniques,^{14,15} a convenient and accurate 3D dosimeter that can overcome all of the above limitations has not yet been reported.

PRESAGE[™] is a transparent, solid polyurethane based dosimeter, in which a radiochromic color change is observed upon radiation exposure.^{31–34} The radiochromic response is well suited for accurate optical CT because of the very low scatter fraction.²⁷ Previous work²⁵ on small volumes has shown the PRESAGE[™] dose response to be robust to the normal laboratory environment given stable temperature and protection from fluorescent light. The radiochromic response varies less than 2% when irradiation temperature is stable within 1 °C,²⁵ and can be stable (<2%) within two days postirradiation.²⁵ The hard plastic texture negates the need for an external container, which provides great convenience in practice and improves accuracy by minimizing edge artifacts arising from refractive index miss matching at the surface. Furthermore, PRESAGE[™] is amenable to machining to different sizes and shapes according to actual needs. The present paper builds on our earlier work²⁵ concerned with an in-depth investigation of the basic dosimetric properties of PRESAGE[™] evaluated with a novel and efficient technique to enable study of a large number of parameters on small volumes of

material. The present work extends this study to include our first experiences with large volumes of PRESAGE™, and an investigation into the viability of PRESAGE™ in combination with a commercial optical-CT scanning system (OCTOPUS™, MGS Research Inc.) as a new system for practical 3D dose measurement in the clinic.

II. MATERIALS AND METHODS

The evaluation of the PRESAGE™/OCTOPUS™ dosimetry system was approached in three distinct phases. In the first phase, the basic dosimetric properties of PRESAGE™ were investigated by precise measurements on small volumes using a customized spectrophotometric technique. This work has been published²⁵ and established the basis for PRESAGE™ dosimetry and the present paper which addresses the second and third phases. In the second phase, (Sec. II A below), the imaging performance of the OCTOPUS™ scanner was evaluated to determine appropriate acquisition parameters, sources of noise and artifacts, geometrical accuracy, spatial resolution, and accuracy of reconstructed attenuation coefficients. In the final third stage, a “whole-system” test was performed by comparing, for a simple “known” dose distribution, the dose measured by the PRESAGE™/OCTOPUS™ system, a commissioned treatment planning system, and independent measurement with GAFCHROMIC® EBT film. The 3D dose distribution recorded in the PRESAGE dosimeter was read out by a commercial optical-CT scanner OCTOPUS™, which had some minor in-house modifications described below.

A. OCTOPUS™ optical-CT scanner

A commercial optical-CT scanner OCTOPUS™ (MGS Research Inc., Madison, CT) was used to scan the PRESAGE™ dosimeter as depicted in Fig. 1. The principle of the optical scanner is similar to the first generation of x-ray CT scanners employing a parallel beam and was described previously.³⁵ Here, we briefly summarize its principle and configurations. The object to be scanned (e.g., the PRESAGE™ dosimeter shown in Fig. 1) is mounted on a turn plate in the water tank. The water tank is filled with a fluid with similar refractive index as the PRESAGE™ to minimize refraction and reflection at the interface. A small amount of blue dye is added to the matching fluid to equalize the light attenuation through the fluid and the unirradiated PRESAGE™ dosimeter and hence maximize the dynamic range of measurement. A He-Ne laser with power of 0.8 mW and a wavelength of 633 nm (Edmund Optics, Barrington, NJ) is incident on a beam splitter placed in front of the laser, dividing the laser beam into two parts: a reflected beam and a transmitted beam. The reflected beam goes directly into a photodiode (reference photodiode) that monitors the fluctuation of laser output. The transmitted laser beam (~1 mm beam width) is guided by traveling mirrors to scan across the dosimeter (horizontally), such that a single projection is acquired for each linear scan across the dosimeter by the second photodiode (signal photodiode). The projections for different orientations (view angles) of the dosimeter are obtained by repeated rotation of the dosimeter followed by the linear scan. Once all the projections are acquired for a specific slice, the laser beam is moved vertically to repeat the scan at a different slice location. The 3D distribution of the dosimeter's attenuation coefficient is then reconstructed from the projection data sets using a filtered backprojection algorithm (FBP).

The scanning and data acquisition are controlled by an in-house program written in TESTPOINT® (CEC Inc., Billerica, MA). The optical-CT scanner was configured to have a pixel size of 0.5 mm for the linear scan (projection data) and each pixel value was an average of 100 ADC reads. The total number of pixels for each projection was 397. Data acquisition has a precision of 16 bit and the reconstruction code was written in MATLAB (Mathworks, Natic, MA). The scanning time for a single slice with 150 projections is about 7 min.

1. Performance evaluation—A number of tests were performed on individual components of the optical-CT scanner to ensure correct functioning. In particular, the output stability of the laser was determined by monitoring the two photodiode readings, at every 10 min for 10 h, with no fluid in the tank (typically, a few hours are needed for a full 3D scan). The effect of the quality of the water tank and the fluid was evaluated by repeated linear scanning of the water tank when containing only fluid, without any object present. The linearity of response of the photodiode was determined by measuring transmittance of light through calibration films with various known transmittance values. System parameters such as speed (2350 motion steps/s for a projection scan), step size (20 steps/mm), linear scan range (20.9 cm), central axis of rotation, and data acquisition rate (24 000 Hz) were optimized in trial experiments to ensure scanning accuracy.

Once the correct function of individual components was verified, the performance of the optical-CT scanner was investigated by performing complete optical-CT scans of phantoms designed to test a range of parameters^{14,15} including spatial resolution, uniformity, geometric accuracy, and linearity. In particular, a uniform gel (10% gelatin and 90% water) was scanned to evaluate the imaging (reconstruction) uniformity. A thin wire (~0.2 mm diameter) embedded vertically in a gel was scanned to evaluate the imaging resolution. A gel phantom containing multiples of such wires at different locations was used to test the geometric accuracy of imaging. The positions of the wires detected by the optical-CT scanner were compared against their true positions shown in an x-ray CT scanner. The optical-CT scan of the wires was registered to their CT scan based on the body boundaries of the gel phantom and one of the wires. The same slice of the phantom was selected from the CT scan and the optical scan for the registration by measuring the distance from the slice to the top surface of the phantom. The gel phantom made for evaluating accuracy of reconstructed coefficients contains gel inserts with different known optical densities (ODs). Different optical densities were generated by varying the proportion of blue dye in the inserts. True OD values of the inserts were measured by a spectrophotometer (SPECTRONIC™ GENESYS™20) at a wavelength of 633 nm. Refractive index matching was achieved by a mixture of glycerol (refractive index 1.473) and water (refractive index 1.333).

B. 3D dosimeter—PRESAGE™

Different formulations of PRESAGE™ dosimeters (Heuris Pharma LLC, Skillman, NJ 08558), containing different kinds and amount of solvent, leuco dye, and free radical initiator, lead to different radiation sensitivity, stability, density, and hardness. The PRESAGE™ dosimeter used in this work is a polyurethane plastic doped with a radiochromic leuco dye. Basic properties include an effective Z number of 8.3, a physical density of 1.07 g/cm³, and a CT number of ~200.²⁵ The radiochromic response is from yellow to green with maximum absorption occurring at the wavelength of 633 nm. The irradiation induced optical absorption for this formulation was found to be stable within 2% for two days post the irradiation.²⁵ Great variations in the stability have been observed with different formulations, however, with some formulations stable for many months, and some fading within a matter of hours. More details can be found in Ref. 25. A cylindrical PRESAGE™ dosimeter was constructed with dimensions of 16 cm diameter×11 cm height. The dosimeter was always handled in low light levels, as a noticeable color change was observed on prolonged exposure to fluorescent room lighting. The PRESAGE™ dosimeter was taken through the entire treatment planning process to simulate as closely as possible the treatment of an actual patient. The treatment procedure included creation of isocentric alignment marks, x-ray CT scan, creation of a treatment plan, followed by treatment. Three visible cross marks were made by a scalpel on the wall of the dosimeter and these alignment marks were used to position the dosimeter for both the CT scanner and for treatment on the linear accelerator (LINAC).

C. 3D dose verification experiment

The basic rationale of the verification experiment was to evaluate PRESAGE™ against independent EBT measurement [two dimensional (2D)] and calculation (3D), for a simple dose distribution where the calculation is known to be highly accurate, but which also had sufficient spatial variation to render a comprehensive test. A coplanar isocentric treatment of five identical open-rectangular fields was selected as coming close to meeting these constraints. The main evaluation of PRESAGE™ was performed in 3D by comparison against the near gold standard of the commissioned planning system dose calculation. The independent EBT measurement was included as although limited to 2D, the high resolution enables independent verification in regions of steep dose falloff (e.g. penumbra) where the planning system is known to have minor modeling errors. These errors arise from the fact that the commissioning data the calculation model is based on was acquired with a relatively large ion chamber collecting volume, leading to a small degree of penumbral blurring.

1. Treatment planning and calculated dose distribution—Three CT markers of 1 mm diameter (X-SPOTS®, BEEKLEY, Bristol, CT 06010) were placed at the locations of the three cross marks on the cylindrical dosimeter. Based on the x-ray CT scan, the 3D five-beam treatment plan was created in the ECLIPSE® treatment planning system. The treatment fields were identical 6 MV rectangular open beams (5×6 cm²), with equi-angular spacing, (gantry angles of 0, 72, 144, 216, and 288°, respectively). In the treatment plan, the isocenter of the fields was set 1 cm off the central axis, and 2 cm inferiorly from the slice with the three marks, to provide asymmetry. The prescribed dose at the isocenter was 15 Gy. The dosimeter was positioned on a treatment couch (Fig. 2) to match the setup in the treatment plan for delivery. It was then irradiated by a Varian 21EX linear accelerator (Varian Corporation, Palo Alto, CA) under room temperature (22 °C) according to the treatment plan. The dose distribution delivered by the treatment plan was calculated by the commissioned pencil beam algorithm in Eclipse, with a spatial resolution of 1.25 mm.

2. 3D dose measurement by PRESAGE™/optical-CT system—The irradiation induced change in optical density (OD) in the PRESAGE™ dosimeter was determined by optical-CT scanning both pre and post the irradiation, and subtracting the pre-irradiation reconstruction from the postirradiation. Because of the linear relationship between OD change and dose,²⁵ the distribution obtained after this subtraction represents the relative distribution of the absorbed dose in the dosimeter. The distribution of OD change was normalized at the beam isocenter for conversion to the relative dose distribution. The optical-CT reconstructions were performed using an in-house program based on the filtered backprojection algorithm (FBP). Each slice was scanned with 150 projections over 180°. Eighteen slices were acquired with 5 mm slice spacing interval. The three marks on the dosimeter were contained in one of the reconstructed slices and were utilized to register the optical-CT and x-ray CT reconstructions and hence the calculated dose that was based on the x-ray CT scans. The laser beam in conjunction with the encoders of the optical scanner (i.e., mirror positions) as well as the marks on the dosimeter were utilized to position the dosimeter to the exact same location in the optical scanner for both pre and post the irradiation scans. The setup and scanning of the dosimeter were performed in a darkroom with air conditioning to prevent the exposure of fluorescent room light and significant temperature change. The refractive index matching fluid was a mixture of octyl salicylate and methoxy octyl cinnamate, which has an index of 1.504 for minimizing the refraction of the laser beam. The scanning time for each slice configured above was about 7 min.

3. Dose measurement by EBT film—The inclusion of an independent measurement of the delivered dose distribution is an important component as it facilitates resolution of discrepancies between the PRESAGE™ and calculated distributions. Although the delivered

distribution was deliberately simple, such that the calculated plan would be close to exact, differences were possible especially in the penumbral regions where penumbral blurring could occur (described above). The independent measurement was made by GAFCHROMIC® EBT film (ISP corporation, NJ), which was inserted into the PRESAGE™ cylinder at the axial slice that contains the isocenter of the irradiation beams. Three marks were made on the film corresponding to the locations of the three alignment marks made on the surface of the PRESAGE™ cylinder. Matching these marks enabled image registration between the EBT, planning and PRESAGE™ dose distributions. The PRESAGE™ cylinder together with the inserted film was then irradiated by the same treatment plan described in Sec. II C 1 but with a reduced prescription dose of 3 Gy to avoid the saturation of the film response. The irradiated EBT film was scanned by an EPSON® Perfection 4990 flat-bed scanner (in transmission mode) the day after irradiation to ensure the completeness of the response (~2 h). The EBT film was also scanned pre-irradiation to enable determination of the radiation induced pixel value change.

The EBT film is self-developing providing great convenience for practical use. It can be used under room light, put into water, and cut into different shapes and sizes. The sensitivity of EBT film ranges from ~1 cGy to 8 Gy.³⁶ The red color map of the scanned EBT film images was extracted and used as the signals (the EBT film has maximum response to red light³⁶). A calibration curve was obtained (see below) and applied to the EBT film scan irradiated in the PRESAGE™ cylinder to enable conversion to dose.

a. Calibration of EBT film: Calibration of EBT was performed by cutting a single sheet into nine pieces of dimension 5×6 cm, and irradiating each with successive known doses in the range 0–8 Gy in 1 Gy increments. The calibration data were measured at regular intervals over the next seven days to determine stability of the scanner-EBT combination. Some of the data were illustrated in Fig. 3. The radiochromic response of EBT film was observed to complete within 2 h postirradiation and was stable during the following week (within 1.3% of the mean value). A calibration curve was obtained from data measured the day after irradiation (consistent with the experimental film) and is described by the equation $y = 4.975x^5 - 126.83x^4 + 1264.8x^3 - 6408.5x^2 + 19086x + 535.06$ with a standard error of estimate of 0.57%. In the equation, x and y represent irradiation dose (Gy) and the corresponding pixel value change in the red color map of the scanning films pre and post the irradiation.

b. Dose registration and evaluation: The 3D dose distribution measured by the PRESAGE™/OCTOPUS system (henceforth referred to as the PRESAGE™ dose distribution), the planar dose measured by the EBT film (referred to as the EBT dose), the calculated 3D dose from the ECLIPSE planning system (referred to as the ECLIPSE dose), and the CT scan of the PRESAGE™ dosimeter, were all loaded into DOSEQA software (www.cognition.com) for 3D dose registration and analysis. The PRESAGE™ dose was registered to the x-ray CT scan using the combination of the three coplanar surface marks and the external shape of the cylinder, all of which were visible in both data sets. By doing so, the PRESAGE™ dose was also registered with the ECLIPSE dose as the coordinate system of the latter is tied to that of the CT scan. The EBT dose was registered with the PRESAGE™ dose in a similar way, except that just the three coplanar marks were necessary. Comparison between the three registered dose distributions was performed in DOSEQA. In particular, dose distributions, isodose lines, dose profiles, and Gamma maps^{37,38} (4% dose difference and 4 mm distance to agreement) were created for comparison. There is much debate as to the most appropriate criteria for gamma map acceptance criteria. In this work we selected 4%-4 mm which is the passing criteria in use in our clinic for evaluating Mapcheck IMRT QA. It is noted that the RPC have a more generous passing criteria (7%/4 mm) for the head-and-neck IMRT credentialing service.³

III. RESULTS AND DISCUSSIONS

A. Performance of the optical-CT scanner

1. Testing of laser, water tank, and photodiodes—The measurement of the laser output stability showed that the normalized laser signal (ratio of the transmitted laser signal to the reflected reference signal) had a variation of only 1% during the 10 h experiment. Individual transmitted and reflected laser signals exhibited a drift of up to 4%. The effect of laser output drift was effectively made negligible by taking the ratio of the transmitted signal over the reflected reference signal. Repeated scanning of the water tank when filled with matching fluid, but without any object inside the tank, showed a highly reproducible profile with a variation of ~2% about the mean. This variation can be reduced by constructing the water bath from high quality anti-reflection coated glass walls, and maintaining clean surfaces. The linearity of photodiode response was evaluated on calibrated OD films with true transmittance values (x) of 85.1, 42.7, 30.2, 20.9, and 3.9%. The measured transmittance values (y) with the OCTOPUS photodiodes were 86.9, 44.1, 31.5, 20.6, and 3.4%, respectively. The linear fit equation between these measurements was $y = 0.97x$ with a R^2 value of 0.9997 and standard error of estimate of 0.63%, indicating high linearity of photodiode response.

2. Resolution, uniformity, geometric accuracy, and linearity of attenuation coefficients

The reconstruction of the 0.2 mm thin wire is shown in Fig. 4(a) with the corresponding profile in Fig. 4(b). The profile shows that the reconstructed size of the wire is about 1 mm (two pixels) determined from full width at half maximum (FWHM). The point-spread function (PSF) is defined as the reconstruction of a point object and is one of the standard terms used for evaluation of the resolution of an imaging system. The reconstruction of the thin wire can be viewed as an approximation of the PSF due to its small size. The actual FWHM of the PSF will be smaller than the FWHM (1 mm) determined from the wire reconstruction. Further analysis of the imaging resolution can be performed by utilizing the modulation transfer function.^{14,15} A large ring artifact that appeared in the reconstruction was generated by the low signal measured at the wall of the container for gel phantoms, where light deflection and refraction occurred due to nonperfect refractive index matching.

The reconstruction of the uniform gel section is shown in Fig. 4(c). A profile along the dotted line in the reconstructed image is given in Fig. 4(d). The standard deviation of the reconstruction value is <1% over the useful region (within ~75% of the radius of the container), which indicates high uniformity in the useful region. Figure 4(e) shows the superimposed x-ray CT wire positions (white dots) and optical-CT wire positions (black dots). Figure 4(f) is a zoomed view of Fig. 4(e). The reconstructed optical-CT positions match their true positions (x-ray CT scan) to within 0.5 mm, indicating little geometric distortion. This is consistent with other observations for first generation optical-CT systems,¹⁵ and is due to the effective elimination of stray and scattered light. The accuracy of optical-CT reconstructed attenuation coefficients was evaluated on a phantom with inserts of known attenuation. The optical-CT coefficients (y) were found to relate to the true attenuation coefficients (x) (measured by spectrophotometer) via the equation $y = 0.97x$ with R^2 value of 0.9979 and a rms error of ~1%. These values indicate a linear relationship enabling accurate relative measurement.

B. Dose measurement by PRESAGETM/optical-CT system

Figure 5 shows examples of the optical-CT projections and reconstructed images of the PRESAGETM dosimeter pre and post the irradiation. Figure 5(a) shows the data acquired for the same single projection pre and post the irradiation. The spikes that appeared at the region close to the wall of the dosimeter in both projections are caused by refraction and reflection due to the nonperfect matching of refractive indices between the fluid and the dosimeter. The minor fluctuation or noise seen in the projection data can come from many sources including

impurity specs in the fluid and the dosimeter, the nonuniform transmittance of the wall of the water tank, and the quality of the optical components. Figures 5(b) and 5(c) show the reconstructed images of the central plane of the dosimeter pre and post the irradiation respectively. Figure 5(d) shows the corresponding profiles along the dashed lines in Figs. 5(b) and 5(c). Comparison between optical-CT scans of the dosimeter before and after the x-ray CT scan showed negligible difference, indicating that the low dose of the x-ray CT (~1 cGy) generated little optical density change in the dosimeter. A striking feature of the reconstructions is that quality data are observed right out close to the edges of the dosimeter (see below). This is an improvement over gel dosimeters where the edge artifacts are noticeably more pronounced due to the refractive index mismatch between gel/container/water-bath-fluid. In this particular PRESAGE™ dosimeter minor scratches and impurity specs were visually observed on the surface and inside the dosimeter, which led to observable specs in the reconstruction. A close inspection of the pre and post the irradiation dosimeter [Figs. 5(b) and 5(c)], shows these specs occurring at the same locations indicating they are real impurities. The noise arising from imperfections in the wall of the water tank may be minimized by dividing projections by “background” projections of the water bath without the presence of any object. However, tests showed that the benefit was not significant if the water tank was kept in good condition and well cleaned (e.g., no major scratches or dusts).

C. Comparison of PRESAGE™ dose, ECLIPSE dose, and EBT dose distributions

1. Comparison on central axial slice—Figure 6 shows the central axial slice view of PRESAGE™ dose (a), ECLIPSE dose (b), and EBT dose (c). All three dose distributions were normalized at the isocenter of the treatment plan located centrally in the high-dose region. Percent isodose lines of 95, 90, 80, 70, 60, 50, 40, 30, and 20% were superimposed onto these images for comparison. Dose profiles along the solid line in Fig. 6(c) are plotted in Fig. 6(d). In general, good agreement between the three dose distributions was observed. However, close inspection reveals that the PRESAGE™ dose agrees slightly better with the EBT dose, especially in the penumbral regions, than with the ECLIPSE dose as shown by the arrows in Fig. 6(d). Such close agreement between independent measurements suggests the accuracy of the dose calculation algorithm in the treatment plan is suspect in these regions. This result is attributed to a known blurring of the calculate distribution in high gradient regions arising from the fact that the calculations are based on models of the commissioning measurements which were made by an IC10 ion chamber with finite size (diameter ~6 mm). The noise in the PRESAGE™ dose appears slightly higher than that in the calculated and EBT distributions. The primary sources of noise in optical-CT arise from impurity particles in the water-bath fluid drifting into the path of the laser beam, and from small scratches and imperfections in and on the surface of the dosimeter itself. It is anticipated that the noise can be reduced further by more sophisticated PRESAGE™ manufacturing techniques, and better fluid filtration.

Overlays of the percent isodose lines (95, 80, 60, 50, 40, and 30%) between the three dose distributions are given in Fig. 7, where (a) is the overlay of the PRESAGE™ dose (blue color) and the EBT dose (red color), (b) is the overlay of the PRESAGE™ dose (blue color) and the ECLIPSE dose (red color), and (c) is the overlay of the EBT dose (blue color) and the ECLIPSE dose (red color). In general, good agreement is observed between all three distributions for doses >30%. PRESAGE™ dose values were observed to be artificially low in regions within about 8 mm (corresponding to ~ <30% isodose in this case) from the edge of the PRESAGE™ cylinder. This is attributed to inaccurate optical-CT scan (hence distorted reconstruction) in the regions close to the edge of the PRESAGE™ dosimeter, where significant refraction and reflection may occur (refer to Fig. 5). A “measurement-region” can be defined for the PRESAGE™ dose, which excludes the outer 8 mm ring, and where the PRESAGE™ dose values are edge-artifact free. The size of this exclusion ring is expected to vary depending on the quality of the match between the fluid and PRESAGE™. The measurement region (useful

reconstruction region) is about 90% of the radius (80 mm) of the PRESAGE™ cylinder, which is an improvement compared to the 75% observed in Ref. 13. EBT film has a full measurement region and shows good agreement with the ECLIPSE dose even for doses <20%.

The isodose overlays show encouraging agreement, but differences are clearly observed especially in regions of steep gradients and low doses. A further analysis was therefore quantitative performed to compare all three distributions using the gamma comparison tool^{37,38} with an acceptance criteria of 4% dose difference and 4 mm distance to agreement. There is much debate about which criteria are most appropriate for IMRT QA.¹ The 4%/4 mm criteria were selected as these values are presently in clinical use in our clinic to assess MAPCHECK IMRT QA. Gamma plots for the central axial slice are shown in Fig. 8. Figure 8(a) shows the gamma plot for PRESAGE™ dose and the ECLIPSE dose, Fig. 8(c) is the gamma plot for PRESAGE™ dose and the EBT dose, and Fig. 8(e) is the gamma plot for EBT dose and the ECLIPSE dose. Figures 8(b), 8(d), and 8(f) are profiles along the solid lines in the gamma maps (a), (c), and (d), respectively. In general, the gamma value is <1 which demonstrates that the PRESAGE™ measurement agrees with both the EBT film measurement and the treatment plan calculation within the 4%/4 mm criteria. The gamma plots also confirm that the PRESAGE™ and EBT measurements agree with each other slightly better than with the treatment plan as indicated by the smaller gamma value in Figs. 8(c) and 8(d). The relatively high gamma values visible in the penumbral regions of both Figs. 8(a) and 8(e) confirm the penumbral blurring in the dose algorithm of the treatment planning system.

2. Comparison on central coronal and sagittal views

Comprehensive verification requires comparison of the dosimetry in 3D or in all axial planes of the dosimeter. Such a comparison was only feasible between the PRESAGE™ dose and the Eclipse dose, as both are 3D data sets. Close inspection revealed that the level of agreement observed in the central axis was maintained throughout the volume. It is not feasible to show this agreement in all 18 axial slices. Instead, we focus on the central axis coronal and sagittal planes as illustrative of the dosimetric evaluation in 3D. The coronal plane is shown in Fig. 9 where (a) is the ECLIPSE dose, (b) is the PRESAGE™ dose, and (c) represents the dose profiles of (a) and (b) along the oblique solid line in (b). Figure 9(d) is the overlay of the percent isodose lines of the PRESAGE™ dose and ECLIPSE dose. The corresponding comparison of dose distributions in the central sagittal view is given in Fig. 10. In general, the PRESAGE™ measurement is in good agreement with the calculated dose from Eclipse. Isodose lines agree to within 3 mm. A distinct noise artifact is clearly observed in both planes (highlighted by arrows) corresponding to streak artifacts in a single axial plane towards the upper end of the dosimeter in Figs. 8(a) and 9(b). This plane corresponds to the alignment plane containing the three marks inscribed on the surface of the dosimeter. These artifacts may be reduced by decreasing the severity of the inscribed indentations made by a scalpel, which caused intense light scattering. The resolution in the coronal and sagittal views of the PRESAGE™ dose was limited by the scanning slice interval which was 5 mm in this case. Acquiring optical scans with smaller slice intervals would generate better axial resolution, but would also take longer.

IV. CONCLUSIONS

The PRESAGE™ measurement of a simple known 3D distribution was compared to the calculated dose from the ECLIPSE treatment planning system, and independent measurement by the GAFCHROMIC® EBT film. The PRESAGE™ measurement was found to agree well both with the calculation and the film measurement at all points except within 8 mm of the edge of the cylinder, where edge artifacts were present. Gamma maps were utilized for more comprehensive dose comparison and the results demonstrate good agreement between the PRESAGE™ measurement, film measurement, and the treatment plan within 4% dose

difference and 4 mm distance to agreement. In penumbra regions, the PRESAGE™ and EBT measurements show better consistency with each other than with the treatment planning system. This is consistent with known penumbral blurring in the dose algorithm of the planning system, arising from the fact that the model was based on beam data acquired with an IC10 chamber of 6 mm diameter.

Three-dimensional dosimetry researchers have long been seeking a practical 3D dosimeter for clinical use to verify modern dose delivery techniques. In this work, we report a reliable, convenient and clinically viable 3D dosimetry system consisting of a solid dosimeter (PRESAGE™) and an optical-CT scanner (OCTOPUS™). The performance of the system for 3D dose measurement was investigated. Our results demonstrate that a full 3D relative dose distribution can be measured with high spatial resolution and accuracy by the system. The robustness of PRESAGE™ to the environment, the radiochromic contrast and stability, and the lack of requirement for an external container, all enhance the practicality and appeal of this system. In summary, the PRESAGE™/optical-CT dosimetry system was found to be a practical and convenient dosimeter with relevance for routine clinical use.

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Fig. 1.

Picture of the OCTOPUS™ optical-CT scanner. The laser beam from a He-Ne laser is guided by translation components to linearly scan the object mounted on a turn plate in the water tank. Tomographic scan of the object is achieved by repeatedly rotating and scanning the object.

Fig. 2. Irradiation of the PRESAGE™ dosimeter by a Varian® 21EX linear accelerator. The irradiation was performed according to a 3D treatment plan with five coplanar (6 MV photons) beams.

Fig. 3.

Calibration curve of the GAFCHROMIC® EBT film. The calibration curve was obtained from the measurements on the next day (Day 2) after irradiation and was represented by the equation $y = 4.975x^5 - 126.83x^4 + 1264.8x^3 - 6408.5x^2 + 19086x + 535.06$, where x and y represent the irradiation dose and the corresponding pixel value change from the scanning measurements pre and post the irradiation.

Fig. 4.

Imaging performance of the optical-CT scanner. (a) Reconstruction of the cross section of the thin wire (diameter 0.2 mm). (b) Profile of the reconstructed wire along the dotted line in (a). Pixel size is 0.5 mm. (c) Reconstruction of the uniform gel. (d) Profile along the dotted line in image (c). (e) Registered images of multiple wires (diameter 0.2 mm). The white dots represent the cross sections of the wires reconstructed by the x-ray CT scanner and the black dots are the reconstructions by the optical-CT scanner. (f) The detailed look of picture (e).

Fig. 5.

Optical-CT scan and reconstructions of the PRESAGE™ dosimeter. (a) A projection of the dosimeter before (dotted line) and after (solid line) it was irradiated. (b) Reconstructed axial slice of the cylindrical dosimeter before it was irradiated. (c) The corresponding reconstruction after the dosimeter was irradiated. (d) Profiles of the reconstructions (b) and (c) along the dotted line in (c). The dotted line corresponds to the profile of the reconstruction pre irradiation and the solid line corresponds to that after the irradiation.

Fig. 6. Comparison of dose distributions between PRESAGE™ measurement (a), ECLIPSE calculation (b), and EBT film measurement (c). Percent isodose lines (95, 80, 70, 60, 50, 40, 30, and 20%) were superimposed onto the dose distributions. (d) Profiles of figures (a), (b), and (c) along the solid line in figure (c).

(a) PRESAGE™ (blue) and EBT (red)

(b) PRESAGE™ (blue) and ECLIPSE (red)

(c) EBT (blue) and ECLIPSE (red)

Fig. 7.

Comparison of percent isodose lines (95, 80, 60, 50, 40, and 30%) between ECLIPSE planning system, EBT film, and PRESAGE™ dosimeter. (a) Overlay of the percent isodose lines from PRESAGE™ (blue) and EBT film (red) measurements. (b) Overlay of the percent isodose lines from PRESAGE™ measurement (blue) and ECLIPSE calculation (red). (c) Overlay of the percent isodose lines from EBT film measurement (blue) and ECLIPSE calculation (red).

Fig. 8.

Gamma comparison of dose distributions between ECLIPSE planning system, EBT film, and PRESAGE™ dosimeter. (a) Gamma map for PRESAGE™ measurement and ECLIPSE calculation. (b) Profile along the solid line in figure (a). (c) Gamma map for EBT film and PRESAGE™ measurements. (d) Profile along the solid line in figure (c). (e) Gamma map for EBT film measurement and ECLIPSE calculation. (f) Profile along the solid line in figure (e).

Fig. 9.

Comparison of the dose distributions between the ECLIPSE calculation (a) and the PRESAGE™ measurement (b) in a coronal view. Percent isodose lines (95, 90, 70, 50, 35, and 30%) were superimposed on both images (a) and (b), respectively. (c) Profiles for the calculated dose distribution (solid line) and the PRESAGE™ measurement (dotted line) along the solid (black) line in figure (b). The artifacts produced by the marks on the surface of the dosimeter are shown in both figures (b) and (c) by the arrows. (d) Overlay of the percent isodose lines from the calculation (dark solid line) and the PRESAGE™ measurement (light solid line).

Fig. 10.

Comparison of the dose distributions between the ECLIPSE calculation (a) and the PRESAGE™ measurement (b) in a sagittal view. The artifact produced by the marks on the surface of the dosimeter is shown by the arrow. Percent isodose lines (95, 90, 70, 50, 35, and 30%) were superimposed on both images (a) and (b), respectively. (c) Profiles for the calculated dose distribution (solid line) and the PRESAGE™ measurement (dotted line) along the solid (black) line in figure (b). (d) Overlay of the percent isodose lines from the calculation (dark solid line) and the PRESAGE™ measurement (light solid line).