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Investigation into the feasibility of using PRESAGE™/optical-CT dosimetry for the verification of gating treatments

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Abstract

This work presents an investigation into the use of PRESAGE™ dosimeters with an optical-CT scanner as a 3D dosimetry system for quantitative verification of respiratory-gated treatments. The CIRS dynamic thorax phantom was modified to incorporate a moving PRESAGE™ dosimeter-simulating respiration motion in the lungs. A simple AP/PA lung treatment plan was delivered three times to the phantom containing a different but geometrically identical PRESAGE™ insert each time. Each delivery represented a treatment scenario: static, motion (free-breathing) and gated. The dose distributions, in the three dosimeters, were digitized by the optical-CT scanner. Improved optical-CT readout yielded an increased signal-to-noise ratio by a factor of 3 and decreased reconstruction artifacts compared with prior work. Independent measurements of dose distributions were obtained in the central plane using EBT film. Dose distributions were normalized to a point corresponding to the 100% isodose region prior to the measurement of dose profiles and gamma maps. These measurements were used to quantify the agreement between measured and ECLIPSE® dose distributions. Average gamma pass rates between PRESAGE™ and EBT were >99% (criteria 3% dose difference and 1.2 mm distance-to-agreement) for all three treatments. Gamma pass rates between PRESAGE™ and ECLIPSE® 3D dose distributions showed excellent agreement for the gated treatment (100% pass rate), but poor for the motion scenario (85% pass rate). This work demonstrates the feasibility of using PRESAGE™/optical-CT 3D dosimetry to verify gating-enabled radiation treatments. The capability of the Varian gating system to compensate for motion in this treatment scenario was demonstrated.

1. Introduction

The necessity for quality assurance (QA) in gated radiation therapy treatments has been established (Niroomand-Rad *et al* 1998, Jiang *et al* 2007). However, the development of QA methods has not kept pace with the innovations in gating techniques. American Association of Physicists in Medicine (AAPM) Task Group 76 outlined the necessity for a respiratory gating QA device to adequately simulate cyclical motion that is similar to human respiration and provide an adequate number of detectors for dose analysis. A variety of dynamic, high-resolution QA devices have surfaced over the years (Nelms *et al* 2007, Nakayama *et al* 2008, Nioutsikou *et al* 2006, Berbeco *et al* 2005, Keall *et al* 2006b, Saw *et al* 2007). However, each technology is inherently two-dimensional (2D) and can only offer QA analysis in one plane of a three-dimensional (3D) dose distribution. 3D QA analysis of a dose distribution is highly desirable since a 2D plane does not represent points throughout the entire dose distribution in the presence of nonlinear respiratory motion. Gel dosimetry

has been shown to be a viable option for 3D gated therapy dosimetry QA (Ceberg *et al* 2008, Mansson *et al* 2006, Ravindran *et al* 2009). Gel dosimeters however have been reported to have undesirable characteristics: PAG dosimeters are susceptible to atmospheric oxygen (O₂) that inhibits the polymerization reaction, and MAGIC dosimeters are formulated with toxic chemicals (Baldock 2009). As an alternative to gel dosimetry, PRESAGETM dosimeters were investigated. Key advantages of PRESAGETM dosimeters include (1) very low scatter due to absorption medium, (2) robustness to laboratory environment (i.e. no O₂ sensitivity) and (3) no need for external container which provides better dosimeter edge resolution through improved refractive index (RI) matching (Guo *et al* 2006b). In this work we investigate the feasibility of PRESAGETM, a 3D plastic dosimeter, with much improved characteristics as a viable option for respiratory-gated 3D QA verification.

The PRESAGETM/optical-CT dosimetry system has previously been developed and tested for several applications of treatment verification, namely 3D conformal (Guo *et al* 2006a) and IMRT (Oldham *et al* 2006, 2008, Sakhalkar *et al* 2009b); this work represents the first attempt toward validating the use of PRESAGETM dosimetry for the verification of a gated treatment. The PRESAGETM/optical-CT dosimetry system consists of a radiochromic plastic dosimeter (PRESAGETM) and a novel fast, high-resolution, optical-computed tomography (optical-CT) scanner for dose readout. PRESAGETM is a 3D leuco-dye doped dosimeter that is clear until irradiated, and once irradiated it changes color proportionately to absorbed dose (Adamovics *et al* 2005, Adamovics and Maryanski 2003, 2004, 2006). In a recent report (Sakhalkar *et al* 2009a), PRESAGETM was shown to be extremely robust with an intra-dosimeter radiochromic response variability of 2%, temporal stability for ~90 h post-irradiation and a reproducibility response of 2% was measured at all investigated dose levels. The optical-CT scanner is a dose readout system that utilizes parallel light and telecentric lens geometry for image readout as previously investigated (Sakhalkar and Oldham 2008). The scanner is capable of acquiring a complete 3D dataset in ~5 min. The scanner is based on telecentric optics to ensure accurate projection imaging that minimizes artifacts from scattered and stray-light sources as first demonstrated by Doran *et al* (2001), Krstajic and Doran (2006) and (2007) and allows isotropic high-resolution 3D dose readout.

This work presents results from the ongoing improvement of the fast, high-resolution optical-CT scanner and the results of three treatment scenarios: static, motion (free breathing) and gated were measured and compared to their respective calculated ECLIPSE[®] treatment plans. The PRESAGETM measurements were benchmarked against radiochromic EBT film. EBT film was considered the gold standard in light of prior studies demonstrating its accuracy (Devic *et al* 2005, Lynch *et al* 2006, Paelinck *et al* 2007, Guo *et al* 2006a).

2. Materials and methods

2.1. PRESAGETM 3D dosimeter and dynamic thorax phantom

PRESAGETM dosimeters (Heuris Pharma LLC, Skillman, NJ) have been previously characterized for 3D dosimetry (Guo *et al* 2006b, Sakhalkar *et al* 2009a). Specific to this study, the PRESAGETM formulation had the following properties: Z_{eff} of 8.3, density of 1.07 g cm⁻³ and a CT number of ~170. Three identical homogenous cylindrical PRESAGETM dosimeters (5 cm diameter × 5 cm length) were designed to fit into the dynamic thorax phantom (CIRS Inc., Norfolk, VA). The PRESAGETM dosimeters were maintained at a temperature of ~4 °C before and after irradiation. The dosimeter was allowed to reacclimatize to room temperature, ~22 °C, before irradiation and optical-CT readout. Approximately 12 h was allowed for the post-irradiation polymerization reaction to stabilize before optical-CT readout.

The dynamic thorax phantom (referred to as the phantom) is a phantom that represents a heterogeneous human thorax in proportion and composition. The phantom consists of a tissue equivalent lung, cortical and trabecular bone and water material, figures 1(A), (B). The phantom simulates motion by oscillating a rod made of lung-equivalent material. The rod was designed to hold 3D dosimeters with a diameter of ~5 cm. The rod was modified to accept a locking mechanism that was manufactured on the base of the PRESAGE™ dosimeter, figure 1(C). The locking mechanism allowed for consistent realignment of the dosimeters within the lung rod insert. All motion studies presented in this work utilized a customized sinusoidal motion profile with 4.5 s cycle time and 15 mm superior to inferior motion that was created to simulate a simple, idealized patient respiration pattern with maximum target displacement in the coronal plane (Dietrich *et al* 2005, Shirato *et al* 2000, Keall *et al* 2006a).

2.2. Optical-CT scanning of the PRESAGE™ dosimeter

2.2.1. Optical-CT scanner readout—PRESAGE™ dose readout was performed using an in-house fast, high-resolution optical-CT scanner that used a charge coupled device (CCD) area detector for signal digitization (Sakhalkar and Oldham 2008), figure 2. In summary, the PRESAGE™ dosimeter is placed on a rotating stage inside an anti-reflection-coated glass aquarium. The aquarium is filled with a RI-matched fluid comprising a mixture of octyl salicylate, methoxy octyl cinnamate and a small amount (3–4 drops) of green oil-based dye. The dye was used to equalize the light attenuation between the dosimeter and the fluid. This optimized the dynamic range of the scanning system. Incident illumination was provided by a 633 nm LED array (Leutron Vision Inc., Burlington, MA). The light source was matched to the peak sensitivity of the PRESAGE™ dosimeters (Guo *et al* 2006a, 2006b). Projection images were acquired by an A-102f 12 bit monochrome CCD camera (Basler Vision Technologies, Ahrensburg, Germany) that digitized at a resolution of 1392×1040 pixel. The camera was coupled to a TECHSPEC 55–349 telecentric lens system (Edmund Optics Inc., Barrington, NJ). A LABVIEW (National Instruments Corp., Austin, TX) script controlled a step-and-image acquisition scheme in which the stage made an incremental rotation after an image from the camera was written to disk. The optical-CT maximum field of view was $\sim 7 \times 7 \text{ cm}^2$, which was limited by the physical size of the telecentric lens. Commercial telecentric lenses were available with a field of view up to 30 cm, though at a significantly increased price. Commercially available tomographic reconstruction software (COBRA, Exxim Corp., Pleasanton, CA), which used a filtered back projection reconstruction algorithm, was used for reconstructing the images readout by the optical-CT scanner. The projection images loaded into the COBRA software were down sampled from 1392×1040 pixel to 160×96 pixel using a bilinear interpolation with a 2×2 pixel kernel to achieve an isotropic spatial resolution of 0.4 mm.

2.2.2. Improved optical-CT scanning technique—Sakhalkar *et al* (2008) demonstrated accurate 3D dosimetry in a novel bench top scanner incorporating telecentric optics. Three limiting artifacts were observed in the reconstructed optical-CT images: concentric rings, high noise-to-signal and significant edge artifact. These three artifacts were minimized in the present work through the following improved scanning technique.

The concentric ring artifact was attributed to relatively stationary structures in all projection images due to particulates in the fluid and defects (e.g. scratches) on the aquarium wall. A $30 \mu\text{m}$ stainless steel wire mesh filter was used to improve the removal of fluid particulates. Increased fluid filtration was necessary to further remove microscopic debris from the fluid to improve the image signal-to-noise ratio (SNR). To correct for aquarium wall defects, a series of 50 flood field images were taken. A flood field image consisted of a full aquarium or RI fluid without a dosimeter in place. One image was generated from a mean of the 50

flood field images and was subtracted from each projection image before 3D image reconstruction.

RI-matching fluid filtration and flood and dark field subtraction improved the SNR by decreasing the high noise-to-signal ratio in the reconstructed images. Dark field images were generated and subtracted from the individual projection images prior to 3D image reconstruction. A dark field image measured the underlying signal generated by thermally induced electrons and captured in the non-cooled CCD camera's photosites. The acquisition of the 3D data set with a non-cooled CCD camera was limited in its dynamic range with increased acquisition time due to the thermal noise. To account for the thermal noise contribution of each projection image, the lens cap was placed over the lens and an identical number of dark fields were captured matching the number and time for the projection images. However, one mean image of only 100 consecutively acquired images (acquired in ~1 min) was determined to be sufficient to account for the overall thermal noise contribution to a whole PRESAGETM scan acquired in ~5–10 min.

The edge enhancement artifact was attributed to imperfect RI matching between the fluid and dosimeter and refracted light rays emerging from the dosimeter boundaries as accepted parallel light rays into the telecentric lens system. The RI of the fluid bath was adjusted adding a small amount of methoxy octyl cinnamate (RI value 1.542) to the octyl salicylate (RI value of 1.502) to match the RI of the PRESAGETM dosimeter (RI value 1.503). Even with the fluid bath and dosimeter RI values matched, the edges of the dosimeter were visible due to non-parallel light, incident on the dosimeter boundaries, refracted such that the angle of refraction of the incident light was within the acceptance angle of the telecentric lens system and thus accepted for image formation. Telecentric lens systems are manufactured to allow only parallel light to be used for image formation. The acceptance angle, or tolerance of the telecentric lens system for non-parallel light, was considered double the angle for parallel light which was accepted for image formation (Krstajic and Doran 2006). The acceptance angle for the telecentric lens system used in this investigation was $<0.1^\circ$ (as quoted by the manufacturer). It is possible that non-parallel light from the diffuse LED source could scatter into the parallel plane, and thus contribute to the image; this component is small due to the high transparency of PRESAGETM, but any component was further reduced by placing the LED source at the end of the bench (~150 cm from the PRESAGETM dosimeter). A smaller scanner could be achieved by replacing the LED source with a telecentric light source.

2.3. Treatment planning

Three treatment scenarios were planned and delivered: (1) static delivery where the PRESAGETM dosimeter was stationary during treatment, (2) motion delivery 'free breathing' where the PRESAGETM dosimeter was in motion during treatment and (3) gated delivery where the PRESAGETM dosimeter was irradiated while in motion, but gated to treat at a specific phase in the breathing cycle. For each of the three treatment scenarios, small field parallel-opposed anterior-posterior (AP/PA) beams were planned using the ECLIPSE[®] treatment planning system (Varian Med. Systems, Palo Alto, CA). AP/PA beams allowed for a realistic lung treatment setup that maximized the accuracy for independent verification of EBT film by rendering film placement insensitive to positional differences in the AP direction, figure 3(A). Small field sizes (~2 cm) were planned to capture the full extent of the delivered dose distribution in the PRESAGETM dosimeter over the full range of dosimeter displacement due to the phantom motion. Field sizes were on the order of sizes used for lung stereotactic radiosurgery (SRS).

2.3.1. CT scanning procedures—The phantom, including a PRESAGETM dosimeter *in situ*, was CT scanned using a multislice CT scanner (Lightspeed, GE Healthcare, Waukesha, WI). The CT scan protocol for the static scenario consisted of a helical four-slice mode with 5 mm collimation at 1.25 mm resolution per slice. The CT scan for the gated scenario (4DCT scan) consisted of an over-sampled CT acquisition at each slice (Rietzel *et al* 2005). This involved continuously scanning each slice in axial ciné four-slice mode for 5.0 s to scan during one full breathing cycle (4.5 s). The slice collimation and resolution used were similar to the static scan protocol. Varian's Real-time Position Management software (RPM) recorded a breathing profile concurrent with the 4DCT scan. The RPM tracked the motion of the phantom using an infrared (IR) camera and an external IR reflective marker mounted on top of the phantom. Advantage 4D software (GE Healthcare, Waukesha, WI) binned the acquired images retrospectively according to spatiotemporally recorded time signatures and table positions. Reconstructed images were assigned to one of ten specific respiratory phase bins, with a $\pm 5\%$ spatiotemporal tolerance for sorting. Each sorted bin was reconstructed into a 3D data set representing spatiotemporally similar images.

2.3.2. Treatment and delivery—Two identical treatment plans were created using ECLIPSE[®] figure 3. The calculation algorithm used in ECLIPSE[®] was AAA 8223 which consisted of a calculation matrix of 1.25 mm. The first plan was developed using the static CT scan and was used to deliver the static and motion treatment scenarios. The second plan was developed using the 4DCT scan where phases nine, zero and one (9-0-1) of the ten respiratory phases were selected and used as the 'gate' for dose calculation and beam delivery of the gated treatment scenario. Phases 9-0-1 represent the point of maximum exhalation. For the delivery of the gated plan, the RPM software was used to track the motion of the externally mounted marker. This respiratory trace was matched with the trace acquired during the 4DCT scan and enabled 'beam on' for the LINAC when the phantom entered into phase nine of the 9-0-1 phases of the respiratory cycle.

2.4. Independent EBT film measurement

Independent verification of the dose distribution was achieved using EBT film (International Specialty Products, Wayne, NJ). EBT film was chosen for its practical convenience as a self-developing radiochromic film, energy and directional independence, and temporal stability (Guo *et al* 2006a). A PRESAGETM dosimeter was cut at its central, long axis, which represented the coronal plane, and a piece of EBT film was placed between the two PRESAGETM halves, figure 4(A). The PRESAGETM dosimeter, with EBT film *in situ*, was placed in the phantom, and the treatment plans for the three scenarios were delivered to the EBT film inserts, figures 4(C)–(E). A calibration curve was prepared at the time of experimental irradiation (Guo *et al* 2006a), figure 4(B). The films were digitized using a 48-bit transmission/reflection flatbed photo-scanner (Perfection 4990 Photo, Epson, Japan). Each film was scanned in transmission mode at a resolution of 72 pixels in⁻¹ (0.4 mm pixel) with no color corrections and saved as RGB uncompressed Tagged Image File Format. Corrections were made for scanner light non-uniformities (Devic *et al* 2004, 2005, Lynch *et al* 2006, Paelinck *et al* 2007). The EPSON scanner employed a Xenon gas cold cathode fluorescent lamp (as quoted by the manufacture) with spectral emission range between 400 and 750 nm. EBT films were analyzed using the red channel (of the RGB channels) due to the film's maximum absorption that occurred at 635 nm (Devic *et al* 2007). The traditional red channel of the RGB format was focused on the 580–700 nm light wavelength range with an approximate center wavelength of 640 nm. EBT film response was converted to dose using the fitting function of the film's calibration data. The EBT film dose responses were then normalized for inter dosimeter comparison.

2.5. Data analysis

Three types of data were available for analysis: (1) 3D static, motion and gated PRESAGETM dose distributions; (2) calculated 3D static and gated ECLIPSE[®] dose distributions and (3) 2D static, motion and gated EBT film central coronal plane dose distributions. The calculated static distribution from ECLIPSE[®] was compared to measured static and motion distributions from PRESAGETM and EBT. The calculated gated distribution from ECLIPSE[®] was compared to the measured gated distributions from PRESAGETM and EBT. Once all three data sets were spatially registered, an identical normalization point was chosen, see figure 3(B) for inter-dosimeter comparison. Film post-processing, dosimeter registration and data analysis were performed using CERR (Washington University, St Louis, MO), a Matlab-based software. Though, Babic *et al* (2008) demonstrated a successful implementation of a 3D gamma analysis, at the time of this investigation, the CERR software did not have a true 3D gamma calculation, so all quantitative analysis between datasets were restricted to a slice-by-slice analysis using line profiles and 2D gamma maps (Low and Dempsey 2003, Low *et al* 1998). The eventual use of 3D absolute dose analysis is currently being developed and will be the topic of future work. The analysis criteria for the gamma map were set at 3% dose difference and 1.2 mm distance-to-agreement (3%–1.2 mm). For the gamma maps, the dose difference acceptance criterion represents a more stringent criterion than currently used for the RTOG head and neck IMRT protocols (7%–4 mm) (Ibbott *et al* 2006). The distance-to-agreement acceptance criterion of 1.2 mm was used to match the dose resolution of the calculated ECLIPSE[®] dose distribution and to more accurately reflect the differences in dose distribution over small distances as represented in this work. Comparisons with EBT film (gold standard) were used to establish PRESAGETM feasibility where 3D comparisons with PRESAGETM and ECLIPSE[®] were used as a preliminary means to measure gating treatment efficacy.

3. Results

3.1. Improvements in the optical-CT scanning technique

A line profile through a reconstructed PRESAGETM dosimeter, figure 5(A), with and without the improved scanning technique is plotted in figure 5(B). The line profile without the improved scanning technique measured 12% variability in the normalized signal, while the line profile with the improved scanning technique measured 4% variability. The improved scanning technique measured a factor of 3 increase in the SNR. The edge artifact decreased from 5 mm to ~2 mm through the improved scanning technique and setup geometry, figure 2.

3.2. Dose distributions in the static, motion and gated treatment scenarios

PRESAGETM, EBT film and ECLIPSE[®] dose distributions are plotted as isodose contour mappings for the three treatment scenarios in figure 6 with corresponding gamma map comparisons shown in figure 7 and line profiles in figure 8. Line profiles were taken along the representative dashed lines in figure 6(I). An inter-dosimeter comparison between PRESAGETM and EBT film distributions was compared for the static, motion and gated treatment scenarios. Pass rates (3%–1.2 mm) of 99.6%, 99.9% and 99.4% were calculated for the static, motion and gated treatments, respectively, as are shown in figures 7(A)–(C).

Close examination of the dose distributions for the static and gated treatment scenarios reveal good agreement between PRESAGETM, EBT film and ECLIPSE[®] as is evident by their similarly shaped and positioned isodose contour maps in figures 6((A)–(C) and (G)–(I)) and closely aligned line profiles in figures 8((A)–(C) and (G)–(I)). Whereas the motion dose distributions, figures 6(D), (E), exhibited broadening of the penumbral regions in both the superior to inferior, figure 8(E), and left–right, figure 8(D), directions as anticipated due

to the phantom motion not modeled in the ECLIPSE[®] calculations, figure 6(F). The measured dose distributions were compared versus the calculated ECLIPSE[®] distributions using the gamma map criteria. The pass rates for the ECLIPSE[®] and PRESAGE[™] distributions were compared for the static, motion and gated treatment scenarios: 84.7%, 84.5% and 100.0%, respectively, and the ECLIPSE[®] and EBT pass rates are 85.5%, 79.8% and 86.0%, respectively.

4. Discussion

An interesting point to note is that the pass rate is higher in the gated scenario than in the static scenario (compare figures 7(D) and (F)). This is attributed to the fact that the ECLIPSE[®] dose distribution incorporates effectively a convolution ‘blurring component’ due to the finite measurement volume of the ion chamber used to acquire the commissioning data. This slight blurring of the dose distribution is not observed in the static measurement of PRESAGE[™], but a similar magnitude of blur is observed in the gated PRESAGE[™] measurement, due to dosimeter motion during the finite time width of the gating window.

Both the PRESAGE[™] and EBT film distributions measured an ~2 mm per side elongation in the left–right directions, as shown in figure 8(A), (G), which is not consistent with the calculated ECLIPSE[®] distributions. The elongation is only measured in the direction parallel to the MLC leaves. However, the superior and inferior ends of the distribution, which are aligned perpendicular to the edges of the MLC leaves, do not measure the same dose elongation (figure 8(B), (H)). The left–right elongation of the dose distributions may be attributed to the x-ray beam passing through the end of a rounded Varian MLC leaf which has been shown to increase penumbral blurring by ~2 mm compared to x-rays exposed to the edge of the same MLC leaf (Butson *et al* 2003).

One possible limitation of this work was the necessity to normalize the dose distributions for comparison. Normalization forces agreement at one dose level and may limit the value of subsequent analyses by masking possible dose differences where large discrepancies in dose magnitude exist. Therefore, the analysis of data sets using absolute dose distributions is generally preferable when available. In the case of PRESAGE[™], calibration to a given dose may be achieved from irradiation of small volumes of PRESAGE[™] from the same batch. This method of establishing a calibration function using small volumes to calibrate a large 3D volume has been shown to introduce errors when comparing dose distributions (MacDougall *et al* 2008). The extent of this volume effect for PRESAGE[™] calibration has not yet been established in sufficient detail to know exactly how accurate the calibration is; a detailed study of the volume effect is part of an ongoing study. The uncertainty of the volume effect on the accuracy of the PRESAGE[™] dosimeter analysis required the use of normalization as a means to compare PRESAGE[™] with ECLIPSE[®] and EBT film dose distributions. However, the precise linearity of the PRESAGE[™] dose response has been extensively confirmed (Guo *et al* 2006b, Sakhalkar *et al* 2009a). In the present paper, the given dose at the normalization point in the PRESAGE[™] dosimeter was within the calibration uncertainty of the planned dose as determined from the film measurements, shown in figure 9. We therefore conclude that the use of PRESAGE[™] as a relative dosimeter, by normalizing to a point corresponding to the 100% isodose region of the planned dose distribution in the coronal plane and exploiting the strength of the linearity of PRESAGE[™] response, will not introduce any limitation on the data analysis and will circumvent the demonstrated volume effect error.

This work presents the first application of PRESAGE[™]/optical-CT 3D dosimetry system to the verification of a simple gating treatment and lays the foundation for more advanced gating work. We envision a role for PRESAGE[™] (and any of the other 3D dosimetry

approaches) as a final whole-system verification test during the commissioning stage. There may also be a future role in repeat or periodic QA of various techniques, i.e. respiratory gating, IMRT, RapidArc™, etc, but probably not on a per patient basis unless the costs and convenience of optical-CT readout improve.

5. Conclusion

Comparison between PRESAGE™ and EBT film showed excellent agreement for the three treatment scenarios. The average pass rate was >99% with respect to gamma map criteria of 3%–1.2 mm. Although the gated treatment plan was simple, this result establishes the feasibility of the PRESAGE™/optical-CT dosimetry system for verifying gating treatments and lays the groundwork for future work to investigate more complex gated treatments. Significant differences were observed between the static planned dose distribution and the measured dose distribution in the presence of breathing motion. Varian's gating system was shown to correctly reduce this motion error through the implementation of a standard gating technique. Improvements in the optical-CT scanner design and acquisition techniques led to reduced edge artifacts and a factor of 3 increase in the SNR while maintaining scanner readout times on the order of ~5–10 min.

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Figure 1.

(A) A CIRS dynamic thorax phantom is shown with a lung tissue-equivalent rod. The cylindrical three-dimensional PRESAGETM dosimeter is placed within the rod and oscillated to simulate respiration motion in the lung. (B) A central CT slice of the phantom shows prominent anatomy with the PRESAGETM dosimeter in the lung. The PRESAGETM dosimeter was manufactured with a docking mechanism (C) to allow for accurate repositioning within the lung rod.

Figure 2.

A simplified schematic depicting light rays through the CCD-based optical-CT scanner. Projection images through the PRESAGETM dosimeter are focused onto the CCD camera chip using a tertiary telecentric lens system (acceptance angle $<0.1^\circ$). A two-dimensional projection image was acquired at each rotation step.

Figure 3.

A central slice axial view of the dynamic thorax phantom with PRESAGETM *in situ* (A) is shown with the AP/PA beam configuration. EBT film was placed along the central axis of the PRESAGETM dosimeter (dashed line in (A)) in the coronal plane (B). The approximate normalization point is shown in (B). Small radiosurgery type field sizes (~2 cm) were used to capture the full extent of the delivered dose distribution in the PRESAGETM dosimeters while the phantom was in motion.

Figure 4. Independent measurement of dose was made with EBT film inside a PRESAGETM dosimeter (A) in the coronal plane. The EBT film calibration curve (B) showed a goodness of fit (R^2) of 0.9984. Distributions of the calibrated EBT film for the three treatment scenarios are shown: static (C), motion (D) and gated (E).

Figure 5.

Reconstructed axial optical density map from the PRESAGE[™] dosimeter showing the AP/PA beam configuration (A). Line profile (B) shows the improved optical-CT dose readout technique ('new technique') with noise reduction compared to the 'old technique'.

Figure 6.

Isodose lines in the central coronal plane (shown in figure 3(A)) demonstrate the maximum motion effect. Note that the ECLIPSE[®] distributions are unchanged since the distributions were calculated from static CT images for (C and F) and from one of the ten scanned respiratory image sets (I).

Figure 7.

Gamma maps (3%–1.2 mm) in the central coronal plane shown in figure 3(A) indicating pass rates. Values of gamma >1 indicate failure of one or both of the gamma criteria. Excellent agreement was observed between PRESAGETM and EBT film (A–C) for all three treatment scenarios that establishes the feasibility of the PRESAGETM/optical-CT dosimetry system. Good agreement between measured gated distribution and ECLIPSE[®] demonstrates the effectiveness of Varian’s gating system at delivering accurate dose distributions by reducing the motion-induced errors (E and H).

Figure 8.

Line profiles of the ECLIPSE[®], PRESAGE[™] and EBT dose distributions, along the dashed line shown in figure 6(I), are shown for all three treatment scenarios. A left-right elongation of the dose distribution, measured by both PRESAGE[™] and EBT film, is visible in the dose profiles (A, D, G). A possible explanation of the elongation effect is increased penumbral blurring when the radiation beam passes through the rounded ends of the Varian's MLC leaves, as reported in Butson *et al* (2003).

Figure 9.

Absolute dose comparisons are presented between ECLIPSE[®] (A) and the calibrated EBT film for the three treatment scenarios (figures 4(C)–(E)). Superior–inferior (B) and lateral (C) line profiles, taken along the dashed lines shown in (A), compare overall ECLIPSE[®] and film absolute dose agreement. Generally, the calibrated film and calculated ECLIPSE[®] dose line profiles demonstrate a similar magnitude of dose and profile shape (except for the film’s motion scenario). Eclipse and film dose difference mappings show, for the three treatment scenarios—static (D), motion (E) and gated (F), good agreement in dose delivery for the central, shallow dose gradient region, but poor agreement for the peripheral, steep dose gradients. The static and gated film dose difference map, shown in (G), demonstrates the ability of the gating technique to minimize motion-induced dose blurring in surrounding regions of the planned target volume. Superior–inferior (H) and lateral (I) line profiles taken from the static and gated film treatment scenario dose distributions (figures 4(C) and (E)) also show the high agreement of the gated treatment with the static scenario.