A comprehensive investigation of the accuracy and reproducibility of a multitarget single isocenter VMAT radiosurgery technique

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Purpose: Recent trends in stereotactic radiosurgery use multifocal volumetric modulated arc therapy (VMAT) plans to simultaneously treat several distinct targets. Conventional verification often involves low resolution measurements in a single plane, a cylinder, or intersecting planes of diodes or ion chambers. This work presents an investigation into the consistency and reproducibility of this new treatment technique using a comprehensive commissioned high-resolution 3D dosimetry system (PRESAGE[®]/Optical-CT).

Methods: A complex VMAT plan consisting of a single isocenter but five separate targets was created in Eclipse for a head phantom containing a cylindrical PRESAGE[®] dosimetry insert of 11 cm diameter and height. The plan contained five VMAT arcs delivering target doses from 12 to 20 Gy. The treatment was delivered to four dosimeters positioned in the head phantom and repeated four times, yielding four separate 3D dosimetry verifications. Each delivery was completely independent and was given after image guided radiation therapy (IGRT) positioning using Brainlab ExacTrac and cone beam computed tomography. A final delivery was given to a modified insert containing a pin-point ion chamber enabling calibration of PRESAGE[®] 3D data to dose. Dosimetric data were read out in an optical-CT scanner. Consistency and reproducibility of the treatment technique (including IGRT setup) was investigated by comparing the dose distributions in the four inserts, and with the predicted treatment planning system distribution.

Results: Dose distributions from the four dosimeters were registered and analyzed to determine the mean and standard deviation at all points throughout the dosimeters. A dose standard deviation of <3% was found from dosimeter to dosimeter. Global 3D gamma maps show that the predicted and measured dose matched well [3D gamma passing rate was 98.0% (3%, 2 mm)].

Conclusions: The deliveries of the irradiation were found to be consistent and matched the treatment plan, demonstrating high accuracy and reproducibility of both the treatment machine and the IGRT procedure. The complexity of the treatment (multiple arcs) and dosimetry (multiple strong gradients) pose a substantial challenge for comprehensive verification. 3D dosimetry can be uniquely effective in this scenario. © 2013 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4829518>]

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1. INTRODUCTION

3D dosimetry systems^{1–3} may play an important role in enhancing patient safety as radiation treatment systems and techniques become more sophisticated and complex.⁴ Case in point is the multifocal stereotactic radiosurgery (SRS) treatment. Several targets using a single isocenter present a quality assurance (QA) challenge for traditional 2D QA technologies. Prior work has shown that the radiochromic 3D dosimetry material PRESAGE[®] (Refs. 5 and 6) in combination with the Duke Large field of view Optical-CT Scanner (DL0S) is capable of providing high quality 3D data.⁷ This commissioned system measures data in 3D, differentiating itself from commercial 3D QA technologies which are not truly a 3D measurement, but rather an interpolation of a cylinder or separate planes of detectors.^{8,9} To date, there have been few truly comprehensive 3D investigations of the accuracy of complex treatment delivery. One recent work (Oldham *et al.*¹⁰) showed

excellent agreement for base-of-skull intensity modulated radiation therapy (IMRT) deliveries. However, that work was limited to small single target volumes. In the present study, we apply a similar approach, but investigate the accuracy of a substantially more complex treatment technique. Five target volumes are irradiated to a high dose in a single fraction using five RapidArc beams sharing a single isocenter. Localization is critical for these irradiations because the small margins added to targets on SRS cases combined with large distances from target to target mean that small angular errors in setup could lead to rather large misses. In addition, we investigate the reproducibility of the cone beam computed tomography image guided radiation therapy (CBCT IGRT) repositioning of Brainlabs U frame immobilization device, a rigid frame that secures a thermoplastic mask. The aims of the study were to investigate the end-to-end accuracy and reproducibility of the five lesion volumetric modulated arc therapy (VMAT) SRS treatment with IGRT setup.

FIG. 1. (a) An anthropomorphic head phantom with a slot for a PRESAGE[®] dosimeter. (b) The Presage dosimeter, 11 cm diameter and height, with mounting plate glued onto the undersurface, which enables precise and repeatable positioning within the optical-CT scanner, (c) dosimeter is placed in the phantom within the Brainlab U frame mask, and aligned to the lasers with the TaPo (Target Positioners) before treatment using IGRT positioning and delivery.

2. METHODS

2.A. Simulation

A cylindrical PRESAGE[®] dosimeter (11 cm diameter, 10 cm height) was placed within the polyurethane head seen in Fig. 1(a). The PRESAGE[®] formulation used in this study had a composition of 1.00% o-MeO-DMA Leuco Malachite Green and 0.75% initiator, a reduced sensitivity formula. This is the same as some of our previous studies, but different from others. All dosimeters used in the study were identical in size and composition and created from the same batch. The phantom was then brought through the treatment chain similarly to a patient. A thermoplastic mask and U-frame were used for immobilization as seen in Fig. 1(b). The CT was performed on a GE Lightspeed X-ray CT scanner with a high-resolution protocol (1 mm slice thickness) covering the entire phantom.

CT images were imported to iPlan (Brainlab, Feldkirchen, Germany) for contouring and isocenter placement. Five targets were contoured to fit within the cylindrical PRESAGE[®] dosimeter. The targets ranged in size from 5 to 24 cm³. The five targets were arranged with one central and four on the periphery. The periphery targets were placed superior and inferior as well as left-right and anterior-posterior of the central target. The two superior targets were placed left-right and the two inferior targets were placed anterior-posterior. Figure 2(b) has an illustration of the target placement for reader clarity. Doses of the targets were as follows: Central target (15 Gy), superior left target (25 Gy), superior right target (18 Gy), inferior anterior target (25 Gy), and inferior posterior (25 Gy). After the targets were placed, the CT and target volume data were brought to Eclipse (Varian Medical Systems, Palo Alto, CA) for arc placement and RapidArc optimization. The collimator angle was set to 20° for each of the five arcs to prevent systematic accumulation of interleaf leakage along the planes parallel to gantry rotation from leakage at the leaf interfaces. Figure 2 shows the arcs used to create the treatment plan for the phantom.

2.B. Irradiation

The plan was delivered on a Novalis Tx commissioned in 2008 for radiosurgery at Duke University. The phantom was

FIG. 2. (a) Schematic from the planning system showing the head-Phantom in U-frame immobilization and the five Rapid-Arc treatments. (b) Transparent view showing the location of five lesions. The common isocenter is located in the central lesion.

setup to be irradiated as a patient would have been. Brainlabs TaPo (Target Positioners) was used for the initial mechanical laser alignment. This was followed by orthogonal kV images utilizing ExacTrac for 6° couch shifts and a CBCT for positional verification. This process does add imaging dose to the dosimeter; however, the imaging dose is less than 1% of the MV dose and thus deemed insignificant in regards to the goals of the experiment.

It should also be noted that the irradiation of each of the four dosimeters occurred on separate days. Thus, the setup of each dosimeter was completely independent of the others and all had unique Exactrac and CBCT scans for positional verification testing the reproducibility of the treatment technique as a whole.

2.C. Dose reconstruction

2.C.1. Optical-CT

The irradiated dosimeters were scanned in the DLOS under its standard imaging protocol.⁷ This system is a telecentric lens based light source (red 3W LED, diffuser, and 632 ± 5 nm filter) and imaging lens with a CCD (Basler, Germany A102f 1024 × 1428). The imaging lens rejects any light with more than a 0.1° deviation from the optical axis, thereby minimizing scattering artifacts from the dosimeter. The dosimeter is immersed in a refractive indexed matched fluid bath to minimize edge artifacts common to optical-CT. The dosimeter was rotated about a central axis over 360° with 360 projection images. Each projection image was the end result of a 25 image acquisition mean after flood field and dark noise corrections (each a 200 image mean). This was done both pre- and postirradiation to eliminate any artificial signal inherent to the scanning system.

Dose reconstruction was performed using a Matlab (Mathworks, Natick, MA) based iradon function with a Ram-Lak filter. Prior to sinogram creation, each pre- and postirradiation flood/dark corrected image was run through a 5 × 5 median filter and then resized to 1 mm pixels from its raw ~175 μm pixel size. The end result was a 3D image with reconstruction

values proportional to dose^{7,11,12} over the range of the doses delivered in this experiment, $\Delta OD \text{ mm}^{-1}$.

2.C.2. Absolute dose conversion

PRESAGE has been thoroughly researched to have a linear response to dose^{5-7,11-13} which results have been verified for all variations in the formula with regard to changes in leucodyes, polyurethanes, and initiators. This linear relationship allows for the creation of the 3D relative dose map. In order to convert the map to absolute dose, the dose needs to be known at one point and the remaining voxels scaled accordingly without a calibration curve. Following the irradiation of each dosimeter, a second delivery occurred on a nearly identical phantom. This phantom had the same shape and composition, however, there was a central bore allowing for the placement of a SRS ion chamber (CC01, Wellhoffer) with a collection volume of 0.01 cm^3 . This was done with the intention of knowing the absolute dose delivered to one point in space in the dose distribution. Knowing the dose to this one point allowed for the scaling of the entire 3D dose map from values proportional to dose to an absolute dose. The charge measurement for each arc was recorded, summed, converted to dose, and compared to the TPSs planned dose at the effective point of measurement to verify proper setup and delivery of the plan. The measured dose had less than 0.5% deviation from the expected dose at the point of measurement in each of the three irradiations.

Conversion of the 3D dose cube from Sec. 2.C.1 was done by normalizing the data set such that the voxel corresponding to the effective point of measurement within the phantom to the value measured by the ion chamber were equal.

2.D. Analysis techniques

The irradiated dosimeters were compared to each other and to the commissioned Eclipse TPS calculation.¹¹ The Eclipse calculation grid was set to create 2.5 mm voxels. Reconstructed 3D maps of the radiation-induced ΔOD , as described at end of Sec. 2.C.1, were imported into CERR for registration. The measured data were manually registered to the calculated plan and normalized as described in Sec. 2.C.2 to the ion chamber measurements. The manual registration was done by aligning three external markers visible on the optical-CT reconstruction to known corresponding alignment points of the phantoms CT. The normalization was done by taking the median value of a nine voxel region of interest surrounding the corresponding measured ion chamber position. This reduced the effects noise could have on the normalization process, but admittedly, introduces possible volume effects from a larger volume. The TPS dose grid was resampled to match that of the measured grid, $1 \times 1 \times 1 \text{ mm}$. Once the distributions were on the same grid a series of global Gamma analyses were run with different dose difference (ΔD) and distance to agreement (Δd) criteria for determination of reproducibility of the delivery, setup, and calculations. The data within 5 mm of the edges were ignored for analysis as imaging artifacts can persist. This analysis looked to offer insight in determining the appropriate gamma analysis (ΔD and Δd), and what percentage of passing voxels would constitute “passing” if these techniques were instituted for clinical verification of delivery. An important aspect of the gamma analysis implemented here is that it was evaluated in 3D. This means that at every point in the planned distribution, gamma was determined from a 3D search in the measured distribution.

FIG. 3. Accuracy: A fully 3D comparison (just the three principle planes shown—axial, sagittal, and frontal) of the Eclipse predicted dose distribution (a), with that measured in PRESAGE[®] (b). Row (c) shows the corresponding gamma maps at 3%, 2 mm criteria with a 5% threshold. The contours of the five target lesions are visible within the dosimeter, superposed onto the dose distributions. Measured dose is absolute after normalization to microion chamber measurement in the largest target (see the chamber channel visible in the CT data in the sagittal views). (d) A line profile along the dashed line indicated in (c).

FIG. 4. Reproducibility: Agreement between the four independent IGRT VMAT deliveries. These plots show the average and one std-dev variability of key isodose lines, averaged over the four independent deliveries, in the three principle views [(a) axial, (b) coronal, (c) sagittal]. Isodose lines of 95, 90, 80, 70, 50, and 30% are shown. There are three lines for each isodose: the middle solid line is the mean isodose (averaged over all dosimeters) and the dashed lines on either side represent the 1σ variation of that isodose line.

3. RESULTS AND DISCUSSION

Figure 3 shows the ability of the dosimetry system to accurately measure a complex verification plan. Two 3D gamma criteria were used here to show the 3D agreement. Both 5%, 3 mm (99.9% passing voxels) and 3%, 2 mm (98.0% passing voxels) show the calculated dose matches the measured and delivered output to within expected tolerances and errors. (a) shows the axial, sagittal, and coronal views for the planned dose distribution created by the treatment planning system (TPS). (b) shows the same distribution as measured by the optical-CT system and (c) shows the corresponding gamma maps for 3%, 2 mm. A line profile can also be seen in the figure extending from the inferior-anterior target through the central target and toward the superior-posterior portion of the dosimeter where no target is present. The line profile matches to within 1% for the majority of the line, however in the inferior-anterior target there is more flatness observed in the plan than measured dose. This appears to be a real deviation as the reproducibility from each dosimeter was less than 3% overall from each other and the noise within each dosimeter's low gradient regions were on the order of 10 cGy or 0.5% of the maximum dose delivered.

Dose distributions showed little variation, with less than 3% standard deviation in voxels located in similar dose regions. Figure 4 shows the range of isodose contour deviations between the three deliveries, with tight agreement in high dose regions. This is a notable finding since each phantom was set up and delivered completely independently on different days—the setup error, machine daily output, dosimeter, and optical scanner variations are all independent of one another in the three scans showing the reproducibility of the entire treatment and verification system.

4. CONCLUSION

The significance of this work arises from the first comprehensive high-resolution 3D dosimetry study of the end-to-end accuracy and consistency of a complex IGRT guided, multiple-

sion, single-isocenter, VMAT treatment. The deliveries of the SRS irradiation were found to be very consistent (less than 3% dose deviation in targets) with each other and the treatment plan, demonstrating high accuracy and reproducibility of the treatment delivery (including IGRT positioning). 98.0% gamma pass rates for 3%, 2 mm criteria show the ability of the treatment technique to plan and deliver the desired dose distribution to within a generally accepted deviation for SRS cases.¹⁴ The complexity of the treatment (multiple arcs) and dosimetry (multiple strong gradients) pose a substantial challenge for comprehensive verification. 3D dosimetry can be uniquely effective in this scenario.

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- ¹C. Baldock, Y. De Deene, S. Doran, G. Ibbott, A. Jirasek, M. Lepage, K. B. McAuley, M. Oldham, and L. J. Schreiner, "Polymer gel dosimetry," *Phys. Med. Biol.* **55**(5), R1–R63 (2010).
- ²N. Krstajić and S. J. Doran, "Characterization of a parallel-beam CCD optical-CT apparatus for 3D radiation dosimetry," *Phys. Med. Biol.* **52**(13), 3693–3713 (2007).
- ³Y. Xu, C.-S. Wu, and M. J. Maryanski, "Performance of a commercial optical CT scanner and polymer gel dosimeters for 3-D dose verification," *Med. Phys.* **31**(11), 3024–3033 (2004).
- ⁴G. S. Ibbott, "QA in radiation therapy: The RPC perspective," *J. Phys. Conf. Ser.* **250**, 012001 (2010).
- ⁵J. Adamovics and M. J. Maryanski, "Characterisation of PRESAGE: A new 3-D radiochromic solid polymer dosimeter for ionising radiation," *Radiat. Prot. Dosim.* **120**(1–4), 107–112 (2006).
- ⁶S. Brown, A. Venning, Y. De Deene, P. Vial, L. Oliver, J. Adamovics, and C. Baldock, "Radiological properties of the PRESAGE and PAGAT polymer dosimeters," *Appl. Radiat. Isot.* **66**(12), 1970–1974 (2008).
- ⁷A. Thomas, J. Newton, J. Adamovics, and M. Oldham, "Commissioning and benchmarking a 3D dosimetry system for clinical use," *Med. Phys.* **38**(8), 4846–4857 (2011).
- ⁸J. L. Bedford, Y. K. Lee, P. Wai, C. P. South, and A. P. Warrington, "Evaluation of the Delta4 phantom for IMRT and VMAT verification," *Phys. Med. Biol.* **54**(9), N167–N176 (2009).
- ⁹D. Létourneau, J. Publicover, J. Kozelka, D. J. Moseley, and D. a. Jaffray, "Novel dosimetric phantom for quality assurance of volumetric modulated arc therapy," *Med. Phys.* **36**(5), 1813–1821 (2009).
- ¹⁰M. Oldham, A. Thomas, J. O'Daniel, T. Juang, G. Ibbott, J. Adamovics, and J. P. Kirkpatrick, "A quality assurance method that utilizes 3D dosimetry and facilitates clinical interpretation," *Int. J. Radiat. Oncol., Biol., Phys.* **84**(2), 540–546 (2012).
- ¹¹H. S. Sakhalkar, J. Adamovics, G. Ibbott, and M. Oldham, "A comprehensive evaluation of the PRESAGE/optical-CT 3D dosimetry system," *Med. Phys.* **36**(1), 71–82 (2009).
- ¹²P. Y. Guo, J. A. Adamovics, and M. Oldham, "Characterization of a new radiochromic three-dimensional dosimeter," *Med. Phys.* **33**(5), 1338–1345 (2006).
- ¹³S. Al-Nowais, A. Nisbet, J. Adamovics, and S. J. Doran, "An attempt to determine the saturation dose for PRESAGE™," *J. Phys.: Conf. Ser.* **164**, 012043 (2009).
- ¹⁴B. E. Nelms and J. a. Simon, "A survey on planar IMRT QA analysis," *J. Appl. Clin. Med. Phys.* **8**(3), 2448–2462 (2007).