Image-guided method for TLD-based in vivo rectal dose verification with endorectal balloon in proton therapy for prostate cancer

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Purpose: To present a practical image-guided method to position an endorectal balloon that improves in vivo thermoluminescent dosimeter (TLD) measurements of rectal doses in proton therapy for prostate cancer.

Methods: TLDs were combined with endorectal balloons to measure dose at the anterior rectal wall during daily proton treatment delivery. Radiopaque metallic markers were employed as surrogates for balloon position reproducibility in rotation and translation. The markers were utilized to guide the balloon orientation during daily treatment employing orthogonal x-ray image-guided patient position- ing. TLDs were placed at the 12 o’clock position on the anterior balloon surface at the midprostatic plane. Markers were placed at the 3 and 9 o’clock positions on the balloon to align it with respect to the planned orientation. The balloon rotation along its stem axis, referred to as roll, causes TLD displacement along the anterior-posterior direction. The magnitude of TLD displacement is revealed by the separation distance between markers at opposite sides of the balloon on sagittal x-ray images.

Results: A total of 81 in vivo TLD measurements were performed on six patients. Eighty-three percent of all measurements (65 TLD readings) were within +5% and −10% of the planning dose with a mean of −2.1% and a standard deviation of 3.5%. Examination of marker positions with in-room x-ray images of measured doses between −10% and −20% of the planned dose revealed a strong correlation between balloon roll and TLD displacement posteriorly from the planned position. The magnitude of the roll was confirmed by separations of 10–20 mm between the markers which could be corrected by manually adjusting the balloon position and verified by a repeat x-ray image prior to proton delivery. This approach could properly correct the balloon roll, resulting in TLD positioning within 2 mm along the anterior-posterior direction.

Conclusions: Our results show that image-guided TLD-based in vivo dosimetry for rectal dose verification can be performed reliably and reproducibly for proton therapy in prostate cancer.

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Key words: Rectal balloon daily positioning, metallic marker, TLD in vivo dosimetry, proton therapy, prostate cancer

I. INTRODUCTION

External beam radiotherapy for prostate cancer utilizing either intensity-modulated radiation therapy (IMRT) or protons can be characterized by steep dose gradients in the rectum along the anterior-posterior (AP) direction at the rectoprostatic interface in order to maximize rectal sparing as shown in Fig. 1. This gradient generally has a dose fall off of nearly 10% per millimeter beyond the posterior edge of planning target volume (PTV) for both protons and IMRT. Beyond 10 mm posterior to the PTV edge, the dose gradient becomes less steep for IMRT. In comparison, the continuously sharp fall off with protons will result in zero dose at approximately 20 mm from the PTV edge. Although high dose gradients are desirable to maximize sparing of the rectal wall dose, they represent a challenge to perform in vivo rectal dosimetry because any displacement in positioning of in vivo dosimeters in the rectoprostatic region can result in unreliable dose measurements. Therefore, the reproducibility of positioning of in vivo dosimeters at the rectoprostatic interface must be carefully investigated to accomplish accurate in vivo rectal wall dosimetry.

In vivo point dose measurement at the rectoprostatic interface has been attempted with various techniques including silicon diode1, plastic scintillation detector,2 and MOSFETs.3 In this study, we focused on accomplishing reproducible positioning of Thermoluminiscent dosimeters (TLDs) at the rectoprostatic interface for in vivo rectal wall dosimetry in patients treated with proton radiotherapy. TLDs were chosen because of their small size (2 × 2 × 1 mm) and tissue equivalence, which avoids dose disturbances in proton therapy. In addition, TLDs have been proven to have the necessary
FIG. 1. (Top) The axial CT image illustrates a 2D dose distribution of two lateral proton fields at a transverse plane across the midprostate level and its relation to the endorectal balloon. The filled area is the CTV (enclosing prostate) and the solid contour around CTV is the PTV. Isodose lines represent 100%, 90%, 80%, 50%, and 20% of the planned dose. (Bottom) The dose profile across the midprostatic plane as illustrated by the solid line in the AP direction shown in the top panel intersects with PTV margin at the open circle representing the planned position of the TLD, indicated by the arrow. The solid line represents dose profile from two opposed lateral proton beams, and the dotted line represents a seven-beam IMRT plan. The squares represent potential displacements of the TLD away from planned position (the solid square).

accuracy and effectiveness for measuring therapeutic proton doses.4,5

The use of endorectal balloons (ERBs) has been shown to reduce prostate motion during radiotherapy treatment delivery and is in routine clinical use.6,7 In this study, we utilized ERBs to achieve improved prostate gland immobilization and as positioning device for deployment and placement of the TLDs against the anterior rectal wall for performing in vivo rectal dose measurement. A free-hand insertion of the ERB with subsequent inflation can result displacements in both rotation and translation of the positioning balloon. When the rotation of the balloon along the stem axis (referred to as balloon roll) occurs during the free-hand insertion, the roll of the balloon is considered to have minimal effect on the overall rectal dose since the rectal position with respect to the proton irradiation fields does not vary. However, the TLD can be rotated away from its planned 12 o’clock position as illustrated in the open circle in the top panel of Fig. 1. This results in posterior displacement on placing TLDs away from the PTV, as indicated in the open squares along Y-axis, shown in the bottom panel of Fig. 1. The impact of positioning variability of an ERB on in vivo dosimetry described in our study has not been previously documented.

We established a practical image-guided method that allows correcting the placement of ERBs to reduce the positional variation of TLDs during treatment delivery. This method utilizes x-ray radiographic images taken during the positioning of the patient with radiopaque metallic markers attached in dedicated locations on the balloon. Balloon rotation and translation displacements can be identified and corrected before treatment delivery. In addition, this method does not impact the workflow for patients undergoing proton radiotherapy for prostate cancer since it utilizes the same daily ERB and maintains similar numbers of x-ray radiographic images taken for image-guided patient positioning. This is a cost-effective method to perform repeat measurements on an individual patient to study temporal variations of delivered doses over the entire treatment course. This paper reports our initial experience on the clinical implementation of in vivo measured rectal doses combining TLD, ERB, and metallic markers with the x-ray base image guidance positioning system.

II. MATERIALS AND METHODS

II.A. TLD placement technique

The ERB used in this study (Radiadyne, Houston, TX) incorporates a metallic fiducial bead at its tip with a dome-shaped stopper for reproducible insertion of the balloon along the cranio-caudal direction of the patient. A template-based schema was used to demarcate visible points on the balloon’s surface, which allowed for placement of the TLDs and the fiducial markers at designated locations in a reproducible manner as shown in the top-left panel of Fig. 2. Four fiducial markers were placed on the balloon (three on the sides and one on the stem). Double-sided adhesive tape was used to affix the TLDs on the balloon’s surface, which allowed for easy retrieval of the TLDs after treatment delivery completion.

The Harshaw TLD-100 LiF dosimeter with a dimension of 2 mm square size and 1 mm thickness was used. The TLD-100 dosimeter with a density similar to soft tissue causes minimal dose perturbation and thus is well suited for dose measurements during proton treatments. Because the TLD-100 is still slightly denser than soft tissues, it can be easily visualized on the computed tomography (CT) images without any significant flaring or starlike artifacts. The TLD reading was
II.B. The image-guided method for positioning the balloon

With metallic markers placed on the balloon in the arrangement described above, the location and rotation of the balloon was examined in the AP and lateral (LAT) scout views before acquiring planning CT images. A specific procedure was developed by staff for balloon preparation and insertion to limit residual air pockets inside the balloon. The AP and LAT scout images were used to determine and compare the actual position of the balloon to its planned orientation. Based on the separation between two lines, passing metallic markers on two sides of the balloon as shown in the LAT scout image in the bottom-left panel of Fig. 2, the magnitude of balloon roll was estimated. When only minimal rolling occurred, the metallic markers on the balloon were aligned along a line as shown in the LAT scout image. We found that the balloon’s pitch along LAT axis or angular rotation along AP axis was determined by the patient’s anatomy and did not vary during multiple insertions (with and without markers) in repeated planning CT image acquisitions.

For daily in-room balloon placement, we provided a step by step procedure to the therapists on how to place the balloon in a reproducible position. A set of AP and LAT x-ray radiographs was acquired using the in-room imaging system for daily positioning of prostate patients without or with balloon. Utilizing acquired radiographs, the therapists aligned VisiCoil linear fiducial markers (IBA Dosimetry) within the prostate to position patients and, at the same time, verified that there was no balloon roll using markers on the surface of balloon. Whenever a balloon roll was identified with more than 2 mm separation between surface markers in the sagittal view of the LAT radiograph, the balloon was manually rotated and a new set of AP and LAT radiographs was acquired to confirm alignment. No more than two attempts are typically required to align properly the balloon, similar to the number of attempts required for daily patient positioning.

By utilizing this method based on metallic markers with x-ray images, the correct TLD position can be accomplished and verified along the AP direction. The TLD position was planned to be between the clinical target volumes (CTV) and PTV contours (3 mm posterior to the CTV) as shown in Fig. 1. The TLD position was verified with respect to lateral and cranio-caudal orientation based on its relative location to the metallic markers on the balloon and the intraprostatic implanted VisiCoils using the scout image at the AP direction. Of note, deviations in the TLD position in the lateral or cranio-caudal direction by as much as 1 cm from the reference planning CT location will not significantly impact the TLD dose reading due to the flatness of the dose distribution in that plane, as shown in the bottom-right panel of Fig. 2.

II.C. TLD dose reading and evaluation compared to planned dose

In principle, the response of a calibrated TLD should not change over time. Because the offset of a TLD reader...
FIG. 3. Total of 81 in vivo TLD measurements were performed on six of eight recruited patients. Two patients were excluded for reasons described in the text. Three measurements show near zero proton doses on patients #2 and #3, which were due to incorrect placement of the balloon (upside-down insertion). Only one TLD measurement with 70% lower dose is indicated by the open circle for patient #4. Nearly 83% of all measurements fall within +5% and −10% dose limits. The three data points marked by hexagonal symbols are discussed in the text.

In parallel to the TLD calibration of proton beam, the TLD reading due to x-ray images taken for positioning patient was also investigated by irradiating several TLDs with 20 times of x-ray as utilized for positional image. According to the TLD readings of x-ray irradiated TLDs, the TLD reading caused by in-room x-ray imaging up to 20 times contributed only 1% of TLD dose due to protons at 160 cGy physical dose, i.e., 180 cGy biological equivalent doses (BED) with the RBE (relative biological effectiveness) value of 1.1 for each actual treatment dose. The value of 1.1 is used for.

To compare measured TLD doses with planned doses, the planned doses at the respective location were scored from the plans performed on CT sets required with balloon but without metallic markers. The treatment plans were used for actual treatments and the overall workflow of the proton prostate treatments remained unchanged. Quality assurance (QA) plans were performed using the same parameters such as apertures and compensators, with a CT set having the TLD and metallic markers placed at the balloon for each patient. Since the TLD and markers were placed at 3 to 4 cm distance proximal to the distal range of the proton beam, the dose perturbation induced by the TLD and markers was minimal as demonstrated in the QA plans.

### III. Results

Over a period of three months, 81 in vivo TLD measurements were performed on six of eight recruited patients as shown in Fig. 3. Two patients (patient #2 and #3) were excluded from this study due to inadvertent large interfractional displacement of the balloon. Significant bowel filling had resulted in suboptimal balloon positioning as seen on two separate CT scans. Three TLD measurements for patients #2 and #3 were near zero as shown in Fig. 3. Retrospective analysis of the in-room x-ray radiographs showed that the metallic markers were on the opposite side of the balloon indicating that the balloon was inadvertently flipped 180° when inserted into the rectum. This resulted in the TLD being on the opposite side of the balloon placed more than 2 cm posterior to its planned location and completely outside of the proton beam, thus resulting in essentially zero dose. One measurement on patient #4 was 70% lower TLD dose than expected. Further analysis revealed that the endorectal balloon was partially inflated. Those measurements with large deviations occurred during the early phase of this study, while we were in the process of understanding and revising our techniques. In addition, there is potential user error and interuser variability when following the image-guidance balloon positioning procedure.

Excluding the above four data points (three zero reading from patient #2 and #3 and one −70% reading from patient #4) but including rest of measurements in patients of #2, #3, and #4, 65 of 77 measurements fell within +5% and −10% range of planned doses with a mean of −2.1% and standard
deviation of 3.5% ($1\sigma$). Most measurements for patients #5, #6, and #8 were within $+/-5\%$ indicating that our balloon insertion and alignment technique enhanced with experience over time resulting in increasingly reproducible TLD readings. The 3.5% deviation from the planned dose means the accuracy of placing TLD to the posterior of PTV is approximately $+/-2\ mm$. This positional accuracy limit is reflected in the proton dose gradient of 2% to 5% per mm in the vicinity of the PTV location as shown in the bottom panel of Fig. 1.

We analyzed further TLD measurements showing deviations between $-10\%$ and $-50\%$ from planned dose, x-ray radiographs for patient #3 (indicated by the hexagonal points in Fig. 3) to understand marker positions with respect to bony anatomic landmarks and shifts with respect to isocenter in the sagittal and coronal views as shown in Fig. 4. The separation between the parallel lines in the top panels in Fig. 4 indicates that the markers deviated from their presumed 9 and 3 o’clock positions due to balloon roll. Larger separation means larger posterior shift of the TLD from its planned position. Magnitude of separation between lines is correlated to TLD dose reductions showing at the tops of corresponding x-ray radiographs for those three measurements. The separations were 3.0 mm, 10.7 mm, and 18.5 mm for $-0.8\%$, $-10.8\%$, and $-21.8\%$ measured TLD doses, respectively. Observed separations of 3.0 mm, 10.7 mm and 18.5 mm were correlated with $20^\circ$, $38^\circ$, and $50^\circ$ of rolling for a balloon with 25 mm radius. When the rolling of balloon occurred, the TLD was displaced posteriorly about one-half of the separation between two lines. Therefore, estimated displacements on TLD were 1.5, 5.4, and 9.3 mm.

Based on the dose gradient shown in the bottom panel of Fig. 1, a dose at 5 mm distance from PTV was $\sim 10\%$ lower compared to the planned dose. Therefore, the observed dose reductions were qualitatively correlated to the amount of displacement from PTV, as shown in the bottom panel of Fig. 1. The coronal images in the lower panel of Fig. 4 indicate that the balloon was well positioned with respect to the intraprostatic VisiCoils and centered medially with respect to the isocenter and bony anatomy for the three fractions with no visible angular deflections such as rotation in the AP direction or pitch in the lateral direction. Therefore, the variation in TLD dose was caused primarily by the posterior shift caused by the rolling of the ERB along the superior-inferior direction as indicated by the degree of separation of the markers on the sagittal image.

IV. DISCUSSION

We report the initial experience consisting of 81 in vivo TLD measurements on six patients to monitor rectal point doses for proton prostate cancer treatments. By employing radiopaque metallic markers with orthogonal x-ray radiographs, a practical image-guided method provides a surrogate of the balloon position reproducibility during actual treatments. With this capability to examine the balloon orientation, we found that balloon roll introduced displacement of the TLD posteriorly from its planned location, thus resulting in significant variations of the measured TLD doses. In addition, given the uniformity of dose distribution along the cranio-caudal direction as shown in the bottom-right panel of Fig. 2, the TLD can be displaced by as much as 10 mm along cranio-caudal direction from its nominal position with little variation of measured TLD doses. Therefore, we believe that the most important factor for reproducible TLD-based in vivo dosimetry method is the balloon roll.

The method employed, using the combination of TLD, ERB, and fiducial markers, represents an option to perform TLD-based in vivo measurements with the TLD placed within $+/-3\ mm$ from its planned location along AP direction (i.e., corresponding to $+/-10\%$ TLD dose variation including the $+/-3\%$ TLD reading variation). However, the variation of measured TLD doses is smaller for later measurements of patient #5, #6, and #8 as shown in Fig. 3, after well-developed guidelines for balloon preparation, insertion, and examination on x-ray images were provided for RTTs. For those three patients, a total of 31 measurements were performed with only three points outside the $\pm 5\%$ dose variation limit (i.e., more than 90% of those data points are within the $\pm 5\%$ dose variation limit).

Based on a smaller deviation of later TLD measurements, a goal of $+/-6\%$ variation of TLD measurements (i.e., $+/-1.5\ mm$ position accuracy along the AP direction) should be achievable by requiring tighter displacement for smaller balloon roll when lateral x-ray radiographic imaged taken during positioning are carefully examined. An accuracy of...
1 mm (equivalent to $\sim 5^\circ$ of balloon roll) by utilizing this image-guided method was achieved by placing a single TLD along the AP direction. It should be noted that the overall trend of rectal dose cannot be investigated by measuring only a point TLD dose as in this study. However, the reproducibility of positioning the balloon is one of the key steps for obtaining volumetric dose information in order for the correlation of measured TLD doses at multiple locations to be evaluated for overall doses delivered to the rectum at each treatment as a future direction of this study.

V. CONCLUSIONS

In this study we developed an image-guided method that allows daily reproducible ERB positioning for in vivo TLD-based rectal dose verification in patients undergoing proton therapy for prostate cancer. The method utilizes radiopaque markers as an alignment surrogate to aid in placing the balloon at the planned position with minimal misalignment in rotation and/or translation. Retrospective analysis of in vivo TLD measurements ($n = 81$) in six patients indicates that the developed image-guided method was performed reliably and reproducibly to measure TLD-based in vivo proton therapy doses based on the surface of the endorectal balloon used to immobilize the prostate. The image-guided method minimized the balloon roll to improve the TLD dose variation on 83% ($n = 65$) measurements over total 81 measurements, having a mean of $-2.1\%$ in relation to the planned dose and a standard deviation of 3.4%.

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