Dose verification of dynamic MLC-tracked radiotherapy using small PRESAGE® 3D dosimeters and a motion phantom

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Dose verification of dynamic MLC-tracked radiotherapy using small PRESAGE® 3D dosimeters and a motion phantom

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Abstract. With the increasing complexity of radiotherapy treatments typical 1D and 2D quality assurance (QA) detectors may fail to detect out-of-plane dose discrepancies, in particular in the presence of motion. In this work, small samples of the PRESAGE® 3D radiochromic dosimeter were used in combination with a motion phantom to measure real-time multileaf collimator (MLC)-tracked radiotherapy treatments. A different sample of PRESAGE® was irradiated for each of three different irradiation scenarios: (1) static: static sample, without tracking (2) motion: moving sample, without tracking and (3) tracking: moving sample, with tracking. Our in-house software DynaTrack dynamically moves the linac's MLC leafs based on the target position. The doses delivered to the samples were reconstructed based on the recorded positions of the MLC and phantom during the beam delivery. PRESAGE® samples were imaged with an in-house optical-CT scanner. Comparison between simulated and measured 3D dose showed good agreement for all three irradiation scenarios (static: 99.2%; motion: 99.7%; tracking: 99.3% with a 3%, 2 mm and a 10% threshold local gamma criterion), failing only at the edges of the PRESAGE® samples (~ 6 mm). Given that the dose distributions deposited using the DynaTrack system have been independently verified, this experiment demonstrates the ability of PRESAGE to measure 3D doses correctly in a tracking context. We conclude that this methodology could be used in the future to validate the delivery of dynamic MLC-tracked radiotherapy.

1. Introduction

Dynamic multileaf collimator (MLC) tracking of moving tumors is able to compensate for intra-fractional tumor motion during radiotherapy and preserve target coverage while reducing the dose received by nearby healthy tissues. Lung stereotactic radiotherapy (SBRT) is especially susceptible to intrafracational motion as tumors are usually very small (less than 5 cm in diameter) and have large and variable motion [1]. When compared with conventional radiotherapy, these treatments require a higher level of accuracy due to the high dose delivered in only a few fractions (1 to 8), and steep dose fall-off outside the planning target volume (PTV). Before clinical implementation of these treatments, validation of the delivered dose is needed using anthropomorphic phantoms. 1D and 2D detectors typically used for dose validation might fail to detect disagreements outside the plane in which the detectors are placed. Additional uncertainties can occur as treatment planning system (TPS) simulations are being performed

in inhomogeneous media, and previous studies have demonstrated discrepancies of the order of 2-3% between TPS calculations, films and ionization chambers [2, 3]. Ideally, high-resolution 3D dosimeters should be used for a better assessment of the delivered dose.

Polymerizing 3D dosimeters [4] have been successfully used before to verify dynamic MLC-tracked dose delivery using both magnetic resonance imaging (MRI) [5] and optical-CT [6] readout, in homogeneous media. PRESAGE® dosimeters (Heuris Pharma, Skillman, NJ, USA) have been used in inhomogeneous media before to validate gated lung radiotherapy treatments [7]. However, to the best of our knowledge, PRESAGE® samples have not been used before to validate tracked treatments.

In this work, we investigate whether small PRESAGE® 3D dosimeters can be used in combination with a lung motion phantom for dosimetric verification, by demonstrating that PRESAGE® correctly reproduces the results of a previously validated real-time in-house MLC-tracked radiotherapy software [8-10].

2. Material and Methods

2.1 Motion phantom/PRESAGE® dosimeter experimental set-up

PRESAGE® is a radio-sensitive 3D dosimeter that consists of a radiochromic plastic that shows an optical density (OD) change when irradiated. This change is linear with the delivered dose and can be measured using an optical-CT scanner [11]. To mimic a simplistic human torso with a tumour in the lung, the QUASAR™ MRI4D motion phantom (Modus Medical, London, ON, Canada) was used together with a sample of PRESAGE®. The phantom, which was filled with deionized water, has two cylindrical holes, one central and one offset. A holder was created in-house to place a sample of 3.5 cm diameter and 5 cm length in one of the cylinders. The offset cylinder was filled with deionized water while PRESAGE® was placed in the central insert (Figure 1) to facilitate phantom positioning. Motion can be applied in superior-inferior direction with and without rotation, by attaching one of the inserts to the piezoelectric motor box.

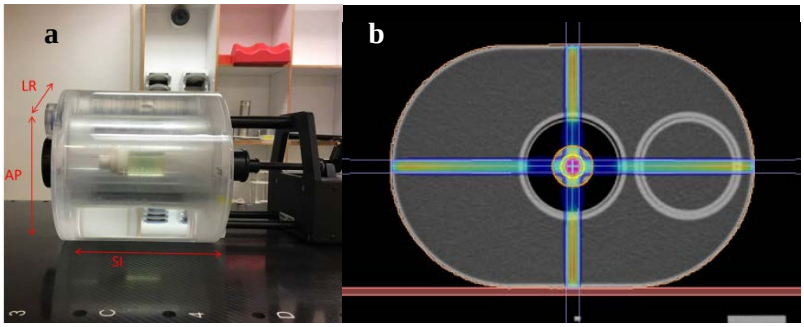

Figure 1. (a) Experimental arrangement with an irradiated sample of PRESAGE® placed, with an in-house holder, inside a cylindrical insert of the QUASAR™ MRI4D motion phantom. SI (superior-inferior); AP (anterior-posterior); LR (left-right) are shown. Motion was applied in the SI direction based on a sinusoidal wave with 7.5 mm amplitude and 4 s period. (b) Central axial slice view of the CT scan of the set-up with PRESAGE® sample in place. The treatment plan with four beams is also visible.

2.2 Experimental set-up workflow

The phantom/PRESAGE® dosimeter experimental set-up was used to perform an end-to-end test. A computed tomography (CT) scan of this set-up, using a dummy sample of PRESAGE®, was acquired and transferred to the Monaco TPS, research version 5.19.03 (Elekta AB, Stockholm, Sweden). A treatment plan with four equidistant beams and field sizes of 1×2.5 cm^2 was created and the dose distribution was calculated with a GPU-based Monte Carlo dose calculation algorithm with a maximum

dose of 9.7 Gy, 1x1x1 mm^3 resolution and 1% statistical uncertainty. The collimator was rotated to 90°, so that the MLC leafs would move in the same direction as the target motion.

Three different plan delivery scenarios were tested on a research Elekta Synergy linac: (1) static: static phantom, without tracking; (2) motion: moving phantom, without tracking; (3) tracking: moving phantom, with tracking. For each scenario a different sample of PRESAGE® was irradiated.

2.3 MLC-tracking dose delivery and simulations

Our in-house MLC-tracking software DynaTrack [8] was used to control the research linac and move the MLC leafs based on the position of the moving target, provided by the phantom. A sinusoidal wave of 4 s period and 7.5 mm amplitude was used to move the sample in the superior-inferior direction for scenarios (2) motion and (3) tracking. The target position was provided by the motion phantom piezoelectric motor box. For each irradiation scenario, log-files containing the recorded MLC and phantom positions at 40 ms intervals were obtained at a rate of 25Hz. These allowed reconstruction of the dose in the delivered conditions, allowing a direct comparison of the simulated dose with the PRESAGE® measured dose distributions [12] (see figure 2).

3D dose distributions from both PRESAGE® samples and Monaco simulations were normalized to the average value at the irradiation isocentre and compared using the 3D gamma criterion, for 3% dose difference and 2 mm distance to agreement (3%, 2 mm) [13].

2.4 Optical-CT/PRESAGE® samples readout

PRESAGE® samples were imaged 60 min after irradiation with an in-house telecentric optical-CT scanner, a modified version of the one described by McErlean *et al* [14]. Each scan takes approximately 1 min to obtain 1000 projections, each of 320 × 320 pixels, over a 180° rotation to obtain a reconstructed image with a voxel size of 0.2 mm^3. Additionally, each sample was scanned before irradiation in order to account for changes due only to dose.

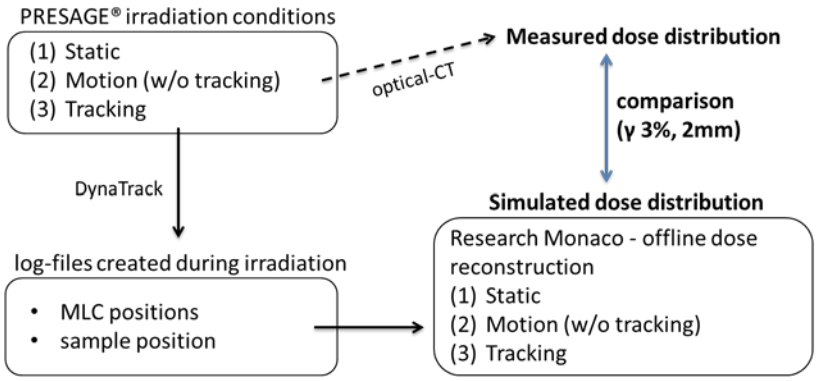

Figure 2. Diagram showing the study workflow.

3. Results and discussion

The agreement between measured and simulated reconstructed dose distributions is visible by taking a profile at the central slice (Figure 3b, e and h) and by applying the 3D gamma analysis for each irradiation scenario (figures 3c, f and i). For a clinically relevant 3D gamma criterion of 3%, 2 mm and a 10% threshold, a passing rate of 99.2%, 99.7% and 99.3% was obtained for the (1) static, (2) motion and (3) tracking scenarios, respectively. A slightly narrower penumbra is visible for the simulated (3) tracking scenario profile in comparison with the respective measured profile. For purposes of reconstructing the dose delivered, the recorded MLC leaf positions were rounded to their nearest integer millimetre value. This could explain the difference between the measurement and the simulated profiles, as particularly small fields are used.

In figures 3c, f and i, the regions where the gamma criterion fails ($\gamma \geq 1$) are shown in red and occur mainly at the axial edges of the sample. The small disagreement at the edges, which is present in all three irradiated samples, can be visualized in more detail in figure 4b but it is not present in figure 4c. We speculate that this is due to dosimetric inhomogeneities that occur within ~6 mm of the dosimeter surface, for doses ≥30% of maximum dose. Related work (data not shown) suggests that this is caused by the manufacturing process of the PRESAGE® itself. Partial correction is possible and was applied here using data from a previously homogeneously irradiated sample, but further work is needed to develop a robust correction strategy.

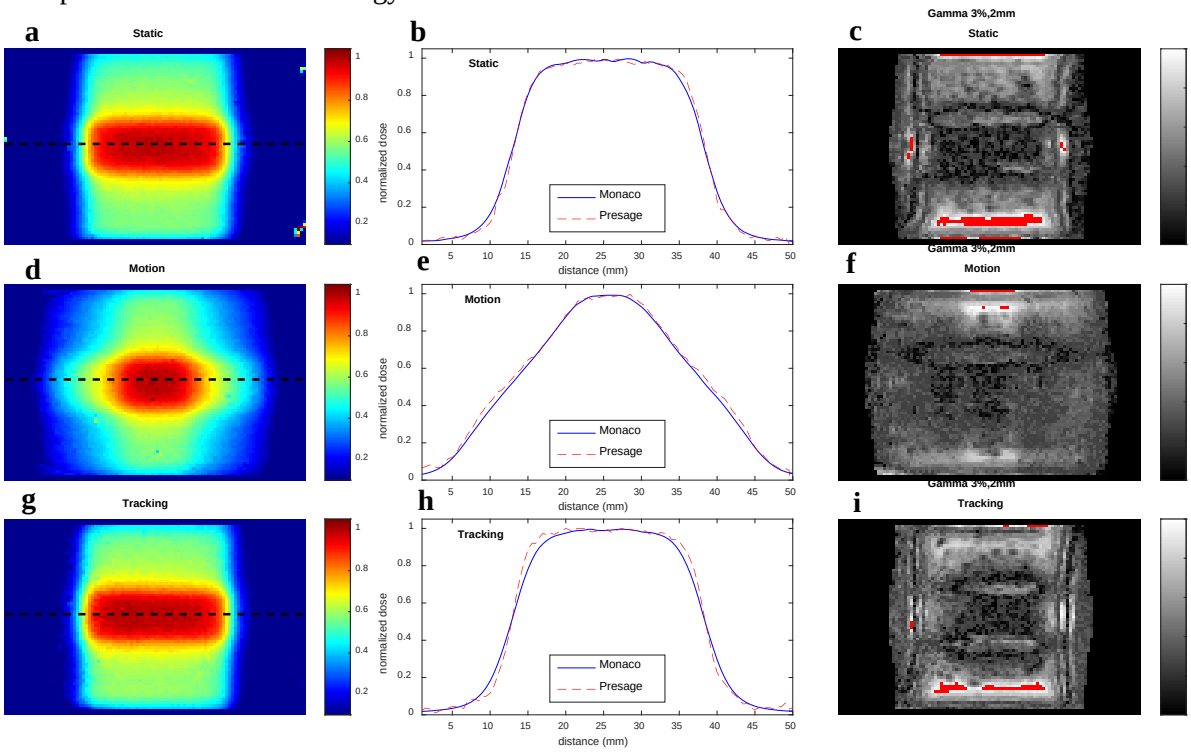

Figure 3. Normalized central sagittal slice showing PRESAGE® color-coded dose distributions and the respective profile along the superior-inferior direction for all three studied scenarios. Central sagittal slice of 3D gamma analysis is shown comparing measurements with simulations. Areas where the gamma criterion fails ($\gamma \geq 1$) are shown in red.

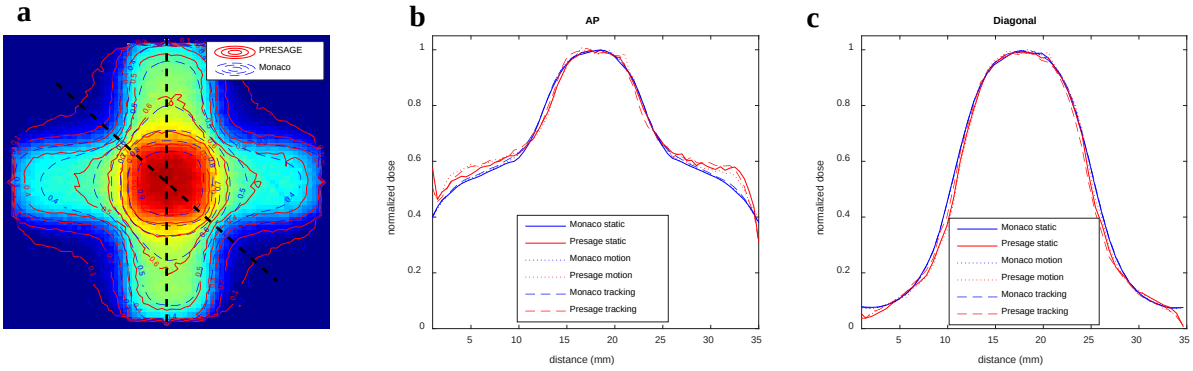

Figure 4. (a) Normalized central axial slice color-coded dose distributions and isodose lines showing PRESAGE® under (1) static conditions. Simulated and measured profiles taken at the central axial slice at (b) anterior-posterior (AP) and (c) diagonal directions are shown for (1) static, (2) motion and (3) tracking scenarios.

Both measured and simulated data show the benefit of using tracking to improve dose coverage of moving targets. The difference in the dose distributions obtained for a sample in (2) motion and (3) tracking scenarios are visible in figures 3d and g, respectively. As expected, in the presence of motion without tracking the 3D dose distribution is blurred as opposed to when MLC-tracking is applied. The same conclusions are drawn from figure 5, where the gamma criterion is applied to compare the PRESAGE® sample irradiated in the (1) static scenario with the two other scenarios where PRESAGE® samples are irradiated while moving. The good agreement between the sample in (1) static conditions with the sample in (3) tracking conditions (figure 5b) shows the reproducibility of the samples and the methodology used.

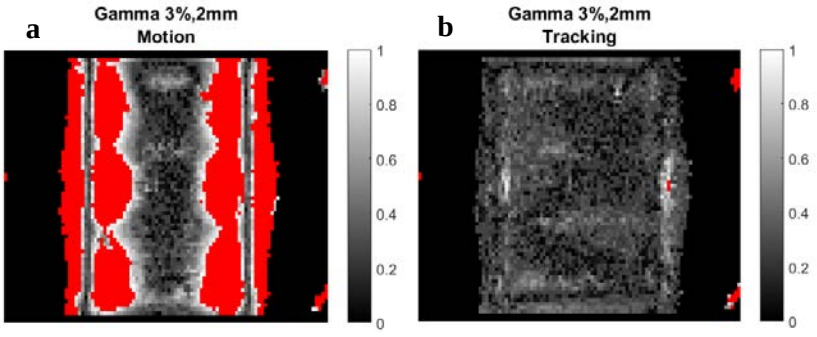

Figure 5. Central sagittal slice of the 3D gamma analysis is shown comparing the PRESAGE® sample in static scenario with: (a) motion no tracking PRESAGE® and (b) tracking PRESAGE®. Areas were the gamma criterion fails ($\gamma \geq 1$) are in red.

4. Conclusion

To our knowledge, this is the first study using small PRESAGE® dosimeters in combination with a lung motion phantom using real-time tracked MLC radiotherapy treatments. Similar 3D dose distributions obtained for (1) static and (3) tracking conditions highlight the ability of MLC-tracking to improve target coverage. Despite dose discrepancies at the edges of the samples, which need further investigation, the methodology used was reproducible and provided valuable 3D dosimetric information that agreed with the simulated data. This suggests that PRESAGE® samples can be used in the future to validate the delivery of MLC-tracked radiotherapy treatments.

In the future, more complex, clinically relevant dose distributions will be investigated, as well as more physically challenging radiation delivery treatments including rotation on an offset target. We intend to use these dosimeters to verify MLC-tracked treatment on the new Elektra MR-linac, and believe the methodology used here will be easily transferred to our MR-linac.

5. Acknowledgements

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