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Dose reconstruction including dynamic six-degree of freedom motion during prostate radiotherapy

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Abstract. An in-house developed program for real-time reconstruction of motion-induced dose errors, DoseTracker, was extended to handle rotational target motion in addition to the previously implemented translational motion, and applied offline for prostate VMAT treatments. For translational motion, the motion-induced errors of DoseTracker were in good agreement with ground truth dose reconstructions performed in a commercial treatment planning system. For rotational motion, no ground truth was available, but DoseTracker showed that the VMAT dose is highly robust against static interfractional rotations but quite sensitive to dynamic intrafraction rotations due to interplay effects between target motion and machine motion.

1. Introduction

Image guidance is commonly used in prostate radiotherapy for daily pre-treatment alignment of implanted markers with the planned marker positions [1]. The alignment will typically only include translational motion although both inter- and intrafractional prostate rotations may be substantial [2]. Real-time monitoring of six-degree of freedom (6DoF) prostate motion during radiotherapy delivery was recently demonstrated using kilovoltage intrafraction monitoring (KIM) [3]. However, real-time motion adaptation by gating or tracking so far only accounts for the translational component of the motion [4-5]. The impact of the uncompensated rotational motion is unknown since commercial treatment planning systems (TPSs) lack the ability to include rotations. In this study, we extend an in-house developed fast motion-including dose reconstruction program to 6DoF motion and demonstrate real-time use of the program to evaluate the dosimetric effects of dynamic prostate translations and rotations during volumetric modulated arc therapy (VMAT) treatments.

2. Material and methods

A software program, DoseTracker, was developed for real-time reconstruction of the dose delivered to any set of moving points within a body contour during radiotherapy delivery [6]. DoseTracker first calculates the 2D dose distribution in the isocenter plane by convolving the beam aperture with a dose kernel and then determines the dose in any point by depth scaling of the isocenter plane dose to the point by use of depth dose curves [7]. DoseTracker currently assumes water density.



In this study, DoseTracker was extended to pelvic applications and handling of 6DoF internal motion. The extended program was applied offline for a prostate cancer patient treated with a dual arc VMAT plan created in the Eclipse TPS (Varian Medical Systems). Connection to the accelerator was simulated by sending a data stream at 21 Hz to DoseTracker with 6DoF prostate positions and accelerator parameters (gantry angle, MLC positions, MU increment, etc.) corresponding to delivery of the VMAT plan. In a repeated loop, DoseTracker continuously calculated the dose increment to a set of calculation points twice: once with motion and once without motion. These were then used to obtain the time-resolved motion-induced dose error for each calculation point. The dose calculations were performed for 50,000 calculation points that included the PTV and constituted a subset of the original TPS calculation points. The same rigid 6DoF motion was applied to all calculation points while the outer body contour was assumed to be static.

A treatment simulation was first performed with dynamic prostate translations measured with implanted electromagnetic transponders [8] to investigate the accuracy of DoseTracker for prostate VMAT. A ground truth motion-including dose reconstruction was obtained by a previously validated dose reconstruction method that emulates rigid target translations as multiple isocenter shifts in the TPS [9] and has been extended for time resolved calculations [10]. A time resolution of 3Hz was used corresponding to a dose calculation for every 2° gantry rotation during the simulated VMAT delivery.

Next, simulations were performed with static prostate rotations about the left-right (LR) axis and with dynamic prostate rotations measured with KIM [2]. The dosimetric impact of the rotations was quantified as the CTV volume covered by 95% of planned mean CTV dose (V95%).

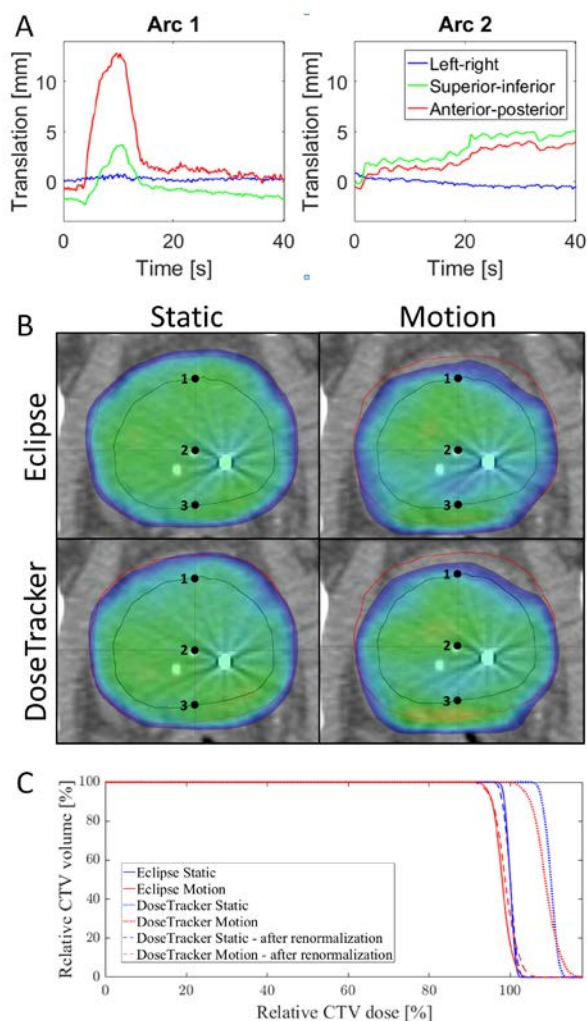


Figure 1. (A) Translational prostate motion during the two VMAT arcs. (B) Reconstructed dose distributions in an axial plane through the prostate CTV (green structure) and PTV (red) calculated by the Eclipse TPS and DoseTracker with and without the motion. The dose color wash shows doses in the range 90-110%. The illustrated DoseTracker doses were renormalized to the same static mean CTV dose as in the TPS. Time resolved doses in the numbered dose points are presented in figure 2. (C) CTV dose volume histograms for reconstructed doses in the Eclipse TPS and in DoseTracker with and without translational motion. The DoseTracker dose is shown with and without renormalization to the same static mean CTV dose as in the TPS.

3. Results and discussion

DoseTracker performed the motion-including and static dose reconstructions with a mean frequency of 1.7 Hz, demonstrating that real-time application is feasible. The translational motion included a large transient excursion in mainly the anterior direction during the first VMAT arc and a more modest continuous drift in the superior-anterior direction during the second arc (figure 1A). DoseTracker overestimated the absolute dose level for the prostate with $\sim 10\%$ (figure 1C) due to its simplified modelling of the output factor and phantom scatter. Still, the distortion of the dose distribution caused by prostate motion during dynamic VMAT delivery (i.e. interplay effects, figure 1B) and the overall impact of motion on the CTV dose-volume histogram (figure 1C) were in good agreement with the ground truth dose reconstruction by the TPS. The motion-induced reduction in CTV D95 relative to the planned dose was 3.6 percent-point for DoseTracker and 3.7 percent-point for the TPS dose reconstruction. The time-resolved dose rate and motion-induced dose rate error of DoseTracker in selected points in the prostate (figure 1B) were also in good agreement with the TPS ground truth as shown in figure 2. Note in particular the large dose deficit in the anterior part of the prostate (Point 1) caused by the large anterior excursion of the prostate 6-12 s into the treatment delivery.

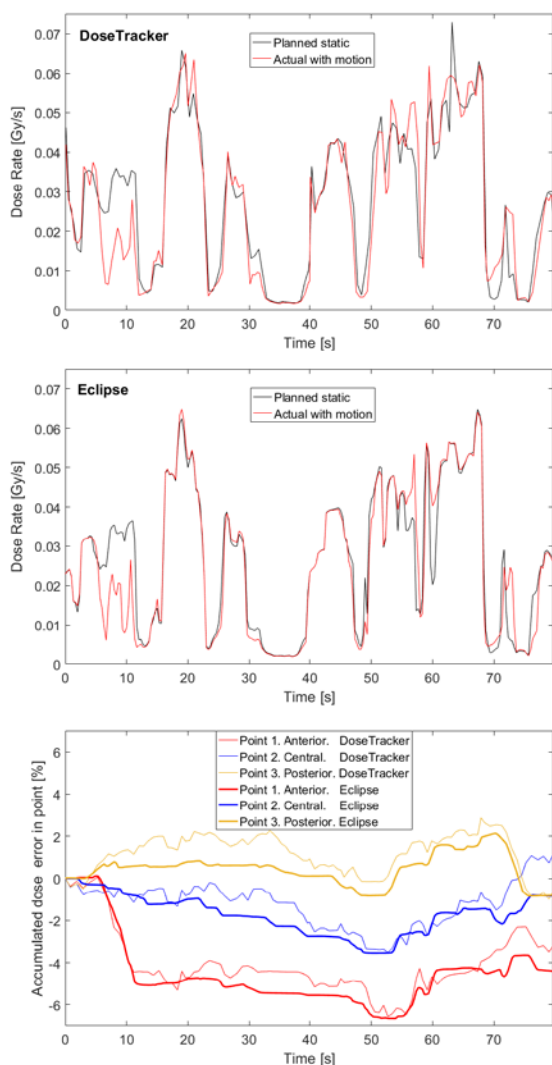


Figure 2. Top and middle: Dose rate during dual arc VMAT delivery as a function of time in Point 1 in figure 1B (anterior part of the prostate) as reconstructed by DoseTracker (top) and the Eclipse TPS (middle) with and without the translational motion of figure 1A. Bottom: Cumulative motion-induced dose error as a function of time (i.e. cumulative difference between the red and black curves in the top and middle figures) in the three prostate calculation points shown in figure 1B as reconstructed by DoseTracker and Eclipse. The dose error is shown in percent of the prescribed fraction dose of 2 Gy.

Static interfractional prostate rotations caused a rotation of the high dose volume relative to the prostate, but otherwise kept its shape almost unchanged (figure 3). For the investigated VMAT plan, CTV V95% remained high for rotations up to $\sim 10^\circ$ and then dropped steeply at larger rotations as the

prostate moved out of the high dose region (figure 3). The patient-measured dynamic prostate rotation was in mean 4.4° (LR axis), 0.5° (superior-inferior axis), and -1.6° (anterior-posterior axis), but it was highly dynamic with a maximum of 19° (figure 4A). Interplay effects between the dynamic rotation and VMAT delivery markedly distorted the dose distribution and reduced the CTV V95% from 100% to 94.9% (figure 4B-C) because of mismatches between the modulated doses received by the prostate from different directions. This was in stark contrast to the small dosimetric impact of static rotations, which can more easily be mitigated by application of safety margins.

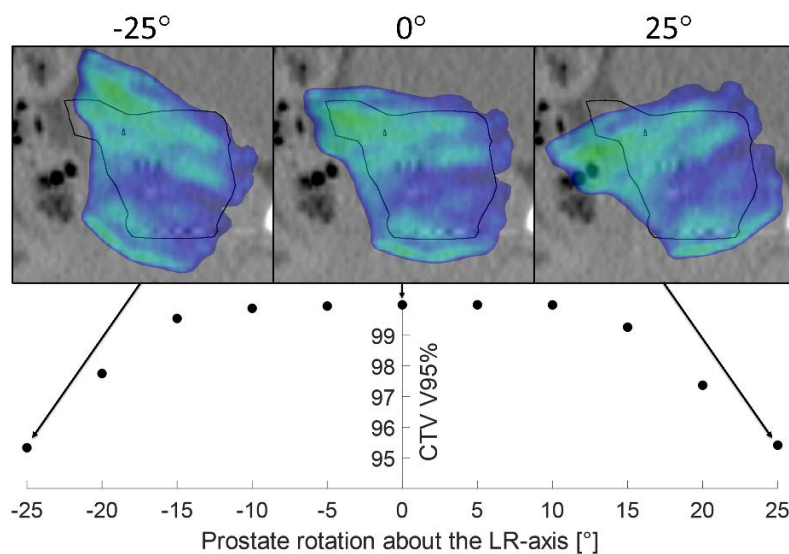


Figure 3. Top: Examples of dose distributions in the sagittal plane with static prostate rotations of -25° , 0° , and 25° about the left-right axis (doses above 95% are shown). Note that only doses inside the CTV (black contour) are relevant since the remaining anatomy outside the prostate (e.g. bones) does not rotate in the same way as the prostate. Bottom: CTV V95% as function of static left-right prostate rotation.

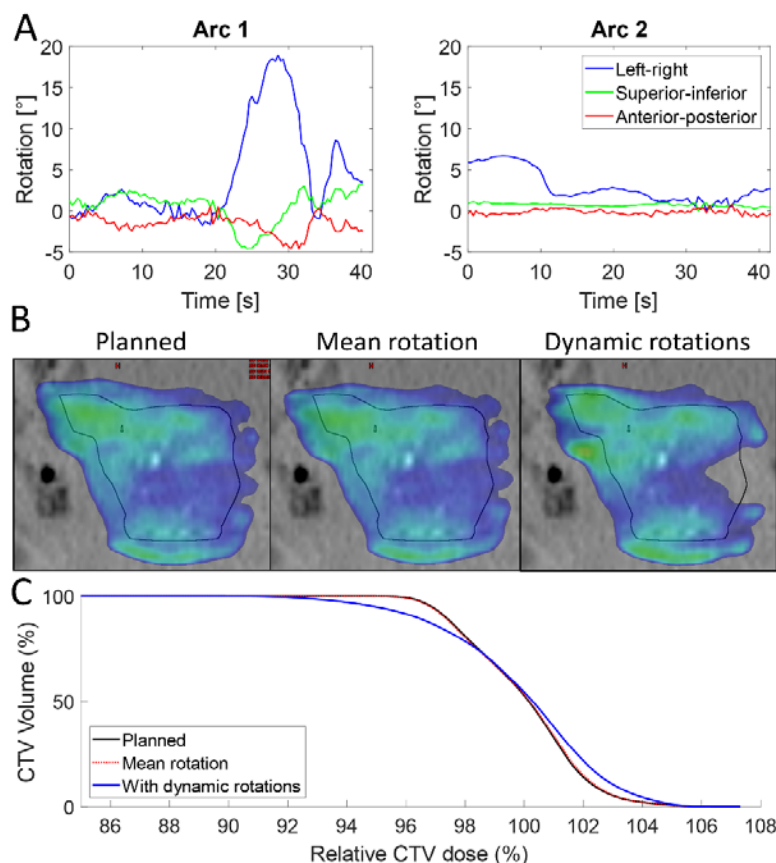


Figure 4. (A) Patient-measured dynamic prostate rotation applied during the simulated VMAT treatment. (B) Reconstructed dose distribution (above 95%) in the sagittal plane as planned, with a static rotation equal to the mean prostate rotation, and with the dynamic rotation of figure 4A. (C) CTV dose volume histogram as planned and delivered using both the mean prostate rotation and the dynamic rotation of figure 4A.

4. Conclusion

Real-time dose reconstruction including the effects of dynamic 6DoF motion was demonstrated during simulated VMAT delivery to the prostate with the in-house developed DoseTracker program. For translational motion, a ground truth dose reconstruction could be created in a commercial TPS demonstrating ~10% overestimation of the absolute dose level by DoseTracker, but good estimation of the motion induced dose errors. Errors in the absolute dose level tend to cancel out when DoseTracker calculations with and without motion are compared. For rotational motion, the CTV dose was much more susceptible to dynamic prostate rotations than to static rotations. The calculations can be integrated with online real-time 6DoF motion monitoring [3] for on-the-fly 6DoF dose reconstruction during treatment delivery, e.g. to estimate the residual dose errors after the translational real-time corrections currently applied in clinical protocols with prostate gating or MLC tracking [5].

5. Acknowledgements

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