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Geometric Characterization of Offline Vs. Online Fiducial Reference Coordinates for Varian Triggered Imaging in Prostate SABR

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ABSTRACT

Recent audits of prostate SABR treatments at BC Cancer – Victoria revealed high mid-arc intervention rates (upper bound of 47%), which prolongs treatment times and allow adverse anatomical changes due to bladder and rectal filling.

To address this, we investigated fiducial stability in a retrospective 40-patient cohort, finding that while gold seeds do not travel appreciably within the prostate, their minor intraprostatic motions cause larger, intervention-triggering displacements when projected onto a kV imager panel.

To mitigate unnecessary interventions, we developed an in-house software workflow that dynamically extracts fiducial coordinates from pre-treatment CBCTs and updates their locations within the planning frame of reference. End-to-end validation using a RANDO anthropomorphic phantom demonstrated that updating marker coordinates on the day of treatment successfully accounts for these small deviations, providing a practical method to reduce mid-treatment intervention rates and improve treatment efficiency.

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INTRODUCTION

Recent clinical audits of the triggered imaging protocol at BC Cancer - Victoria put upper estimates on mid-treatment arc intervention rates at 47% ± 34% for SABR treatments involving the prostate and 57% ± 36% for treatments involving the prostate and pelvic nodes. Each mid-treatment arc intervention extends the treatment time, allowing increased bladder and rectal filling to affect local anatomy. This study investigates the stability of fiducials inside the prostate and proposes a workflow to update the fiducial coordinates on the day of treatment to help reduce these intervention rates.

HOW MUCH DO FIDUCIALS MOVE?

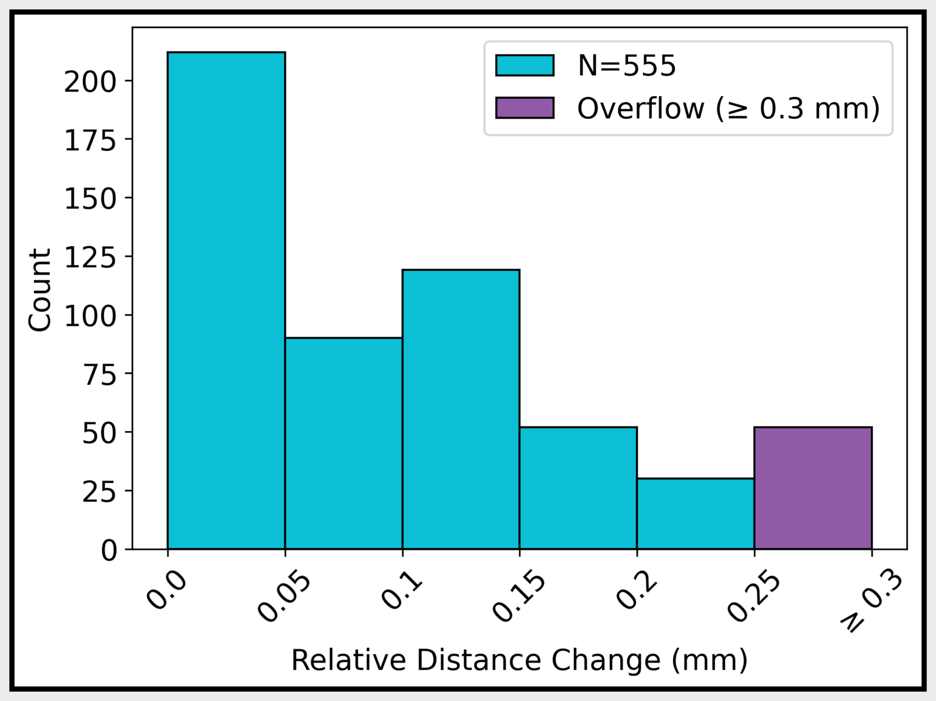

Figure 1. Histogram illustrating the changes in inter-fiducial distances relative to their measurements at CT simulation. The analysis includes a total of 555 measurements. The x-axis denotes the relative distance change in millimeters, with a bin width of 0.05 mm.

To investigate fiducial stability within the prostate, a retrospective cohort of 40 patients who underwent 5-fraction prostate SABR treatments was analyzed. Each patient had SpaceOAR gel inserted between the prostate and the rectum, along with three gold fiducial markers implanted intraprostatically.

For each fraction, a 6-DoF bony match followed by a 3-DoF prostate soft tissue match to the planning CT was completed in Eclipse. The coordinates of each fiducial were recorded in this frame of reference.

First, the drift of the fiducials from their planning coordinates in (x, y, z) was evaluated, with all three coordinates being centered around 0 mm with standard deviations of 0.1 mm, 0.2 mm, and 0.1 mm, respectively.

The relative distances between each marker were also recorded based on the CT simulation scan and compared against the calculated distances from each pre-treatment CBCT. Results showed that 9% of inter-fiducial distances varied by greater than 3 mm. This analysis revealed that the fiducials are expected to remain close to their initial positions relative to their coordinates at the time of the CT simulation.

FIDUCIALS ON THE kV IMAGER PANEL

To get a representation of how these small perturbations would affect the mid-treatment intervention rate, the coordinates of the fiducials from both the plan and online imaging were projected onto the kV imager panel via the transformation,

$$\boldsymbol{U} = FR\boldsymbol{x}_{\text{CBCT}}$$

Where $\boldsymbol{U}$ are the homogeneous coordinates on the panel, $\boldsymbol{x}_{\text{CBCT}}$ are the (x, y, z) coordinates in the frame of reference of the pre-treatment CBCT, and F, R are an imager magnification/ flex map correction and a 3D rotation matrix about the z-axis to account for the angle of the kV imager relative to the gantry rotation angle, (φ) given by

$$F = \begin{pmatrix} 1 & \frac{u_f(\varphi)}{\text{SID}} & 0 & \frac{\text{SAD}}{\text{SID}} u_f(\varphi) \\ 0 & 1 & 0 & 0 \\ 0 & \frac{v_f(\varphi)}{\text{SID}} & 1 & \frac{\text{SAD}}{\text{SID}} v_f(\varphi) \\ 0 & \frac{1}{\text{SID}} & 0 & \frac{\text{SAD}}{\text{SID}} \end{pmatrix}$$

Here, $u_f(\varphi), v_f(\varphi)$ represent the flex map corrections at an angle φ. These was computed by taking the maximum and minimum flex map corrections at an imager angle of 0° and 270° and applying a sinusoidal mapping,

$$u_f(\varphi) = (u_0 - u_{270}) \sin\varphi + u_0$$

The fiducials were then monitored to determine if they fell outside a 3 mm radius sphere centered on the simulation marker coordinates. If two or more fiducials fell outside this neighborhood, the fraction was considered to require an intervention. It was found that 11% of fractions required intervention via this method based on the 40 patient cohort.

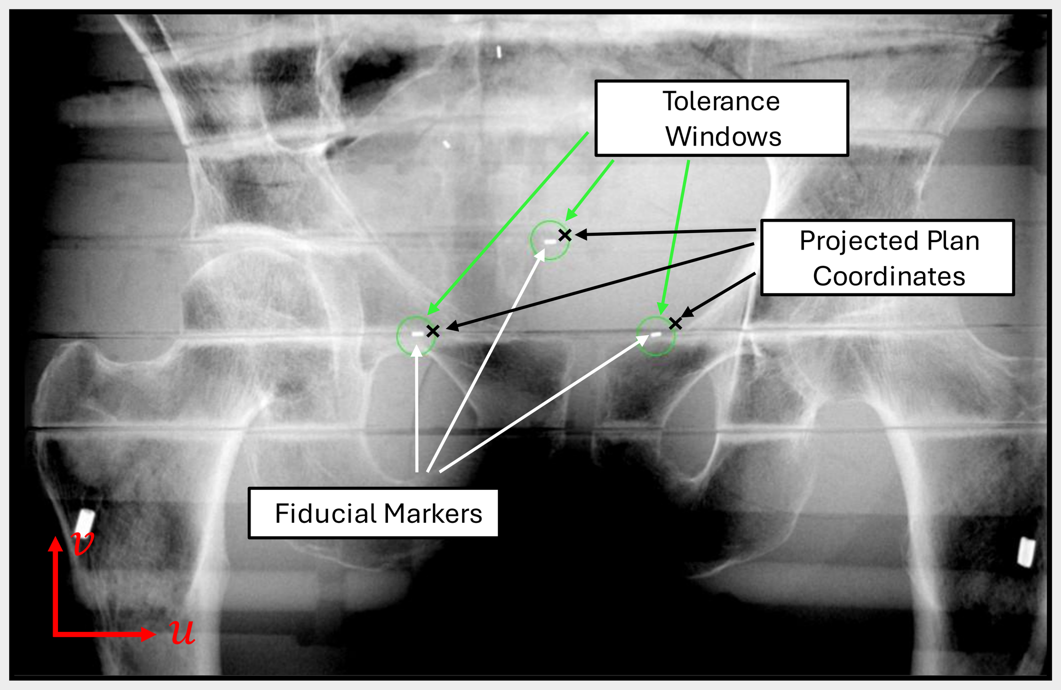

Figure 2. Example of kV imager projection with tolerance windows for a fiducial to be "out" (in green), alongside the online markers (in white) and projected plan marker coordinates (in black).

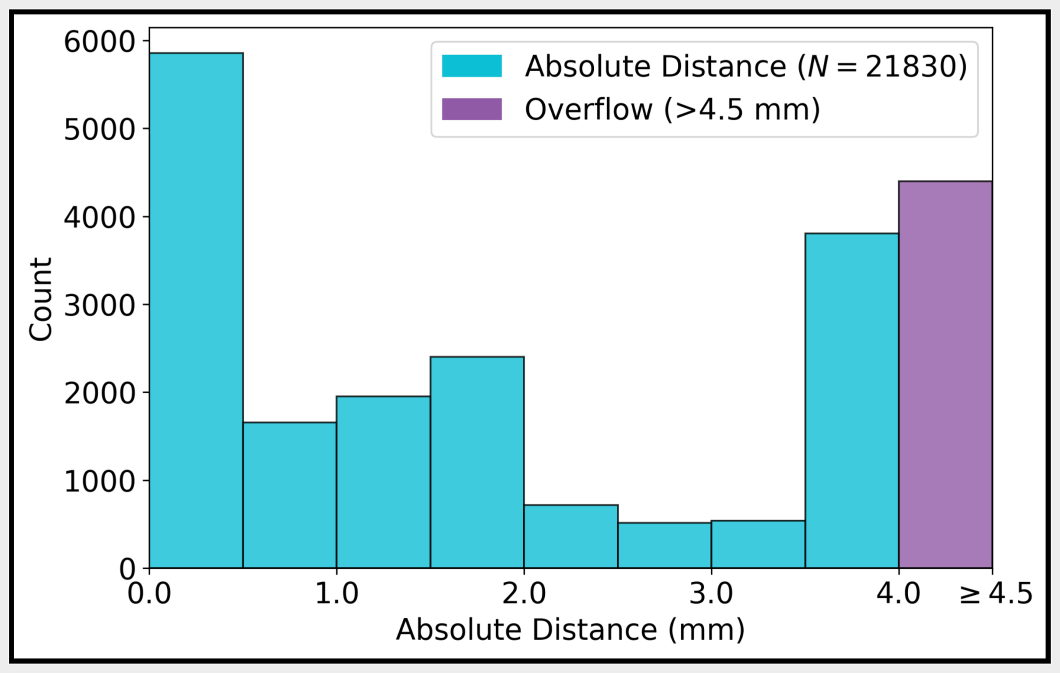

Figure 3. Distribution of distances from CT simulation coordinates to online CBCT coordinates as projected to the online kV imager panel.

ONLINE MARKER UPDATING

To help reduce intervention rates, the proposed workflow utilizes a 6-DoF bony match and a 3-DoF soft tissue match at the treatment unit. Custom software was developed to extract the center of mass for each fiducial from the pre-treatment CBCT, transform the coordinates into the planning frame, and output them for entry into the Eclipse contouring workspace.

The workflow was validated using three fiducials placed in an anthropomorphic RANDO phantom. A simulated SABR treatment was delivered using the standard triggered imaging protocol, tracking the rate at which ≥ 2 fiducials remained within a 3 mm radius of their planned locations. To test the software's accuracy, one seed was physically displaced, and the treatment was re-delivered using both the original and the newly updated marker locations. A QUASAR motion platform was used to induce sup-inf displacements during the treatment arc to determine sensitivity of the system to motion.

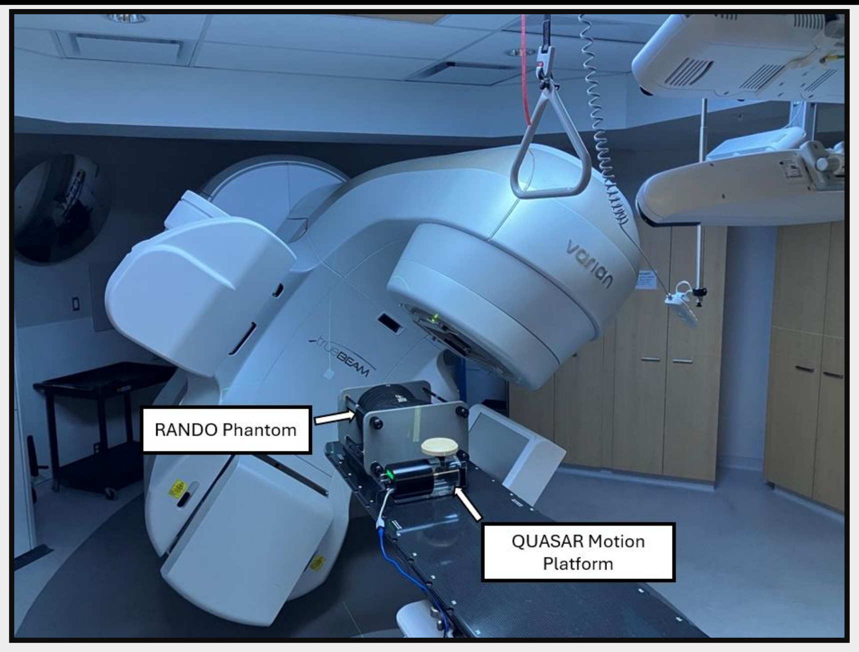

Figure 2. Setup of RANDO and QUASAR motion phantoms for the fiducial updating end-to-end test.

	Sim Location Test	4 mm Offset Test	Updated Marker Test
0 mm	100%	6%	100%
1 mm	100%	0%	100%
2 mm	47%	0%	69%

Table 1. Table of percentage of projections that achieve a "pass" for each fiducial and motion platform setup.

CONCLUSIONS

It was found that cylindrical gold seed fiducials do not travel appreciably inside the prostate, though small intraprostatic motions result in larger displacements when projected onto the kV imager panel used in triggered imaging.

In-house software was developed to track the location of the fiducials on the day of treatment and update the marker coordinates to account for these small deviations. The proposed workflow underwent end-to-end validation using a RANDO anthropomorphic phantom with three gold fiducials inserted into the pelvis.

REFERENCES

[1] Varian Medical Systems. *TrueBeam Technical Reference Guide - Volume 2: Imaging*. Palo Alto, CA: Varian Medical Systems, Inc; 2018

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