Three-Dimensional Fiducial Localization from Adjacent kV Projections: Minimum Gantry Angle Requirements

2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

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Purpose:

To investigate the feasibility of three-dimensional fiducial localization using small-angle kV image pairs from adjacent projections as a time-efficient alternative to conventional orthogonal imaging, and to determine the minimum gantry angle separation.

INTRODUCTION

During IGRT, rapid target re-verification may be required due to events such as coughing, sudden patient motion, or prolonged treatment interruptions. Although three-dimensional target position can be verified using orthogonal kV image pairs in patients with fiducial markers, such as prostate cancer, the requirement for approximately 90° separation introduces time inefficiencies. To address this limitation, we developed an in-house 3D fiducial localization system based on adjacent kV projections. In this study, we quantitatively determine the minimum gantry angle separation required for reliable 3D fiducial localization. The results establish a practical design guideline for projection-based 3D localization and provide a quantitative foundation for reducing additional imaging time and imaging dose in IGRT workflows.

METHODS AND MATERIALS

A cube phantom containing a 2mm-diameter fiducial was placed on the Breathing Phantom Gating Assembly (Varian) and imaged using CBCT on Varian TrueBeam. Projection images were extracted using TIGER toolbox. The phantom was aligned to isocenter at the minimum motion position (on-isocenter). Between gantry angles of 333.7° and 329.7°, the phantom corresponded to the maximum motion position (off-isocenter). The fiducial was automatically detected in each projection image, and 3D localization was performed using an in-house-developed projection-based 3D localization method. Ten projection points were randomly selected at the on- and off-isocenter positions. For each selected projection, a second projection separated by 1, 2, 10, 50, 100, and 200 projections was paired to calculate the three-dimensional fiducial location. Localization accuracy was evaluated by comparing the estimated fiducial position with fiducial positions identified on CBCT images. Based on this analysis, the minimum required gantry angle separation was determined.

RESULTS

From the randomly selected projection points at on-isocenter and off-isocenter positions, the mean angular separations between two selected projections, separated by 1, 2, 10, 50, 100, and 200 projections, were 0.407±0.004°, 0.814±0.004°, 4.054±0.006°, 20.275±0.012°, 40.556±0.011°, and 81.101±0.017°, respectively. For on-isocenter cases, the fiducial localization errors corresponding to separations of 1, 2, 10, 50, 100, and 200 projections were sub-millimeter: 0.33±0.29mm, 0.66±0.87mm, 0.41±0.22mm, 0.51±0.00mm, 0.55±0.09mm, and 0.10±0.22mm, respectively. For off-isocenter cases, the corresponding localization errors were 7.04±5.77mm, 4.34±3.35mm, 1.35±0.69mm, 0.98±0.22mm, 0.89±0.22mm, and 0.70±0.07mm with increasing angular separation, respectively

DISCUSSION

To evaluate the developed system, a motion phantom was set up as shown in Figure 1. CBCT was acquired, and the minimum and maximum positions of the fiducial marker were recorded. To obtain continuous 2D projections, the CBCT projection files were extracted using the TIGER toolkit [1][2]. The extracted images were analyzed together with their corresponding projection angles, and the fiducial marker was detected. The fiducial was automatically detected on each projection image using intensity-based segmentation (Figure 2), and back-projection reconstruction was performed based on the imaging geometry (Figure 3). The three-dimensional fiducial location was estimated from the intersection of two back-projected lines obtained from adjacent projections (Figure 3), and localization errors of the estimated 3D positions were calculated (Figure 4).

CONCLUSIONS

For on-isocenter positions, localization errors were within 1mm for all projection separations. For off-isocenter positions, localization error decreases with increasing separation angle, and angular separations of less than 4.054±0.006° resulted in localization errors greater than 2mm.

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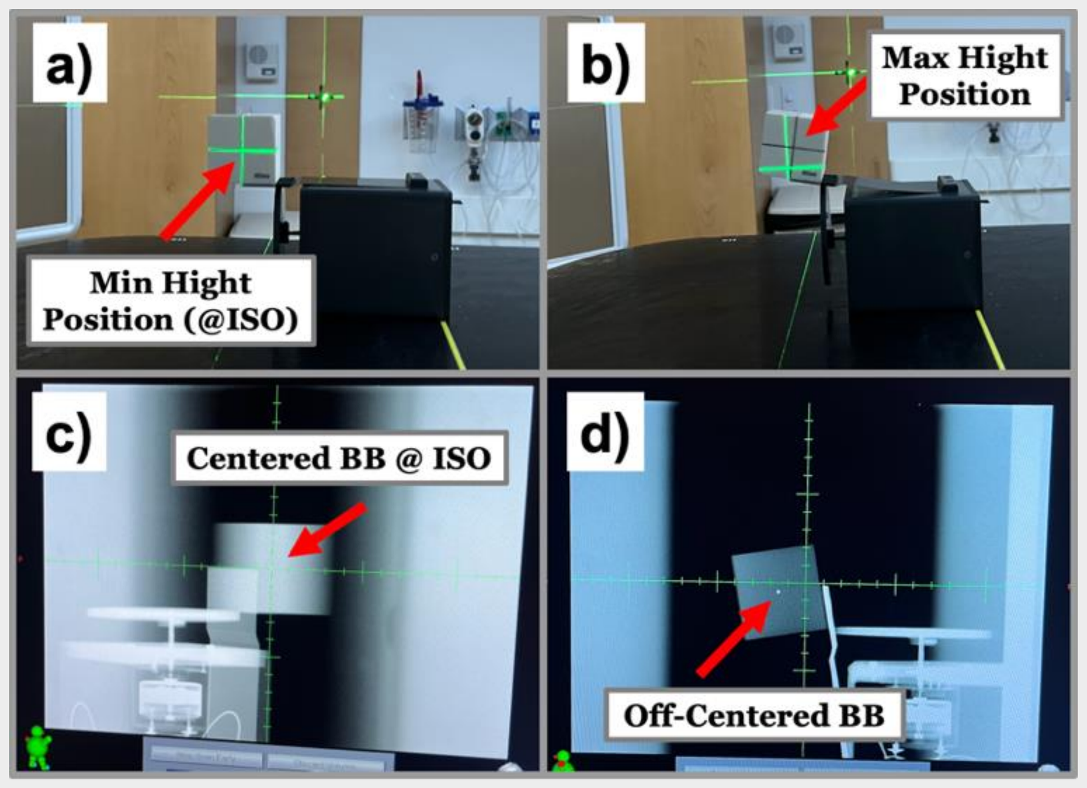

Figure 1. 2mm fiducial cube mounted on a motion phantom. (a, c) The fiducial cube is aligned to isocenter at the minimum motion position. (b, d) The fiducial cube is positioned at the maximum motion position.

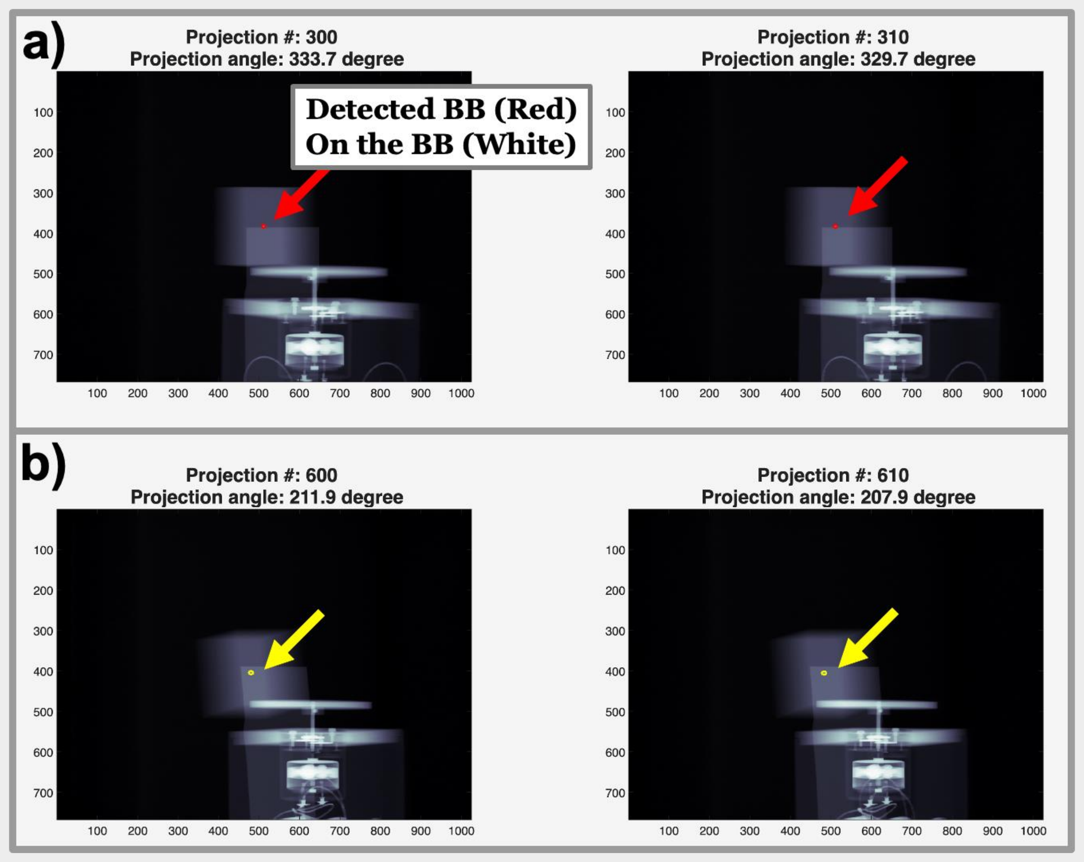

Figure 2. Example of automatically detected fiducial markers on kV projection images.

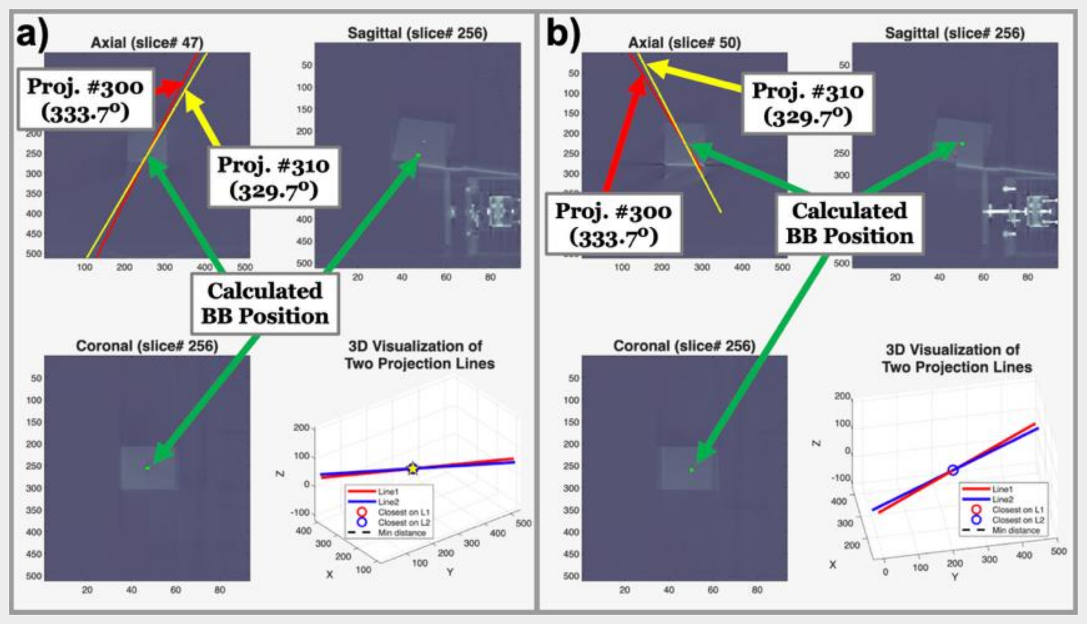

Figure 3. Calculated fiducial marker position (green dot) displayed on the CBCT image with two adjacent projections represented by back-projected lines (red and yellow).

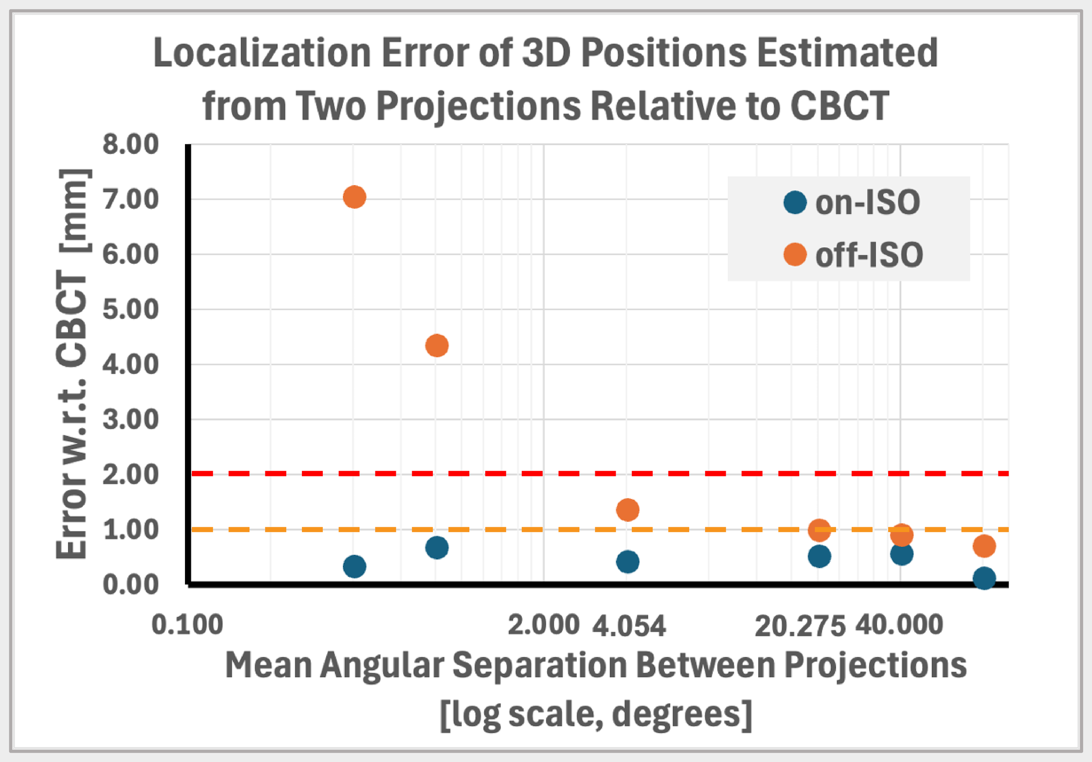

Figure 4. Calculated localization error between the estimated three-dimensional fiducial positions and CBCT-based reference positions. An angular separation of 4.054° resulted in localization errors < 2 mm, and an angular separation of 20.275° resulted in localization errors < 1 mm.

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