Post-Treatment Target Motion Analysis Using Offset-Dependent Three-Dimensional Reconstruction of on-Treatment kV Images

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PURPOSE

This study introduces a metric-driven framework for offset-dependent three-dimensional motion evaluation that utilize the reconstructed on-treatment kV images.

INTRODUCTION

In diagnostic imaging, blind detector offset calibration is often used to estimate detector rotation and tilt by optimizing detector offset parameters based on image quality.

Inspired by this concept, the proposed method estimates patient motion by searching for the motion parameters that maximize reconstruction quality.

The proposed method localizes the three-dimensional target motion through iterative optimization of voxel origin of the reconstructed volume.

By employing MS-SSIM and RMSE as objective functions, the framework provides a hardware-free solution for identifying patient motion components.

This approach offers a practical tool for post-treatment motion analysis and treatment quality assurance within image-guided radiotherapy workflows.

CONCLUSIONS

This study demonstrates that metric-driven, the offset-dependent three-dimensional reconstruction of the on-treatment kV images enables reliable estimation of intrafraction target motion for post-treatment, including the out-of-plane displacement, without requiring the additional imaging hardware.

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METHODS AND MATERIALS

Forty on-treatment kV projection images of a prostate phantom were acquired using a Varian TrueBeam system, with intrafraction motion simulated in the sixteen projections using two-dimensional and three-dimensional translational shifts (10 mm in each coordinate).

Target motion was estimated using an iterative offset-dependent three-dimensional reconstruction framework in which the reconstruction origin was optimized.

Three-dimensional volumes were reconstructed with systematic offset updates of 1 mm and subsequently 0.1 mm along the x, y, and z axes, and RMSE and MS-SSIM were used as objective functions to localize the target displacement in a post-treatment analysis.

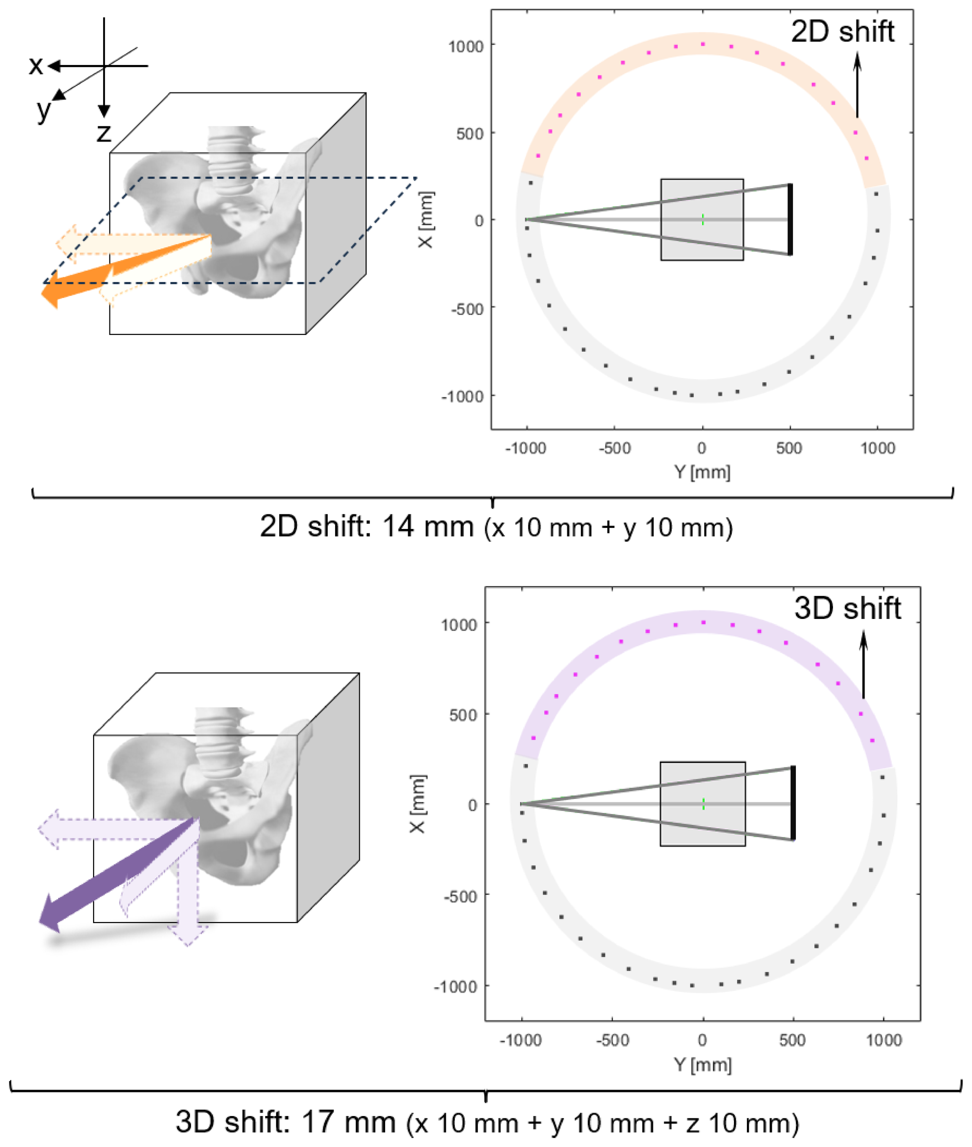
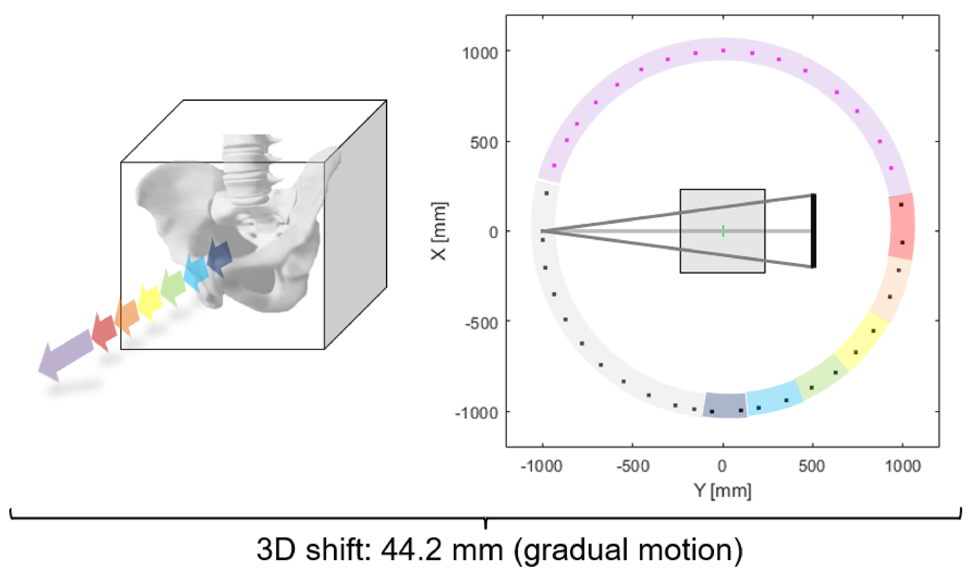


Figure 1. Schematic illustration of the simulated target shift scenarios in the on-treatment kV imaging geometry using a prostate phantom on a Varian TrueBeam system. Two-dimensional(left) and three-dimensional(right) target shifts were simulated by applying 10 mm displacements along each coordinate axis. The kV image acquisition consisted of forty projection views, among which 16 projections were assumed to be affected by the target shift.

DISCUSSIONS

The motion scenario described above represents an abrupt displacement. In contrast, target motion may also change gradually over time. Therefore, the right panel of Fig. 5 illustrates a simulated gradual-motion scenario with the progressively varying target displacements.



RESULTS

The proposed metric-driven, offset-dependent three-dimensional motion evaluation framework successfully localized intrafraction target motion in a post-treatment setting.

For two-dimensional shifts, no-shift and shifted projections were clearly separated, with no-shift projections yielding higher MS-SSIM values on the order of 0.3–0.35 and lower RMSE values on the order of 10^15.

In the three-dimensional shift scenario, no-shift projections exhibited the highest MS-SSIM, whereas projections affected by out-of-plane motion showed reduced MS-SSIM (approximately 0.15–0.25) and increased RMSE (approximately 3.0"-" 3.8×10^15).

In both metrics, motion-related responses were well separated from background levels, enabling reliable discrimination between no-shift and intrafraction motion states.

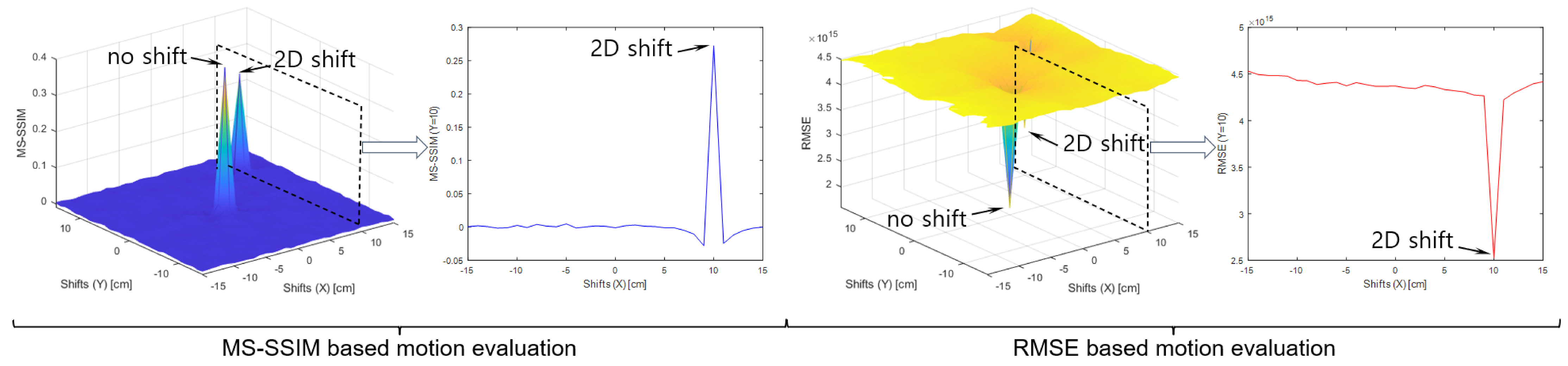


Figure 2. Quantitative assessment of target motion using reconstructed kV imaging volumes for the two-dimensional shift scenario. Among the 40 projection views, the 24 no-shift projections achieved the highest MS-SSIM and lowest RMSE, while the 16 projections affected by 2D shifts exhibited the second highest and lowest MS-SSIM and RMSE.

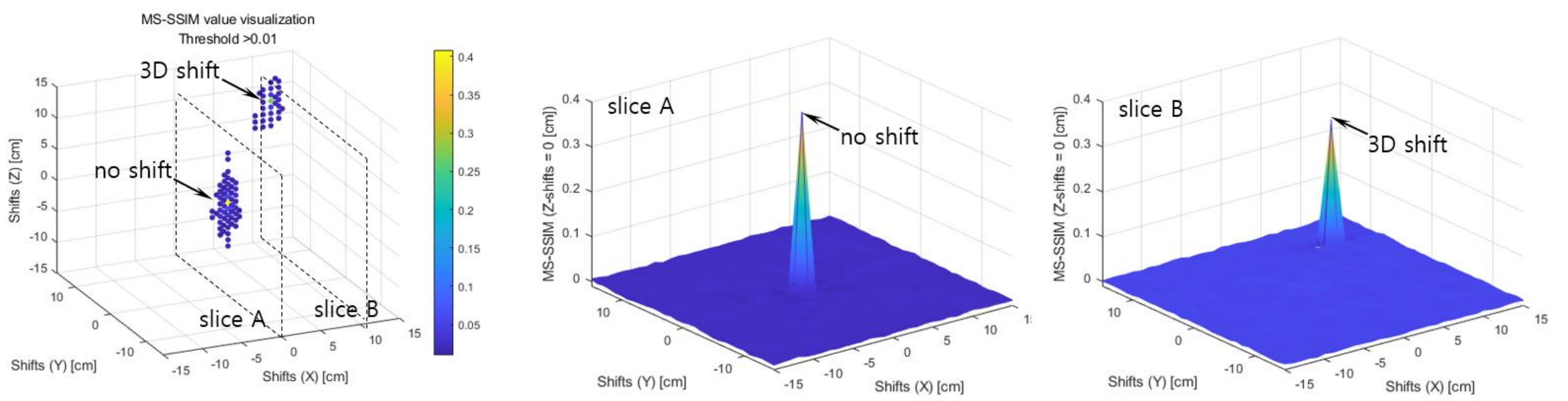


Figure 3. Quantitative assessment of target motion using reconstructed kV imaging volumes for the three-dimensional shift scenario. The left panel shows the distribution of MS-SSIM values across projection shifts, where only values exceeding a threshold of 0.01 are displayed, and clusters corresponding to no-shift and 3D-shift cases are indicated. slices A and B denote the locations used for cross-sectional visualization. The middle and right panels present MS-SSIM surfaces at Z-shift = 0 cm for slice A (no shift) and slice B (3D shift), respectively.

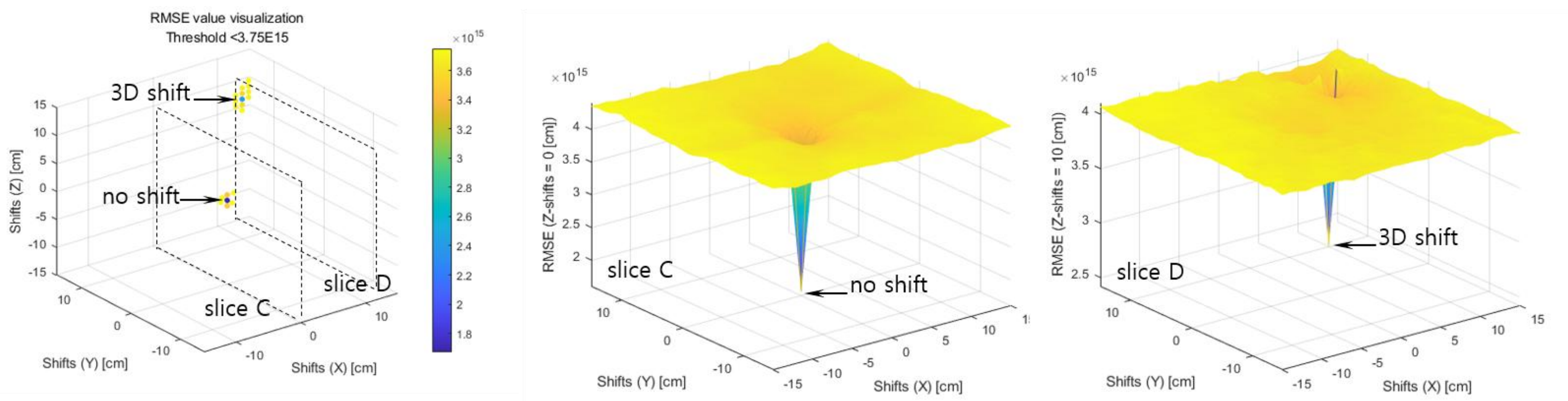


Figure 4. Quantitative assessment of target motion using reconstructed kV imaging volumes for the three-dimensional shift scenario. The left panel shows the distribution of RMSE values across projection shifts, where only values exceeding a threshold of 0.01 are displayed, and clusters corresponding to no-shift and 3D-shift cases are indicated. slices A and B denote the locations used for cross-sectional visualization. The middle and right panels present RMSE surfaces at Z-shift = 0 cm for slice A (no shift) and slice B (3D shift), respectively.

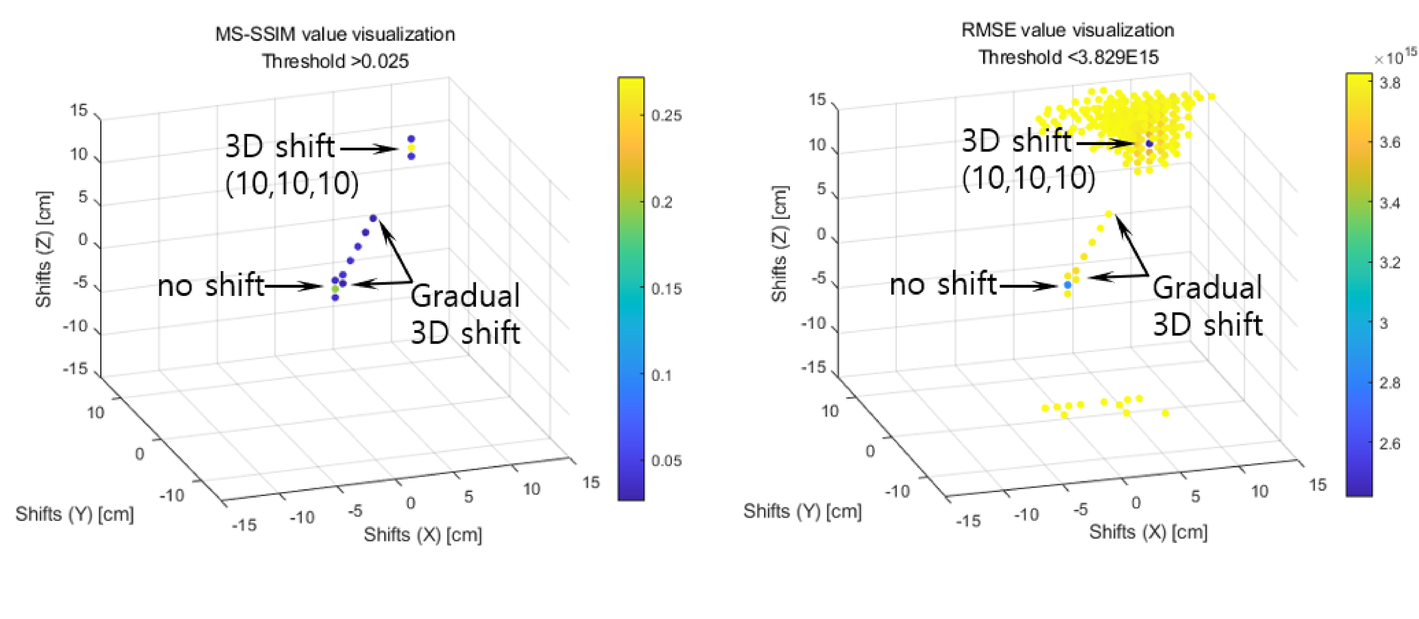


Figure 5. Schematic illustration of the simulated target shift scenarios in the same on-treatment kV imaging geometry shown in Fig. 1. Three-dimensional target motion was applied along the diagonal (1,1,1) direction. For the abrupt-motion scenario, the lowest RMSE and highest MS-SSIM values were observed when 16 projections were acquired at a displacement of (10,10,10) mm and 11 projections were acquired without motion. For the gradual-motion scenario, two projections were assigned to each displacement level of (5,5,5), (4,4,4), (3,3,3), (2,2,2), (1,1,1), and (0.5,0.5,0.5) mm. The results demonstrated that the proposed method was able to track continuous positional changes even when only two projections were available at each displacement level.