Validation of an AI-Empowered Markerless Lung Tumor Tracking Method Using a Dynamic Chest Motion Phantom

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ABSTRACT

Purpose:
Markerless lung tumor tracking has the potential to reduce target margins and improve organ-at-risk (OAR) sparing during radiotherapy. We previously proposed a deep learning–based target decomposition approach for real-time markerless lung tumor tracking. This study aims to quantitatively validate the tracking accuracy of the proposed method using a dynamic chest phantom under multiple respiratory motion patterns.

Methods:
An AZ-M2 chest motion phantom, consisting of a mobile lung tumor and pulmonary vessels embedded within a static thorax (heart, spine, and ribs), was used to simulate respiratory motion. During CT simulation, free-breathing and 4DCT scans were acquired with the tumor moving longitudinally according to a sinusoidal waveform. A patient-specific deep learning model was trained using digitally reconstructed radiography (DRR) and decomposed target image (DTI) pairs to transform raw kV projection images into synthetic DTIs with enhanced tumor contrast. During treatment delivery, the phantom tumor was programmed to follow: (1) a standard sinusoidal motion profile, and (2) three free-breathing (FB) and three deep inspiration breath-hold (DIBH) waveforms acquired from real patients using an RPM system. Tumor motion was tracked on the synthetic DTIs using template matching, and the resulting trajectories were quantitatively compared with the phantom's programmed ground-truth motion.

Results:
The proposed framework achieved maximum tracking errors of 1.2 mm (with Mean Absolute Errors 0.2±0.2 mm) for sinusoidal motion, 1.3 mm (0.3±0.3 mm) for the three FB waveforms, and 1.0 mm(0.3±0.2mm) for the DIBH waveforms. The end-to-end system latency was less than 100 ms, supporting feasibility for real-time tumor tracking in a clinical setting.

Conclusion:
Validation using the AZ-M2 chest motion phantom demonstrates that the proposed target-decomposition-based tracking framework achieves clinically acceptable accuracy across a range of realistic respiratory motion patterns, supporting its potential for real-time markerless lung tumor tracking during radiotherapy.

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INTRODUCTION

❖ **Background**
- Lung RT demands millimeter precision, yet respiratory motion constantly shifts the tumor during delivery
- Low soft-tissue contrast makes the tumor hard to localize on kV images
- External surrogates fail with irregular breathing; implanted fiducials are invasive
- Markerless tracking is non-invasive but needs a rigorous validation before clinical use

❖ **Purpose**
- Markerless tracking can reduce target margins and improve organ-at-risk (OAR) sparing
- Builds on a previously proposed deep learning–based target-decomposition approach for real-time tracking
- This study quantitatively validates tracking accuracy using a dynamic chest phantom under multiple respiratory motion patterns

Figure 1. AZ-M2 dynamic chest motion phantom with independently moving tumor and vessel inserts.

INNOVATIONS

- Independent motion simulation: AZ-M2 phantom moves the tumor rod, pulmonary vessels, and external surface independently — simulating relative motion between the tumor and thoracic/bony anatomy (Fig.1)
- Comprehensive motion testing: validation spans standard sinusoidal motion, irregular patient-specific free-breathing (FB) traces, and DIBH residual-drift patterns

Figure 2. Phantom set up on (a) the Philips Big Bore CT couch for 4DCT (BBs for room laser alignment) and (b) the Varian TrueBeam couch.

METHODS AND MATERIALS

❖ **CT Simulation & Model training**
- FB and 4DCT scans with sinusoidal tumor motion
- DRR-(Decomposed target Image (DTI) pairs → synthetic DTIs with enhanced tumor contrast for localization
- Augmented: Multiple spatial offsets

❖ **Tracking Workflow**
- kV -> DTI (suppress bone, enhance tumor) -> Template matching

❖ Validation
- Sinusoidal + 3FB + 3 DIBH patient waveforms.
- Tracked vs programmed ground truth.

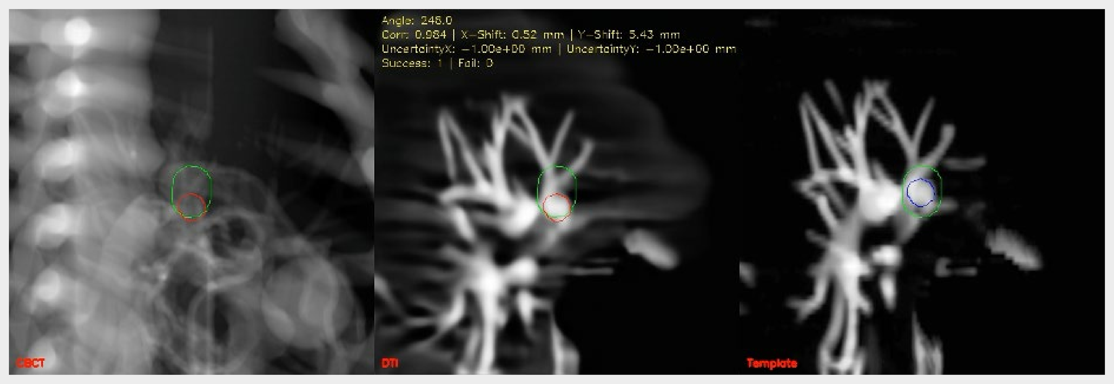
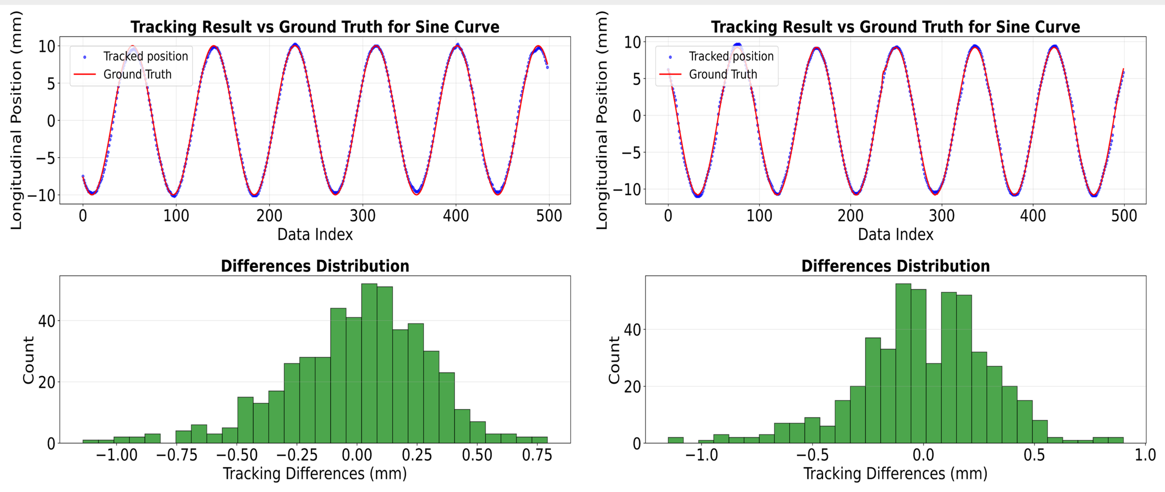


Figure 3. From left to right: CBCT, real-time generated DTI, and the template generated from planning CT. Green circle is PTV and red circle is GTV

RESULTS

❖ **MAE:** 0.3 $\pm$0.2 mm across all motions and tumors
❖ **Accuracy:** >99% frames within 1 mm of ground truth
❖ **End to end latency:** <100 ms



(a) 30 mm Right Tumor
(b) 10 mm Left Tumor

Figure 4: Tracking performance for sinusoidal motion (10 mm amplitude). Each subplot displays the longitudinal tracked position (blue dots) against the ground truth (red line), with corresponding error histograms shown below. (a) Right lung target; (b) Left lung target

Pattern	MAE $\pm$ SD (mm)	Max (mm)	< 1 mm (%)
Sinusoidal	0.2$\pm$0.2	1.2	99.6
FB	0.3 $\pm$0.3	1.3	99.1
DIBH	0.3 $\pm$0.2	1.0	99.8
Overall	0.3 $\pm$0.2	1.3	99.4

Table 1. Tracking accuracy across motion patterns and tumor sizes.

DISCUSSION

- Real-time DTIs suppress bone and enhance tumor contrast
- Meets clinical tolerances in a setting more complex than the MATCH challenge
- Smaller 10 mm tumor near vessels/heart is harder, yet still ~99% within 1 mm
- Handling realistic internal motion supports clinical translation

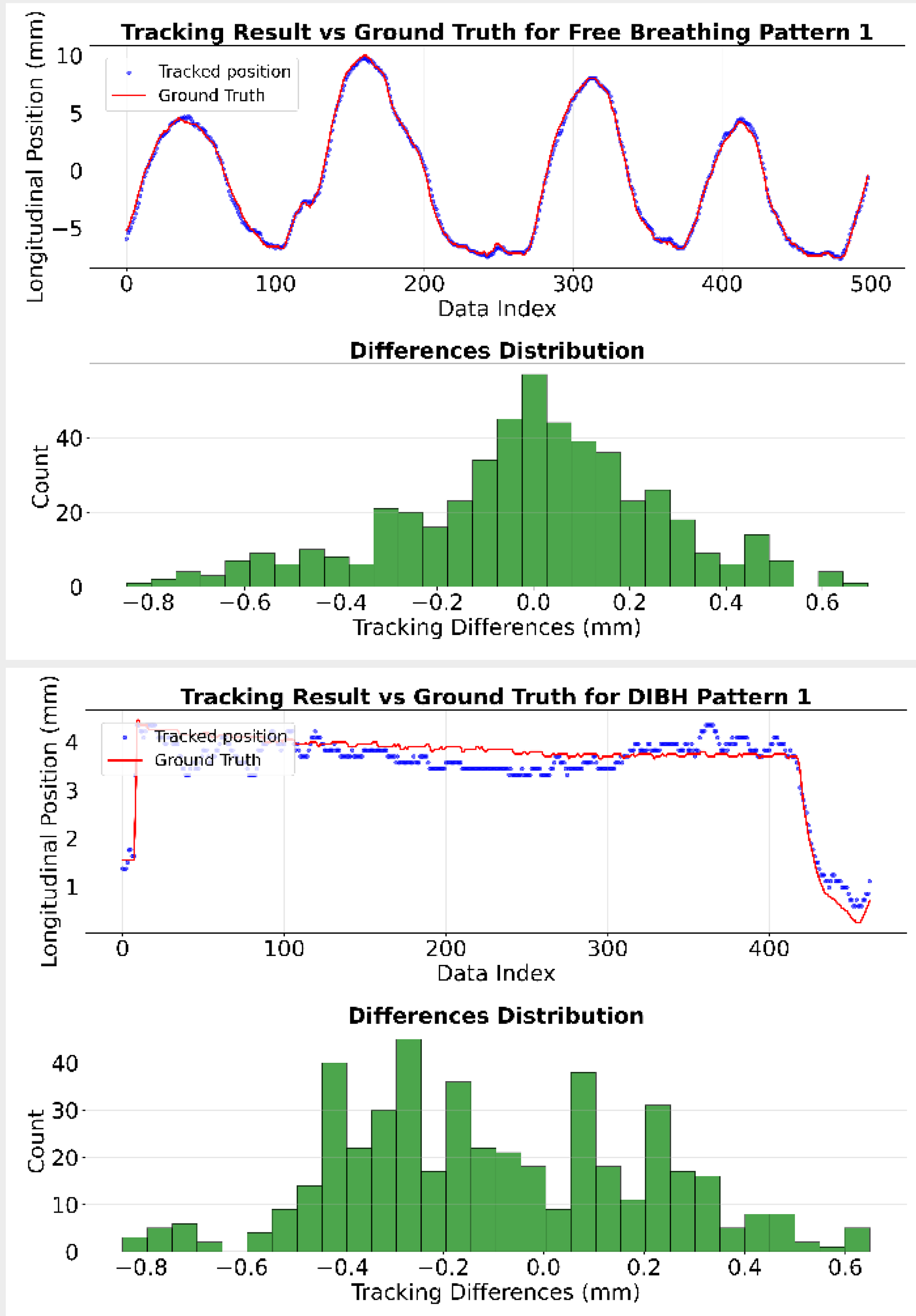


Figure 5: Tracking performance for one FB motion and one DIBH motion. Respiratory traces were exported from real-patient RPM data

CONCLUSIONS

- Validation using the AZ-M2 chest motion phantom demonstrates that the proposed target-decomposition-based tracking framework achieves clinically acceptable accuracy across a range of realistic respiratory motion patterns
- Supports its potential for real-time markerless lung tumor tracking during radiotherapy
- Provides a critical quality assurance foundation necessary for clinical translation

REFERENCES

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