AI-Powered Precision: Real-Time Markerless Tracking in X-Ray Imaging

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Memorial Sloan Kettering
Cancer Center

Conflict of interest

- None

Markerless lung tumor tracking

- X-ray based
  - ❑ CyberKnife
  - ❑ Radixact Tomotherapy
  - ❑ RapidTrac (Varian, not FDA approved)

CyberKnife

- MRI-LINAC
  - ❑ Real-time 2D MR image in CINE mode (5 frames/sec)
  - ❑ Superior soft tissue contrast
  - ❑ Automatic gating system with soft tissue tracking
  - ❑ Template-matching with Cross-correlation

Elekta Unity MR-LINAC with 1.5T MR scanner

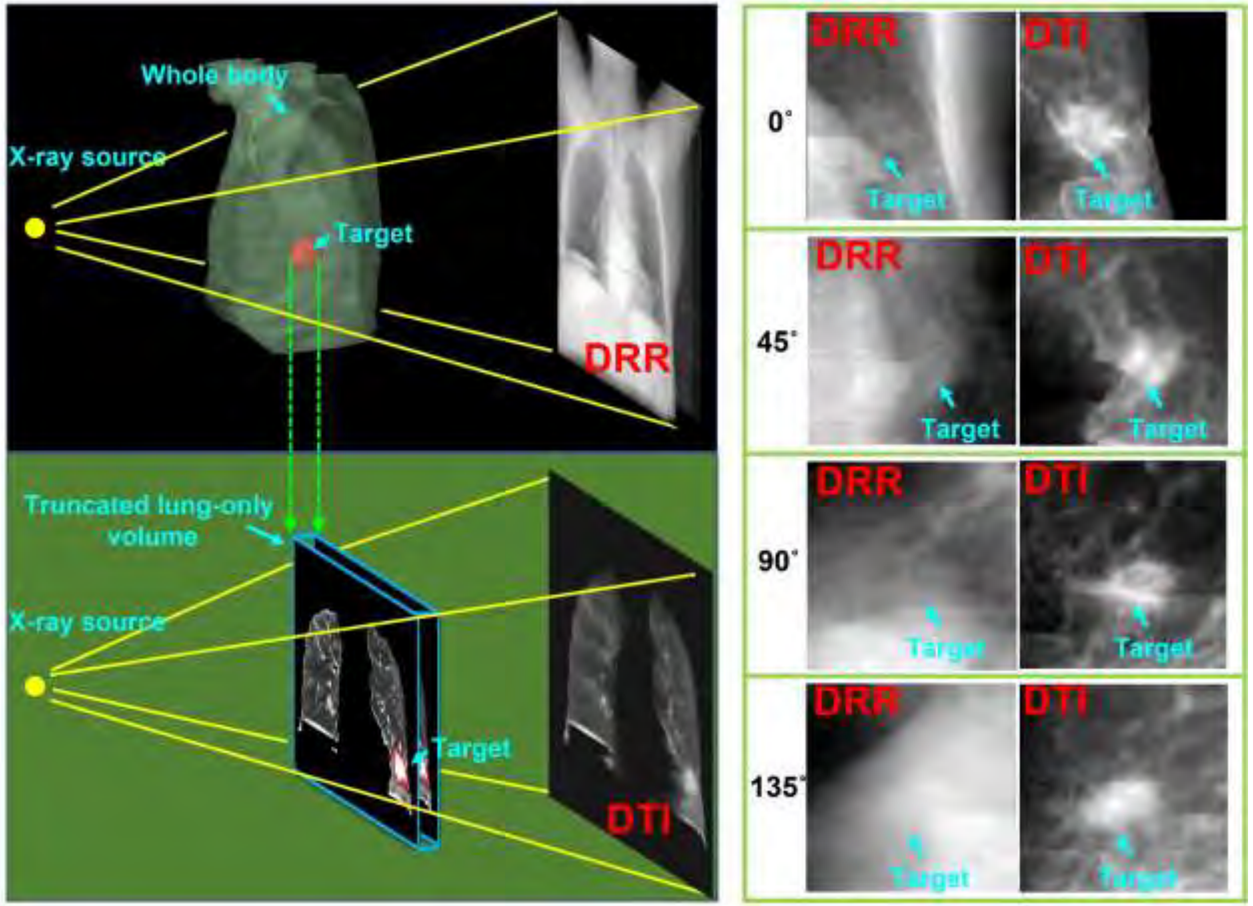
Challenges of x-ray based markerless tumor tracking

- Poor X-ray image quality
  - ❑ Low tumor contrast
  - ❑ Scatter, beam hardening and noise
  - ❑ Superimposition of multiple structures

Can we provide high-quality x-ray imaging to facilitate
more accurate markerless lung tumor tracking on conventional LINAC platform?

AI-based target decomposition technique in on-board KV imaging

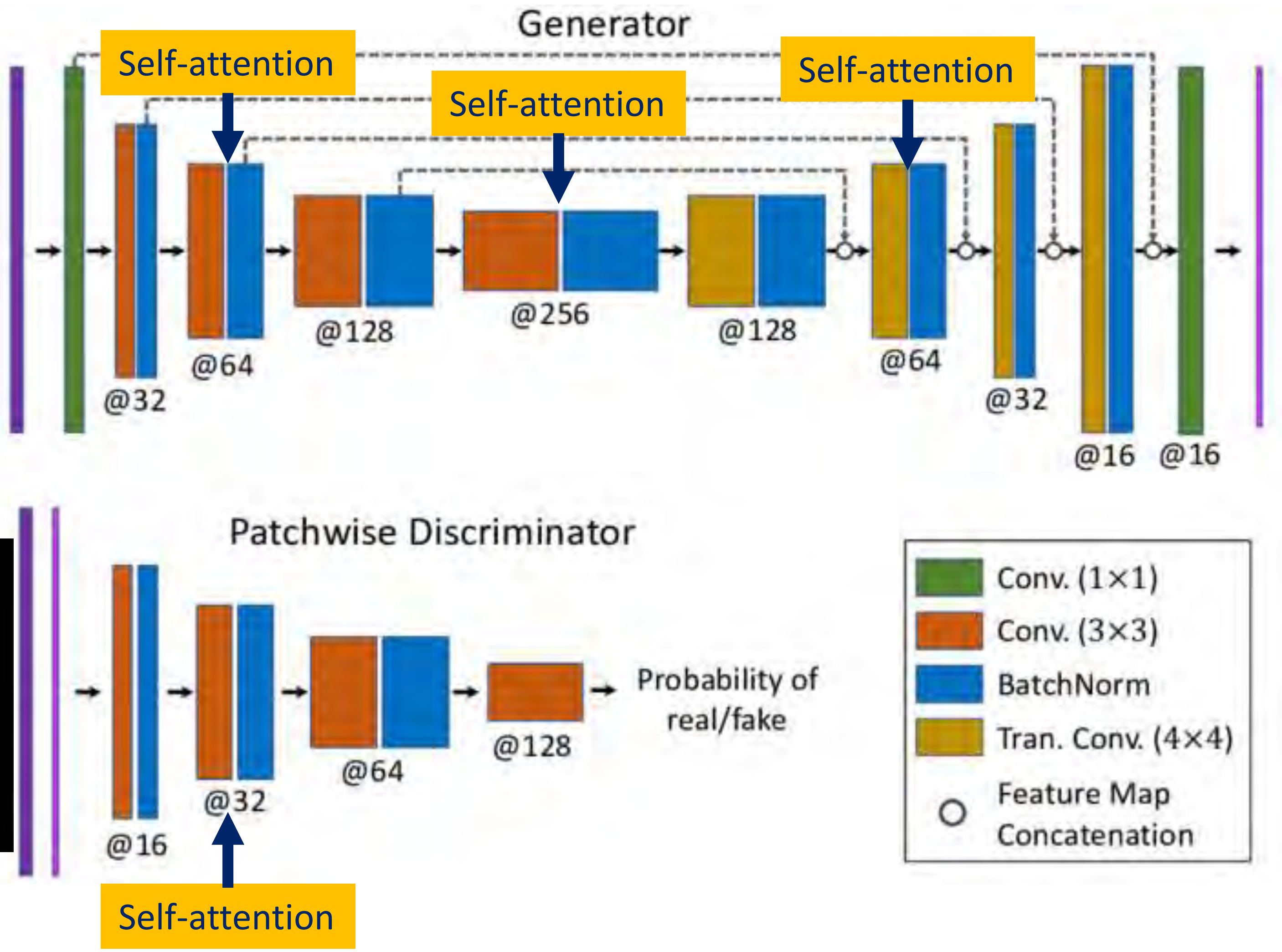
- Decomposed target image (DTI)



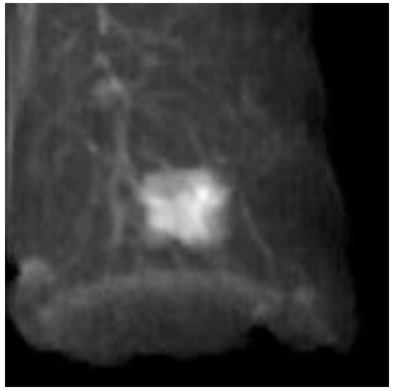
Fu Y, et al, "Enhancing the target visibility with synthetic target specific digitally reconstructed radiograph for intrafraction motion monitoring: A proof-of-concept study. Med. Phys. 2023 50(12):7791-7805

Image Translation using cGAN with self-attention

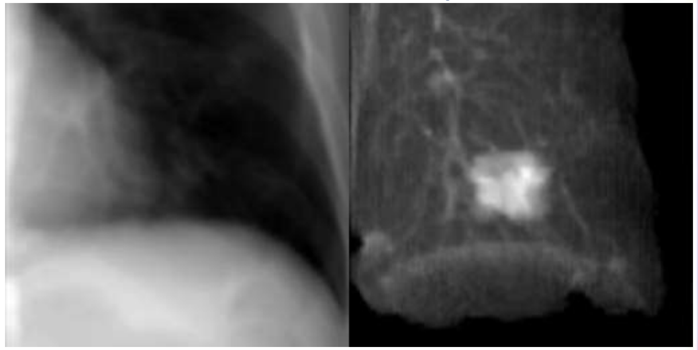
DRR



Target Template



DRR and DTI pair

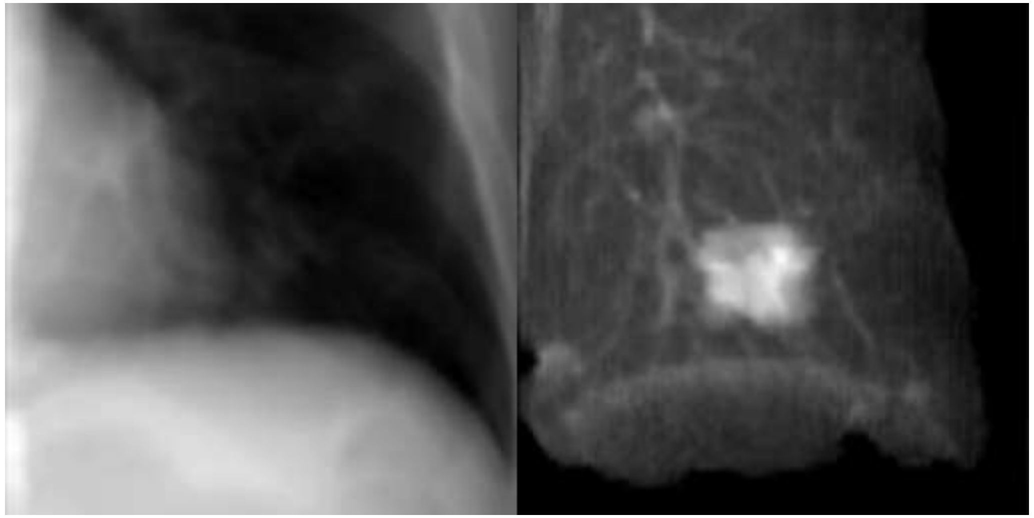


Patient-specific model

- Training image generation
  - ❑ 4DCT, Free-breathing CT, DIBH CT
  - ❑ DRR & DTI pair across 360-degree
  - ❑ Augmentation by CT image translation
  - ❑ # of images: 5000-20,000

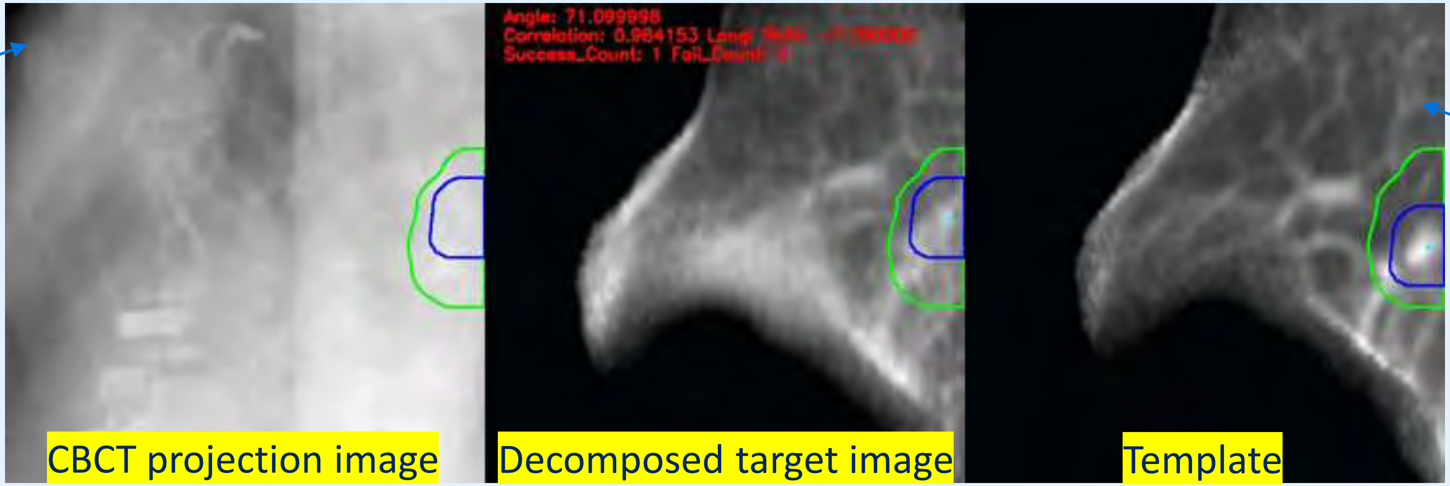
- Model parameters
  - ❑ Generator: 55 M, Discriminator: 3 M
  - ❑ Speed: 6-12 hours for 200 epochs

Training DRR and DTI pair



Tumor tracking using template matching

Free breathing patient: Half-Fan CBCT projection images



DIBH patient: Full-Fan CBCT projection images

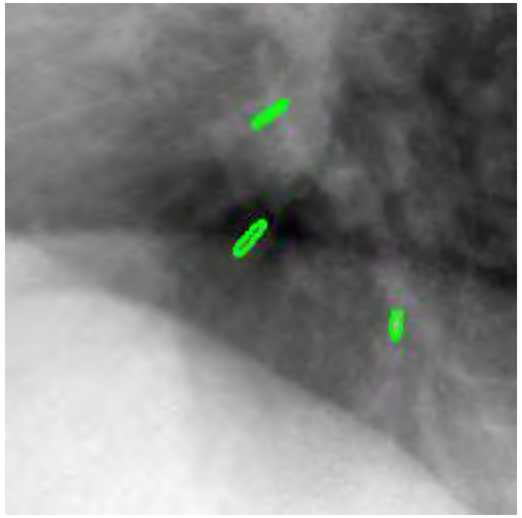
Tumor tracking validation

- MSK 14-225 clinical protocol
- Tumor motion ground truth: beacon transponder trajectories in 2D

Table 1. Tumor characteristics for the nine patients.

Subject	GTV Vol(cm^3)	Equiv. Sphere Diam.(mm) of GTV	DTW(mm)	DTB(mm)	Max SI beacon motion (mm)
Pt 1	1.4	14	30	12	9.1
Pt 2	2.4	17	23	15	4.5
Pt 3	5.2	22	50	28	6.4
Pt 4	0.3	8	53	24	7.4
Pt 5	15.6	31	46	25	20.4
Pt 6	107.7	59	33	30	14.6
Pt 7	9.4	26	20	22	6.2
Pt 8	4.8	21	45	13	11.4
Pt 9	6.58	23	24	17	19.0

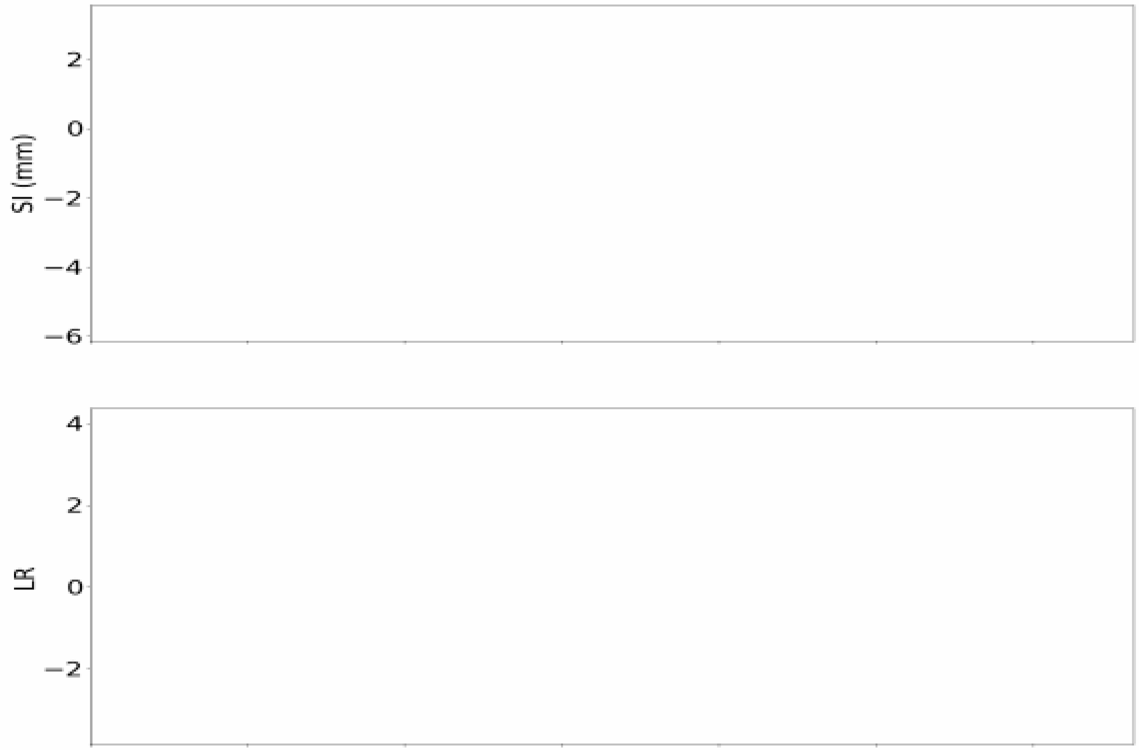
Note: GTV is the gross tumor volume, delineated on the planning CT. DTW is the distance between the tumor and the thorax wall. DTB is the distance between the tumor and the nearest implanted beacon transponder.



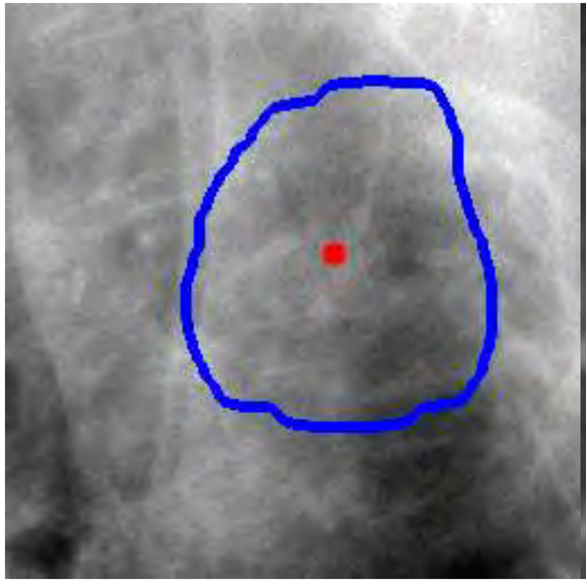
MSK-14-225 clinical protocol:
Investigation of Respiratory Motion-Corrected Cone-Beam CT and Intratreatment Gating Based on Electromagnetic Transponders to Reduce Target Position Uncertainty in Radiation Treatment of Lung Malignancies

Tumor tracking validation

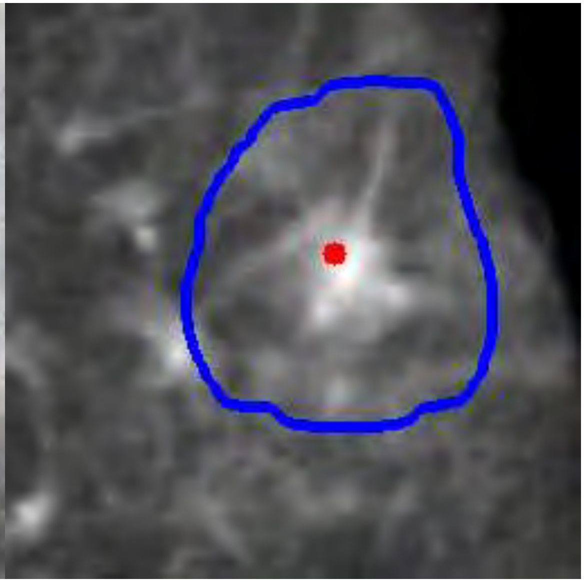
- Beacon trajectory in red curve
- Our tracking trajectory is in blue curve



CBCT projection image



Target Decomposed Image



Tumor tracking validation

- Beacon trajectory in red curve
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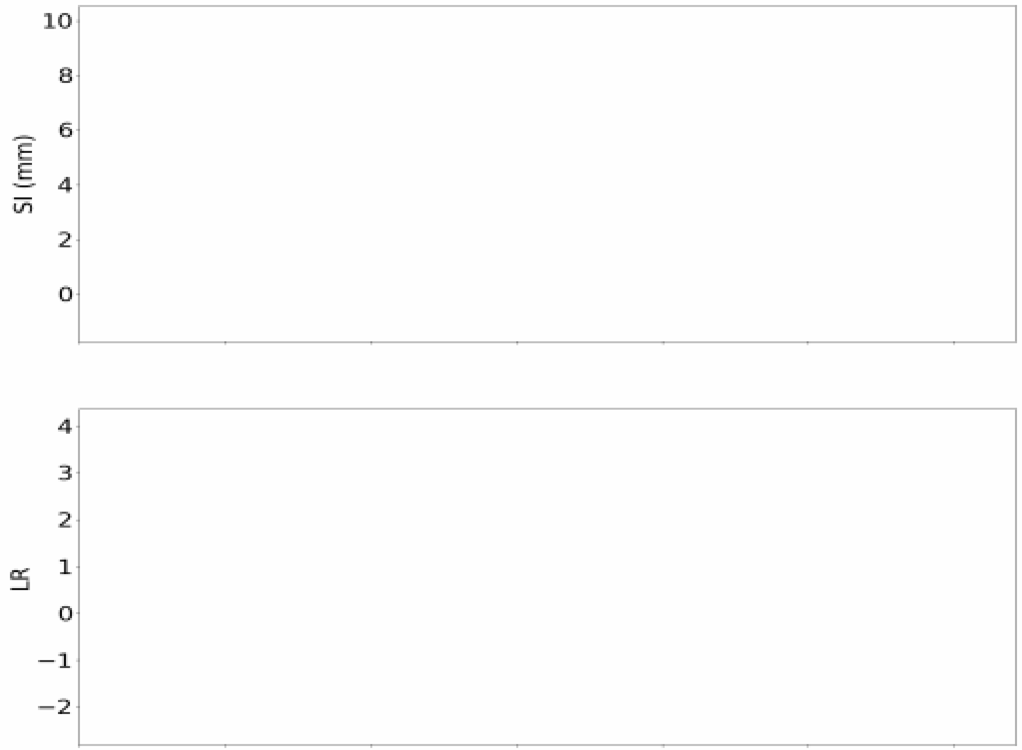
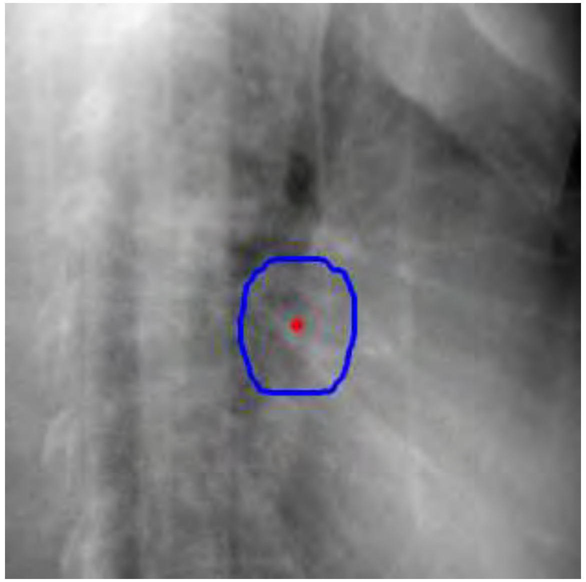
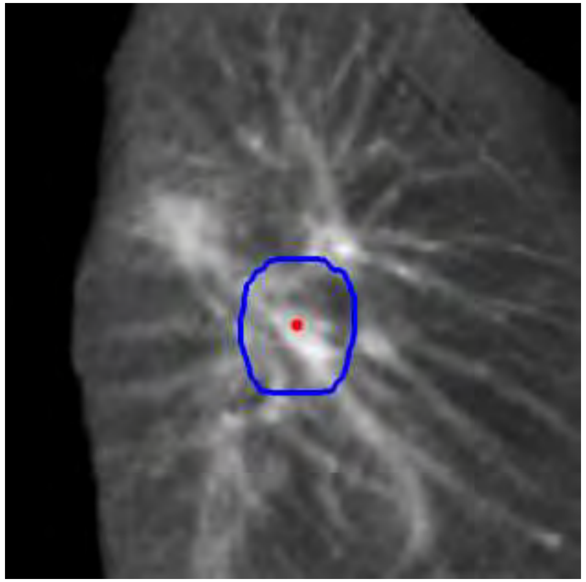


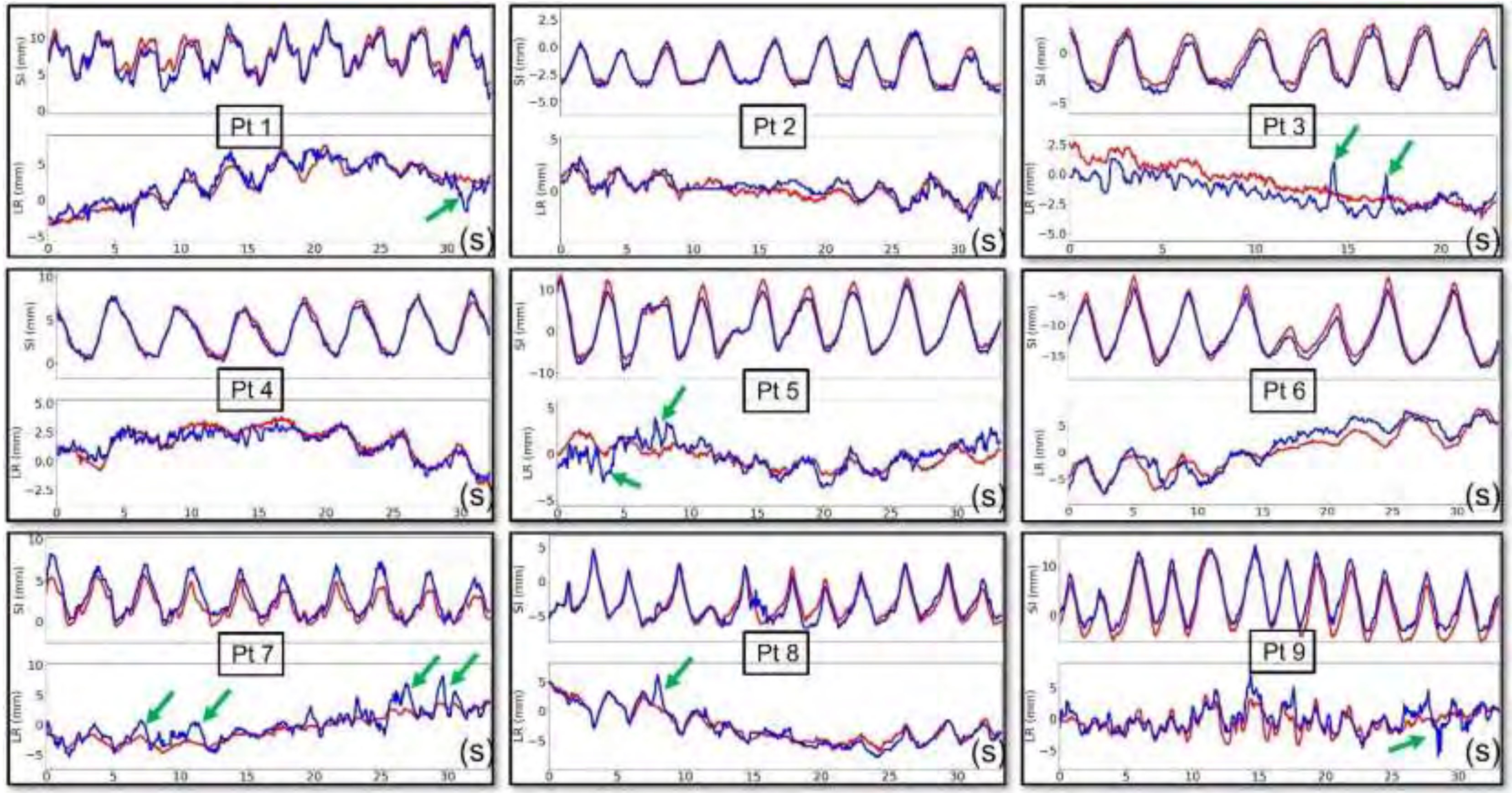
CBCT Projection Image



Target Decomposed Image



Tumor tracking verification using Calypso beacon transponder trajectories



2D tumor trajectories of the beacon transponders (red) and the template matching results (blue) for the nine patients. Green arrows highlight the discrepancies between the red and the blue trajectories.

Tumor tracking results comparison

Proposed

(template matching on DTI)

Table 2. Absolute mean error (AME) in mm using the proposed method, 90 percentile in mm, trajectory correlation coefficients in the SI and IPLR directions, and successful tracking rate for the 9 patients. Compared to Table 3, better results are shown in bold.

Subject	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Avg
AME (SI)	**0.7±0.6**	**0.3±0.2**	**0.7±0.3**	**0.3±0.3**	**1.0±0.8**	**0.9±0.6**	**1.1±0.7**	**0.8±0.6**	**1.7±0.9**	**0.8±0.7**
AME (IPLR)	**0.8±0.8**	**0.5±0.4**	1.0±0.6	**0.4±0.3**	**0.9±0.8**	**1.5±1.0**	**1.1±0.9**	0.7±0.6	**1.1±1.0**	**0.9±0.8**
90 Perc. (SI)	**1.6**	**0.5**	**1.1**	**0.6**	**2.1**	**1.6**	**1.9**	**1.5**	**2.8**	**1.5**
90 Perc. (IPLR)	**1.7**	**1.0**	1.8	**0.9**	**2.2**	**2.7**	**2.3**	**1.3**	**2.3**	**1.8**
Traj. Corr (SI)	**0.93**	**0.98**	**0.99**	**0.98**	**0.99**	**0.99**	**0.95**	**0.92**	**0.98**	**0.97±0.03**
Traj. Corr (IPLR)	**0.92**	**0.79**	0.84	**0.93**	**0.60**	**0.93**	**0.89**	**0.96**	**0.69**	**0.84±0.11**
TR (SI < 5mm)	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**99.8%**	**100.0%**
TR (SI<2mm)	**94.6%**	**100.0%**	**100.0%**	**100.0%**	**87.4%**	**96.6%**	**90.5%**	**96.2%**	**64.1%**	**92.2%**
TR (IPLR<2mm)	**93.0%**	**100%**	92.8%	**100%**	88.2%	**70.9%**	**86.9%**	97.8%	**84.9%**	**90.5%**
TR(SI&IPLR<2mm)	**87.8%**	**100%**	92.8%	**100.0%**	**78.8%**	**69.1%**	**81.5%**	**94.0%**	**57.1%**	**84.6%**

Note: 90 Perc. is the 90 percentile. Traj. Corr is the trajectory correlation coefficient. TR is the successful tracking rate.

Comparison method

(Template matching on band-pass filtered images)

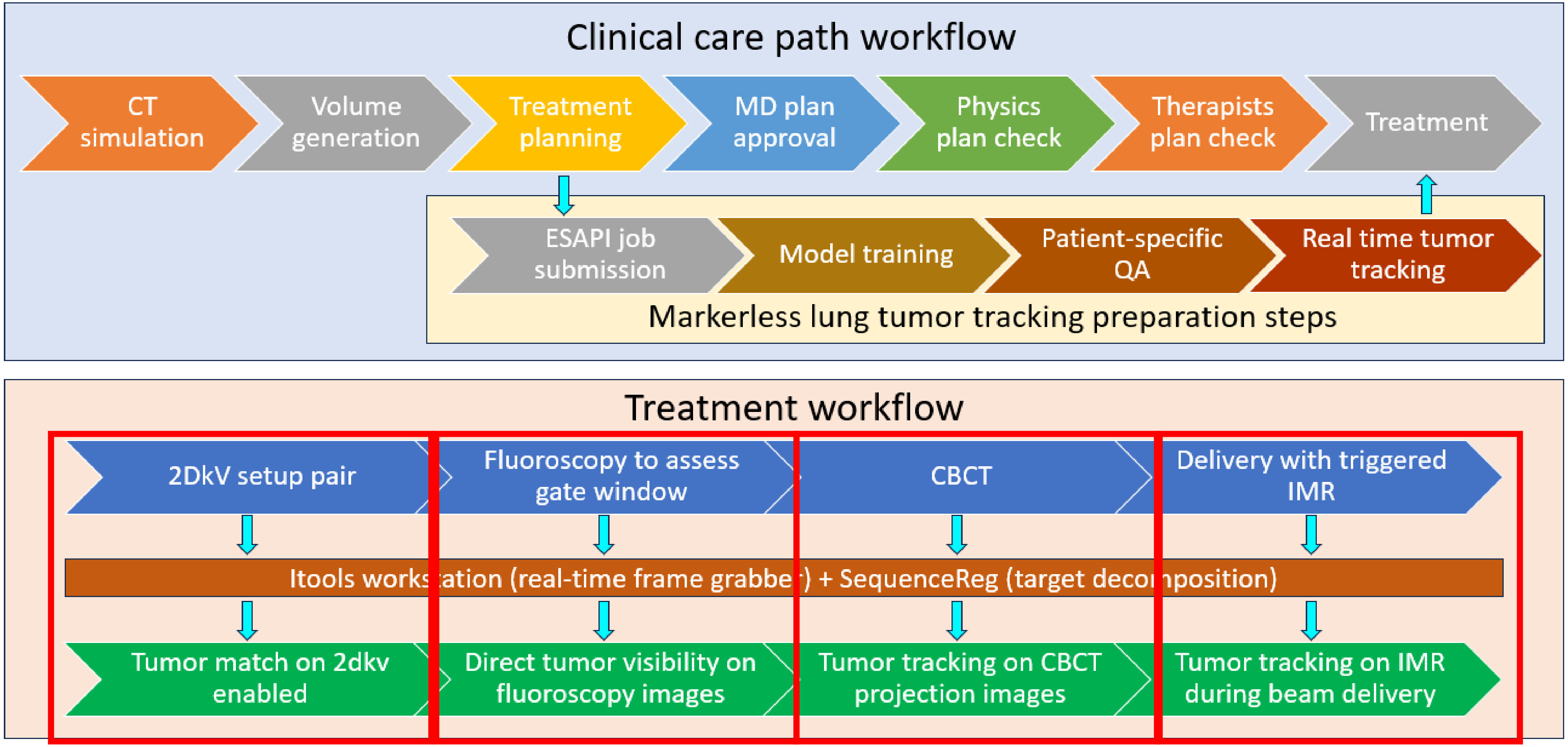
Table 3. Absolute mean error (AME) in mm using the original kV projection images, 90 percentile in mm, trajectory correlation coefficients in the SI and IPLR directions, and successful tracking rate for the 9 patients. Compared to Table 2, better results are shown in bold.

Subject	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Avg
AME (SI)	1.5±1.4	0.4±0.3	0.9±0.6	0.4±0.4	2.4±2.5	1.1±1.5	2.2±1.5	1.1±1.6	3.1±2.9	1.5±1.9
AME (IPLR)	2.3±1.6	0.5±0.4	**0.7±0.4**	0.5±0.4	1.0±0.7	3.4±3.0	1.2±0.9	**0.7±0.5**	1.6±2.0	1.4±1.7
90 Perc. (SI)	3.8	0.7	1.6	1.0	5.4	1.9	4.4	2.7	7.5	3.4
90 Perc. (IPLR)	4.6	1.0	**1.2**	1.0	1.9	9.0	2.5	1.4	4.1	3.1
Traj. Corr (SI)	0.54	0.98	0.96	0.96	0.89	0.88	0.76	0.98	0.27	0.80±0.16
Traj. Corr (IPLR)	0.82	0.61	**0.95**	0.89	0.74	0.65	0.77	0.77	0.39	0.76±0.22
TR (SI < 5mm)	96.0%	100.0%	100.0%	100.0%	100.0%	95.6%	94.8%	93.6%	78.0%	94.7%
TR (SI<2mm)	73.7%	99.8%	95.7%	99.6%	55.9%	91.8%	52.3%	85.8%	25.0%	81.3%
TR (IPLR<2mm)	47.3%	99.6%	**99.1%**	98.8%	**92.0%**	42.8%	76.7%	**99.4%**	73.4%	77.6%
TR(SI&IPLR<2mm)	36.5%	99.6%	**94.8%**	98.8%	52.7%	41.2%	40.6%	85.2%	20.8%	65.0%

Note: 90 Perc. is the 90 percentile. Traj. Corr is the trajectory correlation coefficient. TR is the successful tracking rate.

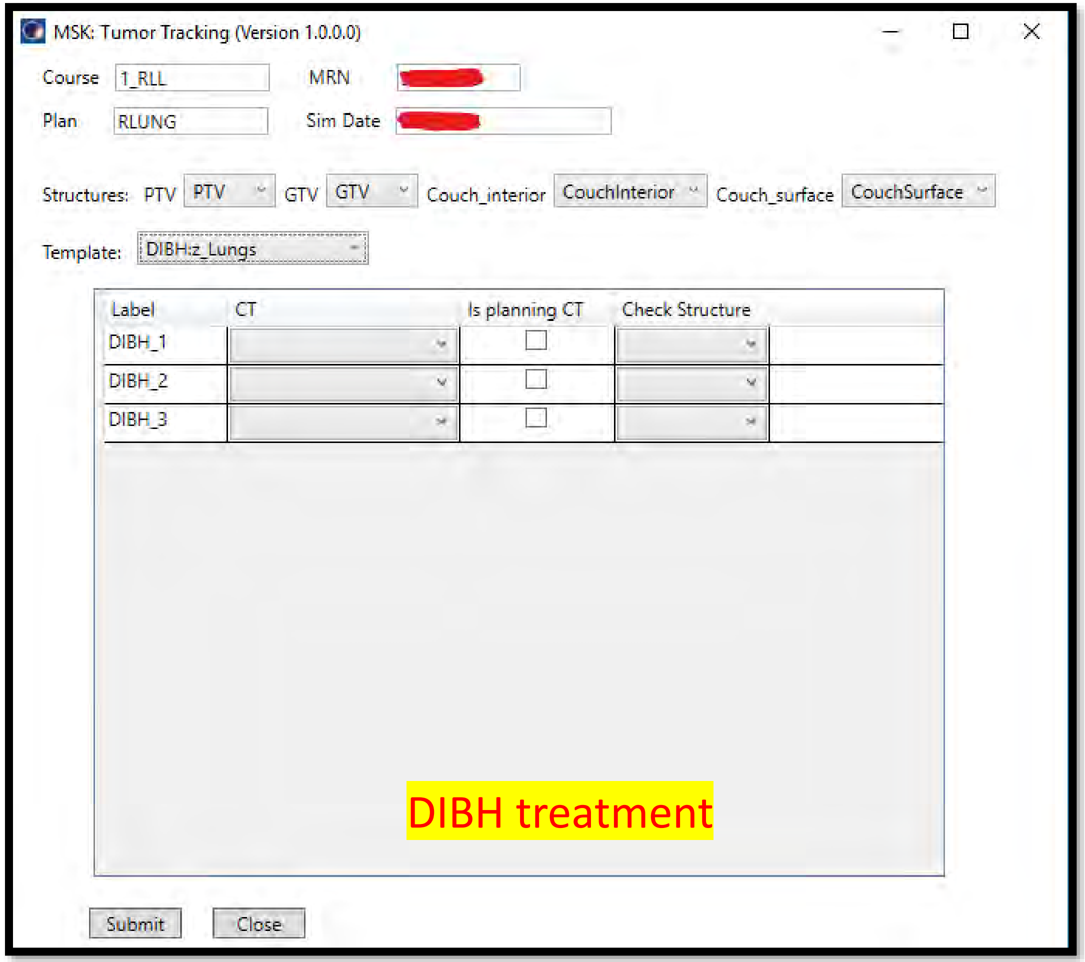
Clinical workflow

- Model training triggered by the planner using ESAPI scripts



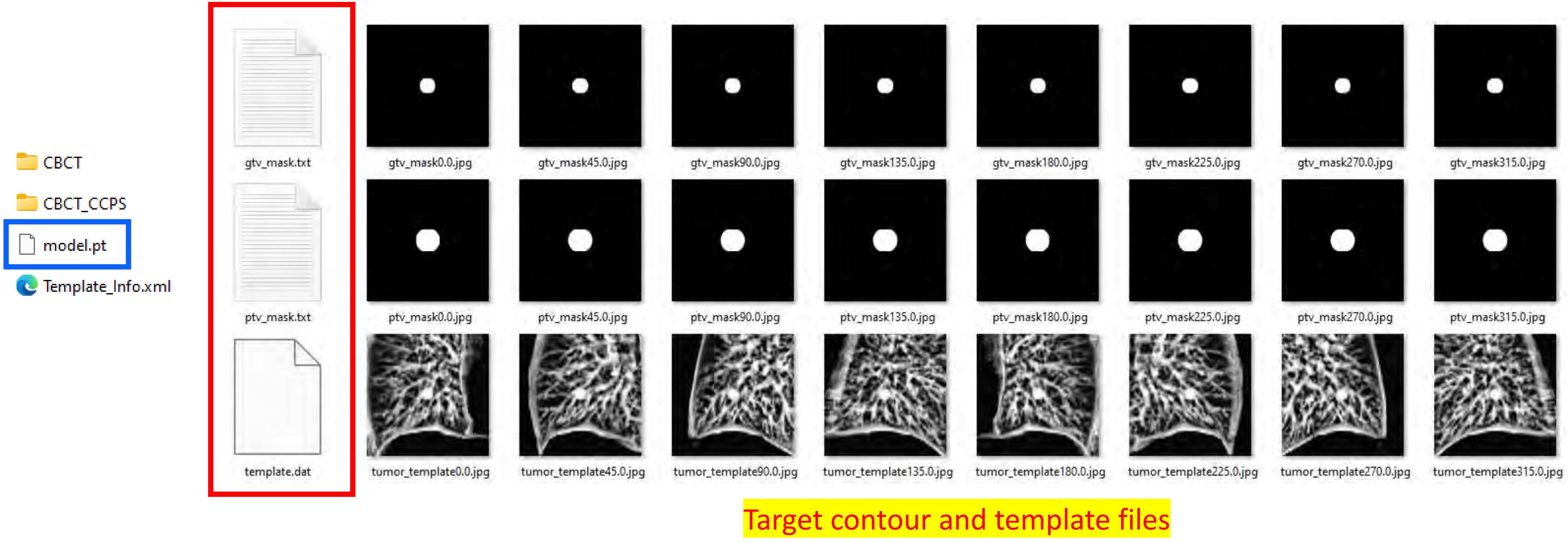
Clinical translation in-progress

- Model training triggered by the planner using ESAPI scripts



Clinical translation in-progress

- Model trained by high performance cluster



Clinical translation in-progress

- GUI demo of the tracking software (under development)

Adjust RPM gating window

Calculate Delta couch shift and compare with the therapists' manual couch shifts as a QA step

- Interrupt beam during delivery if GTV out of PTV,
- Calculate tumor centroid mismatch during delivery

Clinical translation in-progress

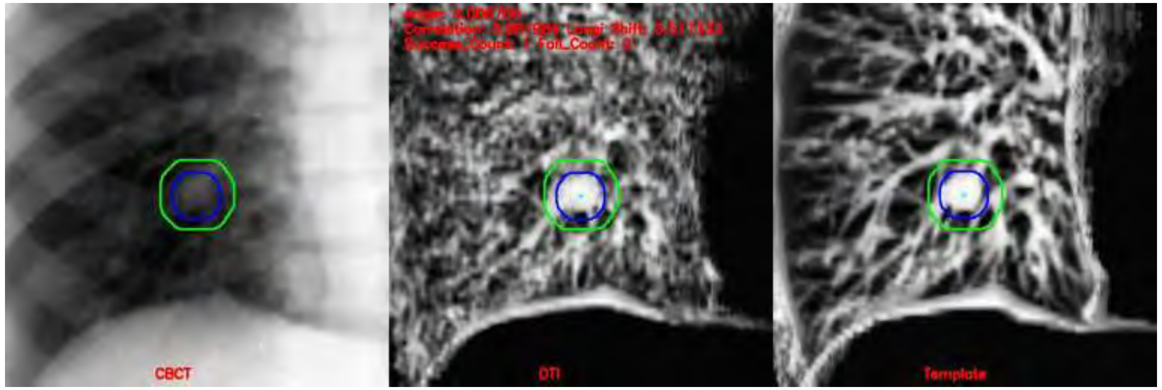
- QA phantom prototype with known tumor motion trace

Clinical translation

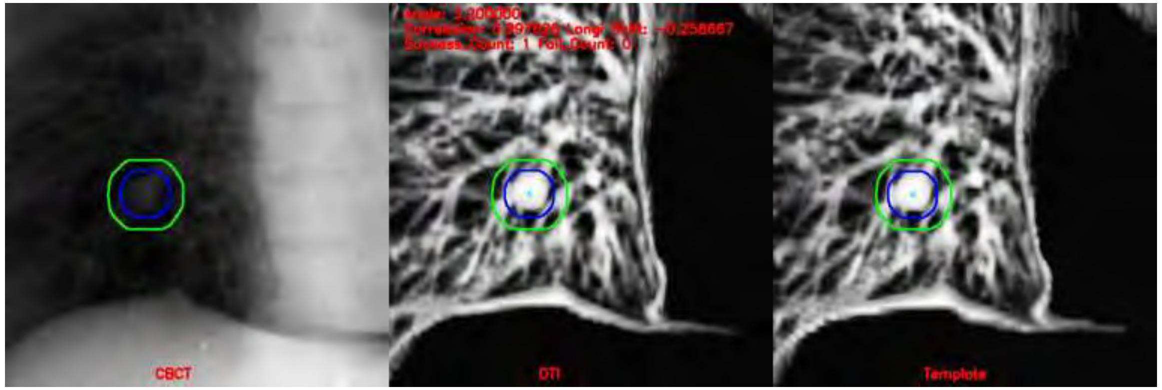
	Calc Couch Delta			True Couch Delta			Error (mm)		
	Vert	Long	Lat	Vert	Long	Lat	Vert	Long	Lat
IMR during beam on	0.4	0.1	0	0	0	0	0.4	0.1	0
spotlight CBCT	0.33	0.13	0	0	0	0	0.33	0.13	0
full CBCT	-2	-0.24	-0.66	-2	-0.3	-0.3	0	0.06	0.36
fluoro		0.5	-0.25		0		0	0.5	0.25

- QA phantom tracking (static DIBH)

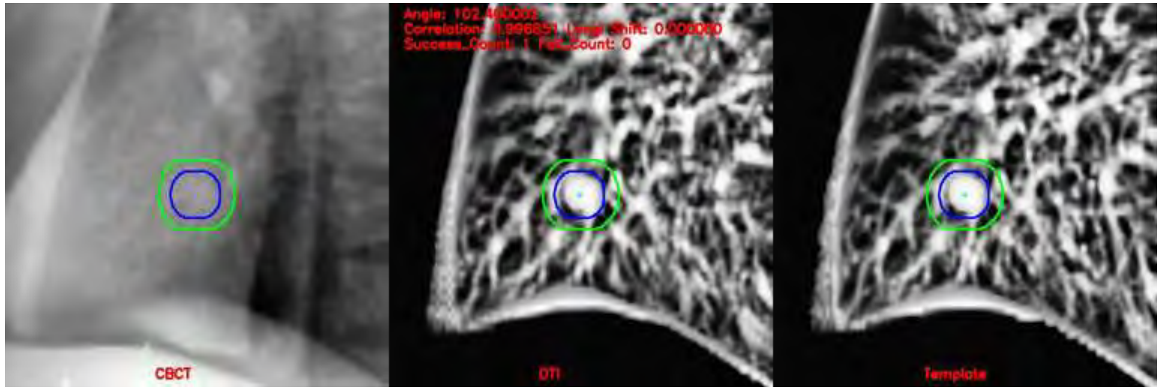
AP Fluoro



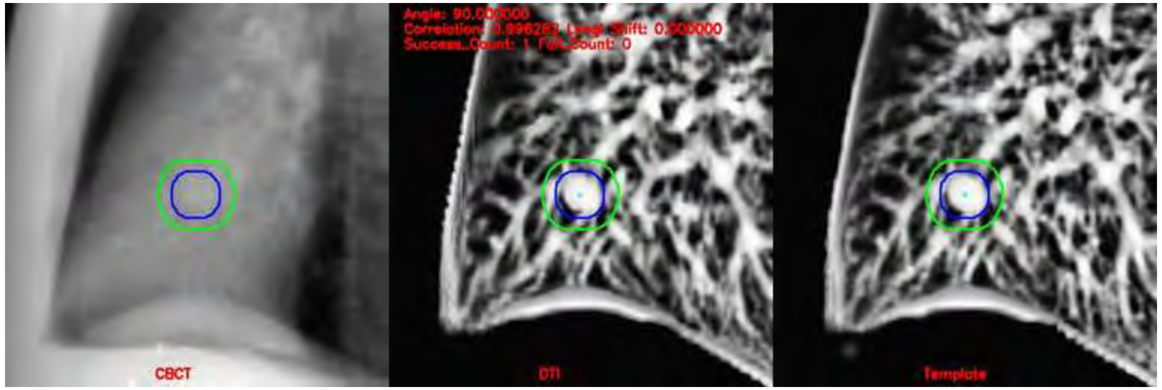
CBCT (Half fan with couch centering)



Triggered IMR tracking during beam on



CBCT (Spotlight)



Conclusion

- AI-based target decomposition technique can provide high-quality x-ray imaging by removing unwanted overlapping structures and highlighting the target of interest on KV projection images.
- Real-time markerless lung motion monitoring is feasible on a conventional Linac platform.

Future works

- Further improve the accuracy and robustness of the target decomposition technique by incorporating the DL-enhanced data augmentation strategy.
- Investigate a population-based model with fast patient-specific fine-tuning for scalability

Research Team

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Thank you for your attention!