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

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Conflict of interest

None

Markerless lung tumor tracking

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

RADIXACT[®] SERIES







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?

Al-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 © 2023 Memorial Sloan Kettering Cancer Center, et al. All rights reserved.

Image Translation using cGAN with self-attention



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





Tumor tracking using template matching



Tumor tracking validation

• MSK 14-225 clinical protocol

Table 1 Tumor characteristics for the nine natients

• Tumor motion ground truth: beacon transponder trajectories in 2D

Subject	GTV Vol(cm³)	Equiv. Sphere Diam.(mm) of GTV	DTW(mm)	DTB(mm)	Max SI beacor 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





Tumor tracking validation

- Beacon trajectory in red curve
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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

	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
Droposod	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
Floposeu	90 Perc. (SI)	1.6	0.5	1.1	0.6	2.1	1.6	1.9	1.5	2.8	1.5
(template matching on DTI)	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%
	TP(SI&IPIP<2mm)	87 8%	100%	0.2 00/	100 00/	70 00/	60 10/	01 E0/	0/ 0%	57 1 0/	8/ 6%
	Table 3. Absolute	e 90 percer e mean er	ntile. Traj. (Sorr is the t	trajectory sing the c	correlation	coefficien projectio	t. TR is the	successful	tracking ra	nm, traject
	Table 3. Absolute correlation coeff	e 90 percer e mean er icients in esults are s	ror (AME) the SI an) in mm u d IPLR dir bold.	trajectory sing the c	original kV	coefficien projectionsful trac	t. TR is the	s, 90 perce for the 9	tracking ra entile in r patients.	ate. nm, traject Compared
	Table 3. Absolute correlation coeff Table 2, better re Subject	e 90 percer e mean er icients in esults are s Pt 1	ror (AME) the SI an shown in Pt 2) in mm u d IPLR dir bold. Pt 3	trajectory sing the c rections, a	original kV and succe	coefficien projectionssful trac Pt 6	t. TR is the on images king rate Pt 7	s, 90 perce for the 9 Pt 8	tracking ra entile in r patients.	nm, traject Compared
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Comparison	Table 3. Absolute correlation coeff ∃Table 2, better re Subject AME (SI) AME (IPLR)	e 90 percer e mean er icients in esults are s Pt 1 1.5±1.4 2.3±1.6	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4) in mm u d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4	rajectory sing the c ections, a Pt 4 0.4±0.4 0.5±0.4	viginal kV original kV and succe Pt 5 2.4±2.5 1.0±0.7	projections projections ssful trac Pt 6 1.1±1.5 3.4±3.0	t. TR is the on images king rate Pt 7 2.2±1.5 1.2±0.9	s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5	tracking rate entile in r patients. Pt 9 3.1±2.9 1.6±2.0	Avg 1.5±1.9 1.4±1.7
Comparison	Table 3. Absolute correlation coeff Table 2, better re Subject AME (SI) AME (IPLR) 90 Perc. (SI)	e 90 percer e mean er icients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8	ntile. Traj. (ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7) in mm u d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6	Itel.0% trajectory sing the c rections, a Pt 4 0.4±0.4 0.5±0.4 1.0	Pt 5 2.4±2.5 1.0±0.7 5.4	projections projections sful trac Pt 6 1.1±1.5 3.4±3.0 1.9	et. 3% t. TR is the on images king rate Pt 7 2.2±1.5 1.2±0.9 4.4	94.0% successful s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5 2.7	tracking ra entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5	Avg 1.5±1.9 3.4
Comparison method	Table 3. Absolute correlation coeff Table 2, better re Subject AME (SI) AME (IPLR) 90 Perc. (SI) 90 Perc. (IPLR)	e 90 percer e mean er icients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8 4.6	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7 1.0) in mm u d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6 1.2	Projectory sing the c ections, a Pt 4 0.4±0.4 0.5±0.4 1.0 1.0	P8.8% correlation priginal kV and succe Pt 5 2.4±2.5 1.0±0.7 5.4 1.9	b9.1% coefficien projectio ssful trac Pt 6 1.1±1.5 3.4±3.0 1.9 9.0	et.3% t. TR is the on images king rate Pt 7 2.2±1.5 1.2±0.9 4.4 2.5	Pt.0% e successful s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5 2.7 1.4	tracking ra entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5 4.1	Avg 1.5±1.9 1.4±1.7 3.4 3.1
Comparison method	Table 3. Absolute Table 3. Absolute correlation coeff Table 2, better re Subject AME (SI) AME (IPLR) 90 Perc. (SI) 90 Perc. (IPLR) Traj. Corr (SI)	e 90 percer e mean erri icients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8 4.6 0.54	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7 1.0 0.98	92.8% Corr is the t d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6 1.2 0.96	Projectory sing the c rections, a Pt 4 0.4±0.4 0.5±0.4 1.0 0.96	Pt 5 2.4±2.5 1.0±0.7 5.4 1.9 0.89	b9.1% coefficien projectio ssful trac Pt 6 1.1±1.5 3.4±3.0 1.9 9.0 0.88	et. 3% t. TR is the on images king rate Pt 7 2.2±1.5 1.2±0.9 4.4 2.5 0.76	P4.0% e successful s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5 2.7 1.4 0.98	b7.1% tracking rate tracking rate entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5 4.1 0.27	Avg 1.5±1.9 1.4±1.7 3.4 3.1 0.80±0.16
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Comparison method (Template matching on band-pass filtered images)	Table 3. Absolute Table 3. Absolute correlation coeff Table 2, better re Subject AME (SI) AME (IPLR) 90 Perc. (SI) 90 Perc. (IPLR) Traj. Corr (IPLR) TR (SI < 5mm)	e 90 percer e mean erri icients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8 4.6 0.54 0.82 96.0% 73.7%	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7 1.0 0.98 0.61 100.0% 99.8%) in mm u d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6 1.2 0.96 0.95 100.0% 95.7%	Pt 4 0.4±0.4 0.5±0.4 1.0 0.96 0.89 100.0% 99.6%	Pt 5 2.4±2.5 1.0±0.7 5.4 1.9 0.89 0.74 100.0% 55.9%	b9.1% coefficien projectio ssful trac Pt 6 1.1±1.5 3.4±3.0 1.9 9.0 0.88 0.65 95.6% 91.8%	Pt 7 2.2±1.5 1.2±0.9 4.4 2.5 0.76 0.77 94.8% 52.3%	94.0% e successful s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5 2.7 1.4 0.98 0.77 93.6% 85.8%	b 7.1% tracking rate tracking rate entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5 4.1 0.27 0.39 78.0% 25.0%	Avg 1.5±1.9 1.4±1.7 3.4 3.1 0.80±0.16 0.76±0.22 94.7% 81.3%
Comparison method (Template matching on band-pass filtered images)	Table 3. Absolute Table 3. Absolute correlation coeff Table 2, better restrict Subject AME (SI) AME (IPLR) 90 Perc. (SI) 90 Perc. (IPLR) Traj. Corr (SI) Traj. Corr (IPLR) TR (SI < 5mm)	e 90 percer e mean er icients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8 4.6 0.54 0.54 0.82 96.0% 73.7% 47.3%	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7 1.0 0.98 0.61 100.0% 99.8% 99.6%	92.8% Corr is the f orr is the f d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6 1.2 0.96 0.95 100.0% 95.7% 99.1%	Pt 4 0.4±0.4 0.5±0.4 1.0 1.0 96 0.89 100.0% 99.6% 98.8%	Pt.5% correlation priginal kV and succe Pt 5 2.4±2.5 1.0±0.7 5.4 1.9 0.89 0.74 100.0% 55.9% 92.0%	b9.1% coefficien projectic ssful trac Pt 6 1.1±1.5 3.4±3.0 1.9 9.0 0.88 0.65 95.6% 91.8% 42.8%	P1.7 t. TR is the on images king rate Pt 7 2.2±1.5 1.2±0.9 4.4 2.5 0.76 0.77 94.8% 52.3% 76.7%	94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0% 94.0%	b 7.1% tracking rate tracking rate entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5 4.1 0.27 0.39 78.0% 25.0% 73.4%	Avg 1.5±1.9 1.4±1.7 3.4 3.1 0.80±0.16 0.76±0.22 94.7% 81.3% 77.6%
Comparison method (Template matching on band-pass filtered images)	Table 3. Absolute correlation coeff Table 2, better re Subject AME (SI) AME (IPLR) 90 Perc. (SI) 90 Perc. (SI) Traj. Corr (SI) Traj. Corr (IPLR) Traj. Corr (IPLR) TR (SI < 5mm) TR (SI<2mm) TR (SI&IPLR<2mm)	e 90 percer e mean erricients in esults are s Pt 1 1.5±1.4 2.3±1.6 3.8 4.6 0.54 0.82 96.0% 73.7% 47.3% 36.5%	ror (AME) the SI an shown in Pt 2 0.4±0.3 0.5±0.4 0.7 1.0 0.98 0.61 100.0% 99.8% 99.6%	92.8% Corr is the f d IPLR dir bold. Pt 3 0.9±0.6 0.7±0.4 1.6 1.2 0.96 0.95 100.0% 95.7% 99.1% 94.8%	100.0% trajectory sing the c ections, a Pt 4 0.4±0.4 0.5±0.4 1.0 1.0 1.0 98.8% 98.8%	Process priginal kV poriginal kV and succe Pt 5 2.4±2.5 1.0±0.7 5.4 1.9 0.89 0.74 100.0% 55.9% 92.0% 52.7%	b9.1% coefficien projectio ssful trac Pt 6 1.1±1.5 3.4±3.0 1.9 9.0 0.88 0.65 95.6% 91.8% 42.8% 41.2%	Pt 7 2.2±1.5 1.2±0.9 4.4 2.5 0.76 0.77 94.8% 52.3% 76.7% 40.6%	94.0% e successful s, 90 perce for the 9 Pt 8 1.1±1.6 0.7±0.5 2.7 1.4 0.98 0.77 93.6% 85.8% 99.4% 85.2%	J7.1% tracking rate tracking rate entile in r patients. Pt 9 3.1±2.9 1.6±2.0 7.5 4.1 0.27 0.39 78.0% 25.0% 73.4% 20.8%	Avg 1.5±1.9 1.4±1.7 3.4 3.1 0.80±0.16 0.76±0.22 94.7% 81.3% 77.6% 65.0%

Clinical workflow

• Model training triggered by the planner using ESAPI scripts





• Model training triggered by the planner using ESAPI scripts

ED.		couch					Struc			Couci		couciesanace	couchourna
Label	gs	Is	planning CT	Check Struct	ure		Temp	Label	cT	ł	s planning CT	Check Structure	
FB	CT_LUNGFB_030824	*	V	z_Lungs	~			DIBH_1		~			
4DCT_00%	CT_00	-		z_Lungs	~			DIBH_2		~		~	
4DCT_10%	CT_10	*		z_Lungs	*			DIBH_3		×		×	
4DCT_20%	CT_20	×		z_Lungs	~			-				,	
4DCT_30%	CT_30	*		z_Lungs	4								
4DCT_40%	CT_40	~		z_Lungs	~								
4DCT_50%	CT_50	*		z_Lungs	Ψ.								
4DCT_60%	CT_60	~		z_Lungs	~								
4DCT_70%	CT_70	*		z_Lungs	*	1							
4DCT_80%	CT_80	2		z_Lungs	~								
4DCT_90%	CT_90	*		z_Lungs	*								

Model trained by high performance cluster



Target contour and template files

• GUI demo of the tracking software (under development)



• QA phantom prototype with known tumor motion trace



Clinical translation

	Calc Couch Delta				True	Couch	Delta	E	Error (mm)			
MR 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	C	0.06	0.36		
fluoro		0.5	-0.25			0		C	0.5	0.25		
	Vert	Long	Lat		Vert	Long	Lat	Vert	Long	Lat		

• QA phantom tracking (static DIBH)

AP Fluoro





CBC

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!