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Real-time Respiratory Tumor Tracking with Implanted Markers

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Disclaimer

- Consultant for Accuray treatment planning service

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Motivation: Lung Motion

Table 2. Lung tumor–motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each cohort of subjects. The motion is in three dimensions (SI, AP, LR).

Observer	Direction		
	SI	AP	LR
Barnes: Lower lobe	18.5 (9–32)	–	–
Middle, upper lobe	7.5 (2–11)	–	–
Chen et al.	(0–50)	–	–
Ekberg et al.	3.9 (0–12)	2.4 (0–5)	2.4 (0–5)
Engelsman et al.:			
Middle/upper lobe	(2–6)	–	–
Lower lobe	(2–9)	–	–
Erridge et al.	12.5 (6–34)	9.4 (5–22)	7.3 (3–12)
Ross: Upper lobe	–	1 (0–5)	1 (0–3)
Middle lobe	–	0	9 (0–16)
Lower lobe	–	1 (0–4)	10.5 (0–13)
Grills et al.	(2–30)	(0–10)	(0–6)
Hanley et al.	12 (1–20)	5 (0–13)	1 (0–1)
Murphy et al.	7 (2–15)	–	–
Plathow: Lower lobe	9.5 (4.5–16.4)	6.1 (2.5–9.8)	6.0 (2.9–9.8)
Middle lobe	7.2 (4.3–10.2)	4.3 (1.9–7.5)	4.3 (1.5–7.1)
Upper lobe	4.3 (2.6–7.1)	2.8 (1.2–5.1)	3.4 (1.3–5.3)
Seppenwoolde et al.	5.8 (0–25)	2.5 (0–8)	1.5 (0–3)
Shimizu et al.	–	6.4 (2–24)	–
Sixel et al.	(0–13)	(0–5)	(0–4)
Stevens et al.	4.5 (0–22)	–	–

AP: anterior–posterior; LR: left–right; SI: superior–inferior.

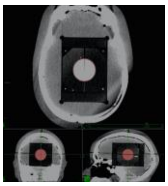
Table 3. Abdominal motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior–inferior (SI) direction.

Site	Observer	Breathing mode	
		Shallow	Deep
Pancreas	Suramo et al.	20 (10–30)	43 (20–80)
	Bryan et al.	20 (0–35)	–
Liver	Weiss et al.	13 +/– 5	–
	Harauz et al.	14	–
	Suramo et al.	25 (10–40)	55 (30–80)
	Davies et al.	10 (5–17)	37 (21–57)
Kidney	Suramo et al.	19 (10–40)	40 (20–70)
	Davies et al.	11 (5–16)	–
Diaphragm	Wade	17	101
	Korin et al.	13	39
	Davies et al.	12 (7–28)	43 (25–57)
	Weiss et al.	13 +/– 5	–
	Giraud et al.	–	35 (3–95)
	Ford et al.	20 (13–31)	–

Keall et al. AAPM TG 76 2006

Motivation: Lung Motion

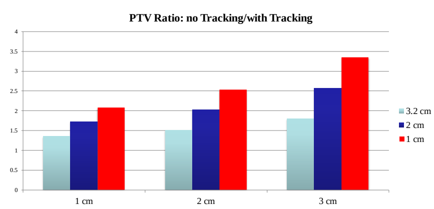
Tx Volume Comparison: 3.2 cm Spherical GTV



Tracking: PTV = GTV + 5mm

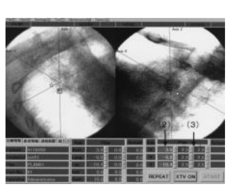
Motion Encompassing: PTV = ITV/iGTV + 5mm

Motivation: Lung Motion



System Review - Mitsubishi/Hokkaido RTRT

http://rad.med.hokudai.ac.jp/



Shirato et al. IJROBP, 2000

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CyberKnife System

- Invented by John Adler, a neurosurgeon at Stanford University
- Had resident training with Lars Leksell in Sweden
- Noticed the GammaKnife
  - Invasive
  - Cannot fractionate
  - Only treat tumor in brain

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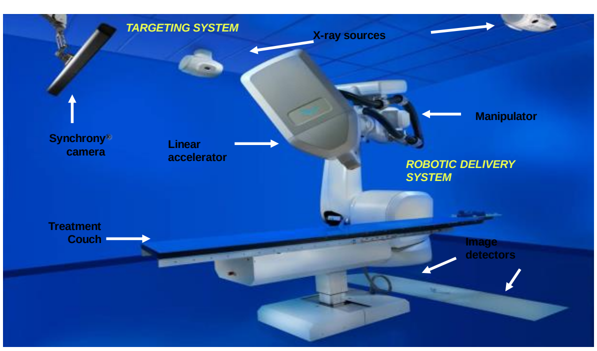
CyberKnife System

- First CyberKnife treatment on June 4, 1994
- More than 10, 0000 patients treated and 244 systems installed worldwide



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CyberKnife System

[redacted]

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Fiducial Placement

- 4-6 fiducials are recommended
  - 1 fiducial can only track translation and at least 3 fiducial to track rotation
- Minimum 2 cm spacing between fiducials
- The triangle formed by 3 fiducials should have the smallest angle > 15 degree
- As close to the target as possible
- Ensure visibility in the 20 cm by 20 cm detector panel

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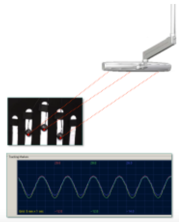
Types of Fiducial

- Gold fiducials most commonly used
  - Diameter: 0.7 to 1.2 mm
  - Length 3 to 6 mm
- Other types of fiducials offer some unique features

IBA Visicoil

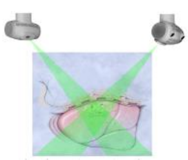
Civco coupled markers

Synchrony Vest and Camera

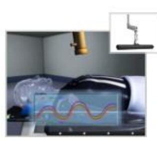


CyberKnife System

- How to derive real-time 3D tumor (fiducial) positions?



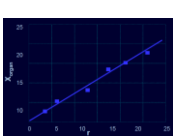
Discrete 3D fiducial positions



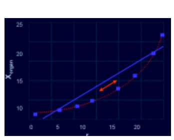
Real-time LED positions

CyberKnife System

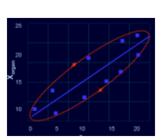
- Correlation Model – training period



Linear



Curvilinear



Dual-curvilinear

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CyberKnife System

Int. J. Radiation Oncology Biol. Phys., Vol. 53, No. 4, pp. 822–834, 2002

0360-3016/02/$–see front matter

ELSEVIER

PII S0360-3016(02)02803-1

CLINICAL INVESTIGATION — **Lung**

PRECISE AND REAL-TIME MEASUREMENT OF 3D TUMOR MOTION IN LUNG DUE TO BREATHING AND HEARTBEAT, MEASURED DURING RADIOTHERAPY

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CyberKnife System

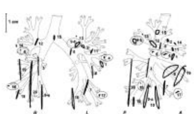

Fig. 4. Orthogonal projections of the trajectories of the 21 tumors on (left) the coronal (LR-CC) and (right) the sagittal (AP-CC) plane. The tumors are displayed at the approximate position, based on the localization mentioned in the treatment chart. Tumors that were attached to bony structures are circled.

- 20 patients were recruited from Mitsubishi/Hokkaido RTRT treatment
- Hysteresis effect was observed in 10 of 21 tumors (1-5 mm)
  - "The tumor followed a different path during inhalation than during exhalation."
  - Mostly in the sagittal plane

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CyberKnife System

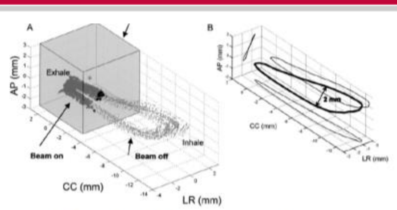

Fig. 3. (A) The 3D path of the tumor of Patient 10 during one treatment portal: The gray dots represent the tumor position throughout the treatment, and the black dots represent the tumor position as the tumor is detected to be inside the RTRT range (transparent box). The asterisk represents the planned zero position. (B) The average 3D curve of the

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CyberKnife System

Patient 8

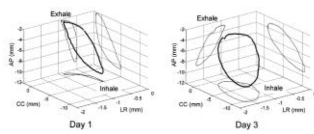

Fig. 5. The 3D trajectory of the tumor of Patient 8: (A) On Day 1, the pattern was similar to that on Day 2 and 4. (B) Day 3. The shape and direction of the motion changed between subsequent days: In the coronal plane on Day 3, hysteresis was present, whereas on Days 1, 2, and 4, this was not the case. In the transaxial (AP-LR) plane, the motion switched from left to right on Days 1, 2, and 4 and to right to left on Day 3.

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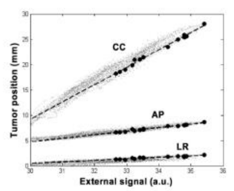
CyberKnife System

- Correlation Model – linear

(1) A linear model, that is simply a linear fit between target positions (3D) and scalar external marker positions (r),

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\text{Target}} = \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} r + \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}.$$

Coefficients (A, B) are found by least-squares fitting to image/marker data-points (Fig. 3).



Seppenwoolde et al. Med. Phys., 2007

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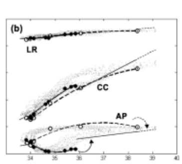
CyberKnife System

- Correlation Model – Dual-curvilinear

(2) A polynomial model with two fitted second-order polynomials, one through the image/marker data-points that are determined to be in the inhale phase of the breathing cycle, and one that is determined for the exhale phase,

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}^{\text{TLS}}_{\text{Target}} = \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} r^2 + \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} r + \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix}.$$

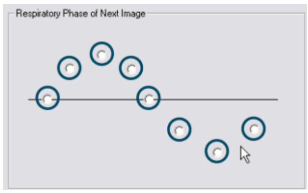
An example is shown in Fig. 4.



Seppenwoolde et al. Med. Phys., 2007

CyberKnife System

- It’s recommended acquisition of model points covering whole breathing period.



CyberKnife System

- Multiple breathing models are allowed
  - Abrupt breathing pattern change
  - Irregular breathing pattern, e.g. cough
  - Patient moves
  - Patient wants a break
  - Different direction could have different model

CyberKnife System

- For the same model during treatment, the model points keep updated once a pair of x-ray images is taken - adaptive
  - To account for slow change of breathing pattern or drifting
  - The oldest model point will be discarded first – last in last out
- Prediction is used to account for system latency (115 ms)
  - Autoaggressive process – normalized least mean square (nLMS)
  - The predicted tumor position is compared to the real detected position
  - Once the difference is beyond a threshold, an E-stop occurs

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CyberKnife System – Uncertainty Evaluation

- CyberKnife doesn't take continuous x-ray image pairs so the ground truth between pairs is missing
- Data from Mitsubishi/NTT hospital RTRT system used to retrospectively evaluate CyberKnife modeling accuracy
  - 8 lung cancer patients
  - Peak to peak motion > 1 cm
  - Synchronized recordings of internal tumor/fiducials motion and external markers motion
- All three models were evaluated to find the optimal model
  - Linear, polynomial and hybrid models

Seppenwoolde et al. Med. Phys., 2007

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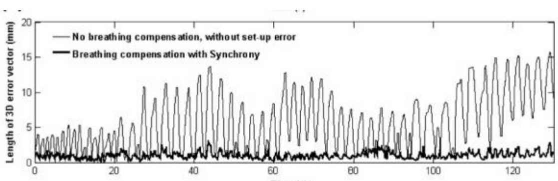
Results



Correction for drifting error

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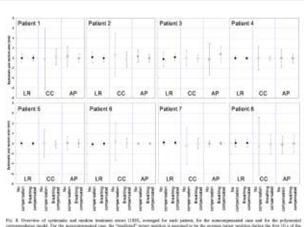
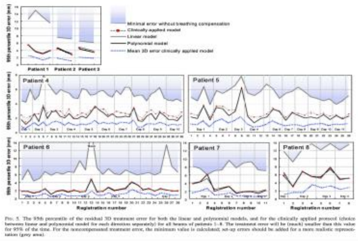
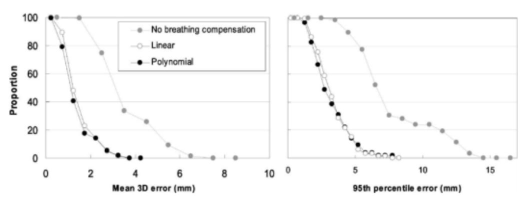
Results – error in each direction



Results – all the patients



Results



Potential Issues

Deformation/Nonrigid Motion

DRR

X-ray image 1

X-ray image 2

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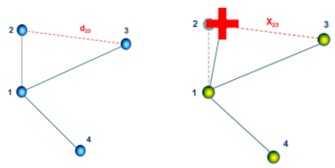
Potential Issues

Deformation/Nonrigid Motion – Rigid Body Error: d23-x23



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Potential Issues - Rotation

- System is capable to correct 1.5° in roll,1.5° in pitch and 3.0° in yaw
- 25 patients, 2796 pairs of images were analyzed
- PTV were created by adding 3 mm (UL) and 5 mm (LL) margins
- CTV were rotated based on reported angles + random shifts
- For 94.4% and 97.1% of the the images in LL and UL, the CTV is 100% covered by the PTV and rest mean CTV coverage were 95.6% (LL) and 99% (UL)

	Roll	Pitch	Yaw
Lower lobe	0.25° ±5.7°	-0.21° ±7.3°	0.23° ±5.3°
Upper lobe	0.40° ±2.1°	0.05° ±1.8°	0.1° ±2.1°

Xu et al. AAPM 2013

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ExacTrac Brainlab

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Summary

- Multiple systems with RTRT capability were reviewed
- Three breathing models were introduced
- Prediction uncertainties were analyzed
- Real-time tumor tracking with fiducials significantly reduce PTV and nearby healthy tissue irradiated
- Deformation and rotation could introduce uncertainties

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Thank you!

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