Real-time Respiratory Tumor Tracking with Implanted Markers

Qianyi Xu PhD, DABR
MD Anderson Cancer Center at Cooper
xu-qianyi@cooperhealth.edu

Disclaimer

- Consultant for Accuray treatment planning service

Motivation: Lung Motion

Keall et al. AAPM TG 76 2005
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/
Shinato et al. IJROBP; 2000
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

First CyberKnife treatment on June 4, 1994
More than 10,000 patients treated and 244 systems installed worldwide

Synchrony® camera
Linear accelerator
Manipulator
X-ray sources
Detectors
Targeting system
Robotic delivery system
Treatment couch
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

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

Discrete 3D fiducial positions
Real-time LED positions

• Correlation Model – training period

Linear Curvilinear Dual-curvilinear
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
CyberKnife System

- Correlation Model – linear

A linear model that is simply a linear fit between target positions (TCP) and vector external marker positions (C). Coefficients (A, B, and C) need to be empirically fitting to tangentialisation data points (Fig. 3).


- Correlation Model – Dual-curvilinear

A polynomial model with non-linear second order polynomials, even through the tangentialisation data points that are determined to be in the initial phase of the headmotion cycle, and one that is determined for the circular phase.

An example is shown in Fig. 4.

CyberKnife System

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

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

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
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


Results

Correction for drifting error

Results – error in each direction
Results – all the patients

Potential Issues

Deformation/Nonrigid Motion

- DRR
- X-ray image 1
- X-ray image 2
### Potential Issues

**Defomation/Nonrigid Motion – Rigid Body Error**

\[ d_{23} - x_{23} \]

---

**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 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)

<table>
<thead>
<tr>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower lobe</td>
<td>0.25° ± 0°</td>
<td>0.23° ± 0°</td>
</tr>
<tr>
<td>Upper lobe</td>
<td>0.40° ± 2°</td>
<td>0.05° ± 1°</td>
</tr>
</tbody>
</table>

---

**ExacTrac Brainlab**
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

Thank you!