Locating and targeting moving tumors with radiation beams

Paul Keall, Ph.D.
Radiation Oncology, Stanford University

Notes

- Next time look at mdacc talk on this subject
- Also look at other aapm invited talk

Thanks to …

Stanford group
- Byungchul Cho
- Dragos Constantin
- Magdalena Constantin
- Sonja Dieffenbacher
- Bill Liu
- Dan Ruan
- Amit Sawant
- Yelin Suh
- Lei Xing
- Tokihiro Yamamoto

Key collaborators
- Herb Cattell
- Stine Korremann
- Per Poulsen
- Jeffrey Siabers
- Elisabeth Weiss
- Jeffrey Williamson

Research support
- Accuray
- Calypso
- CyberHeart
- GE
- NIH
- Philips
- Stanford University
- Varian

Abstract

Locating and Targeting Moving Tumors with Radiation Beams

The current climate of rapid technological evolution is reflected in newer and better methods to modulate and direct radiation beams for cancer therapy. This Continuing Education lecture focuses on one aspect of this evolution, locating and targeting moving tumors. The two processes—locating and targeting tumors—are somewhat independent and in principle different implementations of these processes can be interchanged. Advanced localization and targeting methods have an impact on treatment planning, and also present new challenges for quality assurance (QA), that of verifying real-time delivery. Some methods to locate and target moving tumors with radiation beams are currently FDA approved for clinical use—and this availability and implementation will increase with time. Extensions of current capabilities will be the integration of higher-order dimensionality into the estimate of the patient pose and realtime reoptimization and adaptation of delivery to the dynamically changing anatomy of cancer patients.

Educational objectives:
(1) To describe the technology available to determine real-time target position
(2) To review the systems for real-time target-beam alignment
(3) To discuss the practical considerations of real-time target tracking systems

Research sponsored by Accuray, Calypso, CyberHeart, GE, NIH/NCI, Philips and Varian.
Educational objectives

- Describe the technology available to determine real-time target position
- Review the systems for real-time target-beam alignment
- Discuss the practical considerations of real-time target tracking systems

Question: Lung tumor motion has mean (typical range) of

A. 0.1 cm (0-0.3 cm)
B. 0.2 cm (0-0.5 cm)
C. 0.5 cm (0.1-1.5 cm)
D. 1 cm (0.5-3 cm)
E. 2 cm (1-5 cm)

Answer: Lung tumor motion has mean (typical range) of

A. 0.1 cm (0-0.3 cm)
B. 0.2 cm (0-0.5 cm)
C. 0.5 cm (0.1-1.5 cm)
D. 1 cm (0.5-3 cm)
E. 2 cm (1-5 cm)

What is the problem?
Lung tumor motion

Motion during treatment

CBCT measured displacement Single fx 25 Gy gated IMRT with bodyfix for T1 NSCLC patient

Measurement of lung tumor motion

<table>
<thead>
<tr>
<th>Observer</th>
<th>Direction</th>
<th>LIT</th>
<th>AAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross 2</td>
<td>-</td>
<td>1.0 (0 - 5)</td>
<td>1.0 (0 - 5)</td>
</tr>
<tr>
<td>McCluskey 3</td>
<td>3.5 (0 - 10)</td>
<td>3.5 (0 - 10)</td>
<td></td>
</tr>
<tr>
<td>Harnan 2</td>
<td>7.5 (0 - 10)</td>
<td>7.5 (0 - 10)</td>
<td></td>
</tr>
<tr>
<td>Simonton 4</td>
<td>7.5 (0 - 10)</td>
<td>7.5 (0 - 10)</td>
<td></td>
</tr>
<tr>
<td>Fessler 5</td>
<td>1.0 (0 - 5)</td>
<td>1.0 (0 - 5)</td>
<td></td>
</tr>
<tr>
<td>Gingles 6</td>
<td>3.5 (0 - 10)</td>
<td>3.5 (0 - 10)</td>
<td></td>
</tr>
</tbody>
</table>

[Images and figures are not included in the text.]
Prostate motion

Question: Which of the following has the largest uncertainty?

A. Tumor delineation
B. Deformable registration uncertainty
C. Real-time position estimation
D. Motion prediction uncertainty
E. Tracking uncertainty

Answer: Which of the following has the largest uncertainty?

A. Tumor delineation
B. Deformable registration uncertainty
C. Real-time position estimation
D. Motion prediction uncertainty
E. Tracking uncertainty

What do we want?
### Goal

- The goal of IGRT is to have knowledge, or a good estimate of, the anatomy of the target and normal tissues intersected by the beam during radiation delivery, and appropriately adjust the radiation delivery for the anatomy.
- 4D in-room imaging facilitates the measurement or estimate of the anatomy with time.

### Desirable 4D In-Room Imaging Features

- Volumetric
- High spatial resolution
- High temporal resolution
- High fidelity
- Can transfer planning contour & dose information to & from
- Low latency
- No interference with delivery system
- Non-invasive
- No imaging dose
- Can optimize and compute dose on
- Reduces treatment time
- Cheap with low operational costs
- …

### 4D in-room imaging

What have we got?

Not currently available!
Technologies available for real-time imaging

- Electromagnetic
- Radioisotope
- EPI
- X-ray

Electromagnetic

- Requires implantation - internal
- High accuracy/precision
- 10-25 Hz frame rate

Radioisotope

• Requires implantation - internal
• High accuracy/precision
• 10-25 Hz frame rate
Radioisotope

- Requires implantation - internal
- High accuracy
- 10 Hz frame rate

kV/MV/Optical combinations:
MV alone

MV fluoro for marker tracking

Treatment verification with an EPID in cine mode

Courtesy Dr. Ross Berbeco
MV imaging

- Mainstay of in-room imaging
- Applicable to 4D with cine frame rates ~10Hz
- With IMRT can get some information some of the time - can use for IMRT optimization
- ‘Free’ information

X-ray in room imaging

X-ray

kV/MV/Optical combinations:

kV alone
kV/MV/Optical combinations:

- **kV and kV**

- **kV and MV**

---

**Combined kV/MV**

---

**Combined kV/MV**

---

(Wiersma et al. Med Phys 2008)

---

**Optical**

- High frame rate near real time
- Skeletal/chest/abdomen motion
- External only
- ‘Free’, rich source of information
- To be combined with other data streams...

**Combined x-ray/optical**

**kV/MV/Optical combinations:**

- kV and optical
**kV/MV/Optical combinations:**

**MV, and optical**

- MV Beam
- Optical Camera
- MV Imager

**kV/MV/Optical combinations:**

**kV, kV, and optical**

- kV source
- MV Beam
- kV source

**kV/MV/Optical combinations:**

**kV, MV, and optical**

- MV Beam
- Optical Camera
- MV Imager
- kV Source
- kV Imager

**Integrated DMLC tracking system accuracy**

<table>
<thead>
<tr>
<th>Guidance Method</th>
<th>Accuracy</th>
<th>Experimentally verified?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM (Calypso)</td>
<td>&lt; 1mm prostate, &lt; 2mm lung</td>
<td>Yes</td>
<td>Sawant, Smith IJRBP 2009</td>
</tr>
<tr>
<td>kV alone</td>
<td>&lt; 1mm prostate, &lt; 2mm lung</td>
<td>Yes</td>
<td>Poulsen PMB, IJRBP 2009</td>
</tr>
<tr>
<td>MV alone</td>
<td>&lt; 2mm (lung)</td>
<td>Yes</td>
<td>Poulsen AAPM 2009</td>
</tr>
<tr>
<td>kV &amp; MV</td>
<td>&lt; 1mm lung (ideal case)</td>
<td>Yes</td>
<td>Cho IJRBP 2009</td>
</tr>
<tr>
<td>kV &amp; optical</td>
<td>&lt; 2mm lung</td>
<td>Yes</td>
<td>Cho PMB 2008</td>
</tr>
<tr>
<td>kV, MV &amp; optical</td>
<td>&lt; 2mm lung</td>
<td>Yes</td>
<td>Cho PMB 2008</td>
</tr>
</tbody>
</table>
• Recent developments in probe technology
• Ongoing developments in IG surgery
• Ongoing developments in segmentation
• 3D data at 2-10 Hz possible
MRI

- Three groups developing MRI-linacs
- Volumetric data
- Acceptable frame rate
- Many tumor sites
- RF interference, electron transport issues

Technology comparison

<table>
<thead>
<tr>
<th>4D Imaging In-Room Method</th>
<th>Data magnitude and frequency</th>
<th>Invasive?</th>
<th>Additional radiation dose?</th>
<th>Available?</th>
<th>Compatible with beam on?</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPs</td>
<td>2D array ~ 10 Hz</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>X-ray</td>
<td>2D array ~ 10 Hz</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Optical</td>
<td>Point(s)/surface ~ 30 Hz</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>CBCT</td>
<td>3D volume ~ 0.02 Hz</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>4D CBCT</td>
<td>4D volume ~ 0.01 Hz</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Electromagnetic (below visible)</td>
<td>Point(s) ~ 10 Hz</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Volume ~ 1 Hz</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>MRI</td>
<td>Volume ~ 1 Hz</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y,N</td>
</tr>
<tr>
<td>Combined x-ray/optical...</td>
<td>Combination</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

What use is 4D imaging?

- Response systems:
  - Passive/Motion inclusive
  - Gating
  - Tracking
  - Adaptation

[Images of 4D imaging examples]
Desirable Response System

- Integrates all sources of imaging information
- Integrates all sources of uncertainty
- Optimizes in real-time using all available degrees of freedom
- Modifies delivery appropriately

Tumor tracking

What have we got?

Question: Target tracking has been demonstrated with:
A. Couch  
B. Gimbaled linac  
C. MLC  
D. Robot  
E. All of the above

Answer: Target tracking has been demonstrated with:
A. Couch  
B. Gimbaled linac  
C. MLC  
D. Robot  
E. All of the above
Technologies available

- Block tracking
- Couch tracking
- Linac tracking
- MLC tracking
- Robotic tracking

Beam repositioning systems

<table>
<thead>
<tr>
<th>Position/motion detection device</th>
<th>Motion-compensation strategy</th>
<th>Dynamic beam patient-alignment technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical/kinetic</td>
<td>Passive</td>
<td>Robotic</td>
</tr>
<tr>
<td>X-ray/fluoroscopy</td>
<td></td>
<td>Couch</td>
</tr>
<tr>
<td>Ultrasound</td>
<td></td>
<td>Black</td>
</tr>
<tr>
<td>MRI</td>
<td></td>
<td>DALC</td>
</tr>
<tr>
<td>Spectrometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cyberknife Synchrony

Robotic tracking
Cyberknife synchrony

Block tracking

Couch tracking

 Courtesy Warren D'Souza
 University of Maryland

Schematic  No tracking  Tracking
Linac tracking

4D IGRT system

DMLC tracking

Institute of Biomedical Research and Innovation, Kobe, Japan
Extract Shape
Parallel Motion
Perpendicular Motion
Along beam axis (mag/deg)
Rotation
Deformation

DMLC tracking demo
Image-based DMLC tracking with RapidArc to a moving target, Stanford University
Dosimetric results
Tracking motion 2cm \||\ leaf, 0.5cm ↓

VMAT Results

Other MLC approaches
• Siemens 160 leaf MLC (Tacke et al. PMB)
• Tomotherapy (Olivera et al.)
• AccuKnife/AccuLeaf

Real-time targeting
Practical considerations
Practical considerations

• Issues with integrated position estimation/tumor tracking systems include:
  – Latency (160-570ms)/prediction algorithms
  – Position monitoring system accuracy, noise
  – Quality assurance
  – Reliance on automation
  – Impact on planning
  – Target focus- normal tissue ignored?

What can we conclude?

Conclusions

• All tumors and critical structures move during treatment
• Many techniques are available/in development to image changing anatomy
• Several techniques are available/in development to dynamically treat changing anatomy
• Watch this space!