Tumor Tracking – Current & Future Developments

Josh Evans, Ph.D.
Virginia Commonwealth University
Richmond, VA
Disclosures

• None.
Learning Objectives

• To understand:
  – the physiological characteristics of tumor motion in different treatment sites.
  – the basics of existing technology for tumor tracking and their limitations.
  – the background and concept of future technologies for tumor tracking.
Outline

• Tumor motion characteristics
  – Lung, prostate, brain

• Requirements for successful tumor tracking
  – Identify, anticipate, reposition, adapt dosimetry

• Current and Future Systems
  – CyberKnife, Robotic couch, Vero, integrated MRI-Treatment
What organs move?

• Breathing
  – Kidneys
  – Lungs
  – Pancreas
  – Esophagus
  – Liver
  – Breast

• Peristalsis
  – Gyn
  – GU
Lung motion

- Periodic, but can be irregular
- Hysteresis
- Location of tumor in lung can be important

Breathing motion

- Surface monitoring illustrates baseline breathing amplitude changes over time

Fig. 2. Variations in respiratory patterns from the same patient taken a few minutes apart. The three curves in each plot correspond to infra-red reflector

Prostate

- Calypso EM motion traces (9 – 10 mins)

- Prostate motion can be irregular and unpredictable

Fig. 6. Examples of behaviors observed in the continuous tracking data: (a) continuous target drift; (b) transient excursion; (c) stable target at baseline; (d) persistent excursion; (e) high-frequency excursions; (f) erratic behavior. Red: vertical, green: longitudinal, blue: lateral, black: vector length.

Brain

• CyberKnife tracking experience of brain SRS patient
• Baseline drift of skull position over 30 min
• Emphasizes need for treatment efficiency and intra-fraction position monitoring

---

Motion management approaches

- Motion-encompassing methods
- Respiratory-gating
- Breath-hold
- Forced shallow breathing (compression)
- *Respiration-synchronized techniques*

Outline

• Tumor motion characteristics
  – Lung, prostate, brain

• Requirements for successful tumor tracking
  – Identify, anticipate, reposition, adapt dosimetry

• Current and Future Systems
  – CyberKnife, Robotic couch, Vero, integrated MRI-Treatment
Successful tumor tracking...

1. **Identify** tumor position in real time
2. **Anticipate** tumor motion (compensate for system lag)
3. **Reposition** beam in real time
4. **Adapt dosimetry** for changing target and critical structure locations.
Successful tumor tracking…

1. How am I going to locate the target?
2. How far ahead do I need to know where the target is?
3. How am I re-aligning the beam & target?
4. Could this affect my target coverage or OAR sparing?
Successful tumor tracking...

1. How am I going to locate the target?
   - What are you locating?
     • Visualize target directly
     • Implanted fiducials
     • Target position surrogates
   - Imaging modality
     • Ionizing: 2d, 3d, x-ray
     • Non-ionizing: EM transponders, MRI, ultrasound
   - Imaging frequency
     • If ionizing; cumulative dose considerations
Calypso

1. How am I going to locate the target?
   - EM transponder fiducial tracking

FDA approved for prostate; under consideration for lung tracking
Successful tumor tracking...

2. How far ahead do I need to know where the target is?
   - What is the total system lag time?
     • Image acquisition, data processing, target/beam realignment
   - Predictive motion models
     • Residual uncertainty: add to target margin
Motion prediction

2. How far ahead do I need to know where the target is?
   - System latency
   - Prediction algorithm accuracy
     - Most work done for breathing motion

Krauss 2011 - compare 4 motion prediction models for breathing motion
   - RMSE prediction errors
     ~ 1 mm (0.2 s latency)
     to 2 mm (0.6 s latency)

TG-76 recommends total system latency < 0.5 sec

Successful tumor tracking...

3. How am I re-aligning the beam and target?
   - Move the beam
     - MLC tracking
     - Gimbaled linac head
     - Robot-mounted linac
   - Move the patient
     - Re-position couch
Dynamic MLC tracking

3. How am I re-aligning the beam & target?
   - Move the MLC to align with the moving target

Sawant 2008
   - Good tracking accuracy < 1 mm for in plane motion
   - Lower efficiency for high frequency motion perpendicular to leaf direction.

Successful tumor tracking...

4. Could this affect my target coverage or OAR sparing?
   • Will I miss my target?
   • Am I moving my beam in to normal tissues?
   • Are target and normal tissues moving rigidly or deformably?
   • What’s the dosimetric effect of not tracking? How much improvement with tracking?
4. Could this affect my target coverage or OAR sparing?
   - “Time-resolved dosimetry”

Poulsen 2012
- TPS calculation of time-resolved dosimetry
- Validated in dynamic thorax phantom with film dosimetry (simple 1D motion)
- Limitations:
  - Rigid shift of whole patient: no rotations, no deformations

Dynamic Prostate Tracking

- Keall 2014 – recent technical note on dynamic tracking for prostate patient
  1. Calypso EM transponder fiducials used for target tracking
  2. No prediction used since prostate motion typically slow and non-periodic
  3. Dynamic MLC repositioning
  4. Dose perturbation
     - Fractional rectum V60Gy:
       - + 5% (with tracking)
       - + 30% (no tracking)

Very active research topic

• Relevant articles in June 2014 issue of Medical Physics:


Outline

• Tumor motion characteristics
  – Lung, prostate, brain

• Requirements for successful tumor tracking
  – Identify, anticipate, reposition, adapt dosimetry

• Current and Future Systems
  – CyberKnife, Robotic couch, Vero, integrated MRI-Treatment
CyberKnife

- First clinical system designed to detect and compensate for intra-fx motion.

- Hybrid tumor monitoring
  - Surface imaging for continuous breathing monitoring
  - Fiducial based tracking of tumor on stereoscopic x-ray system
  - Build correspondence model

- Move entire linac mounted on robot.
Cyberknife lung tumor tracking

- Seppenwoolde 2007
  - Simulation to test the CyberKnife correspondence model
  - 8 patients with external and internal lung tumor tracking data
  - 95th percentile of 3D errors ~ 2-4 mm
  - Good discussion on model update frequency

Robotic couch re-positioning

3. How am I moving my beam?
   - Move the patient to align with the statically positioned beam

   - Translate and rotate around a virtual pivot point set to isocenter

Images courtesy of Civco
• 3. How am I moving my beam?
  – Move the patient to align with the statically positioned beam

• McNamara 2013
  – 10 patient breathing traces: 2 – 10 mins each
  – Program phantom: record motion with IR cameras
  – Average over 3 breathing cycles to estimate baseline drift
  – Lower frequency couch correction scheme: 10 sec delivery bins

• Overall mean RMSD from 4.9 mm (no correction) to 1.7 mm (couch correction)

Vero

- Ring gantry for stability
- MV EPID imaging
- Orthogonal kV imaging
- Gimbaled MV linac with MLC
  - Improve isocenter accuracy
  - Tumor tracking

Images courtesy of Vero
Vero tumor tracking

- **3. How am I moving my beam?**
  - Use gimbaled linac

- **Depuydt 2011**
  - Assess gimbals tracking with moving beam’s light field and digital camera
  - 2d Lego robot reproduce lung tumor trajectories
  - System lag = 47.7 ms for both directions (total ~ 200 ms for real-time flouroscopic tracking)
  - 2d tumor tracking errors: 0.54 mm ± 0.21 mm

---

Vero tumor tracking

- Depuydt 2013
  - Simulate dynamic tumor tracking process to assess workflow with Vero (5 patients)
  - Continuous surface imaging and fiducial based x-ray imaging
    - Visicoil placed in tumor for tracking
    - 3.2 mins to build correspondence model
  - Average of ~ 9 mins from entering room to first beam on.
  - Tracking errors of ~ 0.5 mm to 1.0 mm
    - *Image dose:* average = 1.8 mGy/min for 1 Hz x-ray monitoring

Integrated MRI-MV treatment machines

- **MRI Vs. x-ray:**
  - Improved soft tissue contrast
    - No need to implant fiducials
  - Non-ionizing
    - No imaging frequency / imaging dose tradeoff

- Integrating MRI scanner with MV treatment machine is technically challenging
  - Magnet strength: 0.3 – 3.0 Tesla
  - MV source: Co-60 Vs. Linac
  - MRI-MV orientation: in-line, perpendicular, rotating …
MRI-MV configurations

- Orientation of magnetic field and treatment beam has important implications
  - Engineering challenges
  - Linac output
  - Patient dosimetry


First clinically available: ViewRay

- Fixed cylindrical configuration
- 0.35 T super-conducting magnet
- 3x Co-60 sources

Images courtesy of ViewRay
ViewRay imaging

- Can image either
  - 1 plane @ 4 frames / second
    - OR
  - 3 planes @ 2 frames / second

Images courtesy of ViewRay
Successful tumor tracking...

1. Identify tumor position
2. Anticipate tumor motion (system lag)
3. Reposition beam
4. Adapt dosimetry
What was the first clinical system to employ real-time motion correction?

94% 1. CyberKnife
2% 2. GammaKnife
3% 3. Calypso
0% 4. ViewRay
0% 5. Vero
What was the first clinical system to employ real-time motion correction?

1. CyberKnife
2. GammaKnife
3. Calypso
4. ViewRay
5. Vero


ANSWER = 1: ref = Murphy 2004 seminars in RO & Schwiekkard 2000
The Vero system uses _______ to compensate for tumor motion and has been shown in phantom studies to achieve a mean tracking accuracy of ~ _______ mm:

5%  1. Dynamic couch movement / ~ 2 mm
77%  2. Gimbaled linac motion / ~ 0.5 mm
0%  3. Dynamic MLC motion / ~ 0.8 mm
14%  4. Gimbaled linac motion / ~ 3 mm
5%  5. Dynamic MLC motion / ~ 1 mm
The Vero system uses ________ to compensate for tumor motion and has been shown in phantom studies to achieve a mean tracking accuracy of ~ ________ mm:

1. Dynamic couch movement / ~ 2 mm
2. Gimbaled linac motion / ~ 0.5 mm
3. Dynamic MLC motion / ~ 0.8 mm
4. Gimbaled linac motion / ~ 3 mm
5. Dynamic MLC motion / ~ 1 mm

**ANSWER = 2: ref = Depuydt 2011**

The ViewRay system has a ______ configuration and can image a single plane up to ______ times / second

10%  1. Parallel / 2 times per sec
11%  2. Perpendicular / 8 times per sec
5%   3. Oblique / 2 times per sec
18%  4. Parallel / 4 times per sec
56%  5. Perpendicular / 4 times per sec
The ViewRay system has a ______ configuration and can image a single plane up to ______ times / second

1. Parallel / 2 times per sec
2. Perpendicular / 8 times per sec
3. Oblique / 2 times per sec
4. Parallel / 4 times per sec
5. Perpendicular / 4 times per sec

ANSWER = 5: ref = Dempsey 2005

To minimize the impact of breathing irregularity on lung target prediction algorithms, TG-76 recommends that overall system lag for real-time tumor tracking should not exceed ____:

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>9%</td>
<td>1. 50 ms</td>
</tr>
<tr>
<td>88%</td>
<td>2. 500 ms</td>
</tr>
<tr>
<td>1%</td>
<td>3. 1000 ms</td>
</tr>
<tr>
<td>2%</td>
<td>4. 1500 ms</td>
</tr>
<tr>
<td>2%</td>
<td>5. 2000 ms</td>
</tr>
</tbody>
</table>
To minimize the impact of breathing irregularity on lung target prediction algorithms, TG-76 recommends that overall system lag for real-time tumor tracking should not exceed ____:

1. 50 ms
2. 500 ms
3. 1000 ms
4. 1500 ms
5. 2000 ms

ANSWER = 2: ref = Keall 2006 (TG-76)

Tumor Tracking – Current & Future Developments

Josh Evans, Ph.D.
Virginia Commonwealth University
Richmond, VA