Respiratory Gated and Four-Dimensional Tumor Tracking Radiotherapy

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Potential conflicts-of-interest

- I am PI of a sponsored research agreement between Stanford University and Varian Medical Systems

Educational objectives

- Understand the rationale for accounting for respiratory motion during imaging, treatment planning and radiation delivery
- Learn about respiratory gated radiotherapy and 4D tumor tracking radiotherapy
- Understand the advantages and disadvantages of respiratory gated and tumor tracking radiotherapy

Overview

- Effects of poor motion management
- Clinical rationale for improved motion management
- Target position monitoring systems
- Uses of target position information
- Summary

Measurement of respiratory motion

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Measurement of lung tumor motion

The tumor moves with time

Distorted images, incorrect anatomical positions, volumes or shapes

Treatment Planning: Large margins are added to the clinical target volume

IMRT Delivery: Interplay between anatomy and MLC leaf motion leads to motion artifacts
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Clinical rationale

- An RTOG retrospective analysis of 1290 NSCLC patients demonstrates that every 10-Gy increase in BED results in an 18% decrease in the risk of death
- Martel et al. estimate that 85 Gy is needed to achieve 50% local progression-free survival at 30 months
- The cost of dose escalation is normal tissue toxicity, which has been shown to be dose dependent for lung, heart, esophagus and bronchus

Improved targeting will allow improved tumor control

Wulf, Rad Onc, 2005
Improved targeting will allow improved tumor control

Improved targeting will allow reduced treatment toxicity

Clinical rationale

- Simultaneously increase tumor dose and reduce normal tissue dose?
  - Increase treatment accuracy
- Other methods
  - Improve dose calculation accuracy
  - Improve IMRT
  - Increase degrees of freedom in delivery
  - Normal tissue displacement
  - Particles
  - Synergistic biologic modifiers

Clinical rationale

- The skeletal, respiratory, GU, GI and cardiac systems cause tumor motion
- The magnitude of motion is variable and unpredictable

Respiratory variability

Case study: T1 NSCLC; non-operative due to COPD
Case study: Gated IMRT
70Gy in 2Gy/fx

Prior to gated IMRT 3 wks after 70 Gy gated IMRT

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Respiration signals
- External
  - Optical
  - Spirometer
  - Strain gauge
  - Nasal thermistor
  - Pressure sensors
- Internal
  - Fluoroscopy
  - EPID
  - Indoor GPS
  - EM
  - MRI
  - US

Target position monitoring systems
- Uses of target position information

Summary

Respiration signals

Surrogate choices

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<th>Surrogate</th>
<th>The good</th>
<th>The bad</th>
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<tr>
<td>External respiration signal</td>
<td>Real time</td>
<td>Limited dimensionality, no positional information, variable tumor correlation</td>
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<tr>
<td>Implanted markers</td>
<td>Real time</td>
<td>Limited dimensionality, migration, invasive</td>
</tr>
<tr>
<td>4D CT</td>
<td>Large dimensionality</td>
<td>Not real time</td>
</tr>
<tr>
<td>MRI/US</td>
<td>Large dimensionality, real time</td>
<td>Not yet commercially available</td>
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Surrogate vs. tumor motion

\[ R(t) = S + I + M \left[ T(t + \Delta 0) \right] + \epsilon(t) \]

\[ R(t) = \text{motion signal at time } t \]
\[ S = \text{set-up error} \]
\[ I = \text{internal motion} \]
\[ M = \text{motion ratio (surrogate/tumor)} \]
\[ T(t) = \text{tumor motion} \]
\[ \Delta 0 = \text{phase difference} \]
\[ \epsilon(t) = \text{error term} \]
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Action threshold

- Continuously receive position information
- Beam on if position < threshold
- Beam hold if position > threshold

Respiratory gating

- Similar to action threshold but applicable to periodic motion
- Continuously receive position information
- Beam on if position < threshold
- Beam hold if position > threshold

Respiratory gated treatment

Motion inclusive treatment
RPM system components

- **IR Reflective marker block**: Reflects infrared light, making them appear as bright areas on CCD camera images.
- **IR Illuminator**: Infra-red light source.
- **IR Reflective marker block**: Markers reflect IR light, making them appear as bright areas on CCD camera images.
- **Junction Box**: Power supply source and routing center for signals.
- **Video distribution amplifier**: Amplify video signals.
- **In room View Finder**: Ensure markers are within the field of view for the CCD camera.
- **Gating switch box**: Enables/Disables gated treatments at Linac.

Motion tracking

**Dynamic motion compensation**

- **Open loop - move beam**
  - Robotic control of the linear accelerator (clinically available)
  - Block motion (used clinically at one center)
  - DMLC (proof of principle but not clinical)
- **Closed loop - move patient**
  - Couch motion (proof of principle but not clinical)

**Couch tracking**

- Schematic
- No tracking
- Tracking

**Beam tracking**

- Courtesy Accuray

**Block tracking**

- Courtesy Warren D’Souza
  - University of Maryland
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- Position monitoring devices provide useful information
- This information can be used in several ways
- A targeted radiotherapy control system can minimize geometric error
- Geometric errors translate to dosimetric errors
- Engineering and implementation issues remain

Integrated position monitoring and targeted radiotherapy systems

can

- Significantly reduce systematic and random treatment errors
- Reduce set-up time
- Reduce operator error

Integrated position monitoring and targeted radiotherapy systems
are limited by

- Accuracy of position monitoring system
- Relationship of surrogate to target
  - Deformation
  - Rotation
  - Migration
  - Anatomic and physiologic changes
- Tracking of normal anatomy

Radiotherapy challenge?

Courtesy Steve Jiang
Massachusetts General Hospital