The integration of position monitoring and targeted radiotherapy control systems

P Keall\textsuperscript{1,2}, S Vedam\textsuperscript{2,3} and M Murphy\textsuperscript{2}

\textsuperscript{1}Stanford University
\textsuperscript{2}Virginia Commonwealth University
\textsuperscript{3}UT MD Anderson Cancer Center
Potential conflicts-of-interest

I am PI of a sponsored research agreement between Stanford University and Varian Medical Systems.
Educational objectives

By the end of this lecture you should be able to:

– Describe basic control systems
– Explain how control systems can be used for targeted radiotherapy
– Describe passive, gated and dynamic motion compensation
– Describe the role of motion prediction algorithms and the effect of system response time
Overview

- Clinical rationale
- Control systems
- System response time and motion prediction
- Motion compensation strategies
- Summary
### Overview

<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/video</td>
<td>Passive</td>
<td>Robotic</td>
</tr>
<tr>
<td>X-ray/fluoroscopy</td>
<td>Gated</td>
<td>Couch</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Dynamic</td>
<td>Block</td>
</tr>
<tr>
<td>MRI</td>
<td></td>
<td>DMLC</td>
</tr>
<tr>
<td>Spirometer</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>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Previous talks**

**This talk**
Clinical rationale
Clinical rationale

- The skeletal, respiratory, GU, GI and cardiac systems cause tumor motion
- The magnitude of motion is variable and unpredictable
Geometric error translates to dosimetric error
Geometric error translates to dosimetric error
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
Improved targeting will allow improved tumor control

Wulf, Rad Onc, 2005
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
  - …
Control systems
Control systems

- Consist of methods assembled for the purpose of controlling the outputs of processes
- Provides an output or response for a given input
- Two broad classes
  - Open loop
  - Closed loop
Open loop systems

- Target position → + Difference signal → Motion controller
- Motion controller → Updated position → Beam control
- Beam control → Position feedback → Beam position
- Beam position → - Difference signal

Target position + Difference signal → Motion controller → Updated position → Beam control → Position feedback → Beam position
Open loop systems

- The radiation beam is redirected to account for target motion
- Examples:
  - Linear accelerator
  - Block
  - MLC
- Advantage:
  - Cannot become unstable as long as the controlled object is stable
Closed loop system

Target position \(\rightarrow\) Difference signal \(\rightarrow\) Motion controller

Updated position \(\rightarrow\) Target control
Closed loop system

- The target itself is redirected to negate target motion
- Example is moving the patient via the couch
- Advantage
  - Use negative feedback to counteract against disturbances
- Disadvantage
  - Can potentially become unstable, i.e., the controlled variable does not fade away, but grows to an infinite value
System response time and motion prediction
System response/latency

- Camera
- Optical reflector
- DMLC
- Patient motion simulator

Images for analysis

Camera 1
Camera 2
MLC controller
4D controller
RPM system

Leaf positions
Reflector positions

Images

Patient motion simulator
Motion prediction

For any given sequence \( \{x\} = x_{\text{act}}(t_n)_{n=1}^{n_2} \) at a given time instant \( t_n \), prediction provides an estimate \( x_{\text{pred}}(t_{n+\Delta}) \) of \( \{x\} \), ahead by an interval \( \Delta \). The prediction \( x_{\text{pred}}(t_{n+\Delta}) \) is based on a number of previous values of the sequence, referred to as signal history window; the length of which is referred to as signal history length \( SHL \), as seen in the equation below:

\[
x_{\text{pred}}(t_{n+\Delta}) = f\{x_{\text{act}}(t_n), x_{\text{act}}(t_{n-1}), \ldots, x_{\text{act}}(t_{n-SHL})\}.
\]

- Well defined problem with clear metric and few constraints on solution method
  - Metric: Predicted – actual position
  - Constraint: Calculate \( << \Delta \)
Motion prediction

Without prediction

- Acquire new target position
- Current MLC leaf position feedback
- Compute error in position and correction
- Initiate MLC mechanical response

Continual motion of target during each of the tasks above results in a consistent delay in the response of the MLC by a value \( \Delta \) (Response time)

With prediction

- Acquire new target position
- Predict next target position in advance by \( \Delta \) (Response time)
- MLC response

MLC response based on prediction accounts for the delay and ensures synchronized treatment delivery

- No prediction: Residual error due to response time
- Prediction: Residual error due to signal/model
Motion prediction algorithms

- None
- Parametric modeling
- Kalman/adaptive filters
- Neural networks
- …
Error increases with response time
Prediction error < latency error
Dosimetric error increases too!

![Graph showing IMRT - Free breathing - PA Beams with various error metrics]

- 6 MV Pred Error
- 6 MV Latency Error
- 6 MV Resp Motion Error
- 18 MV Pred Error
- 18 MV Latency Error
- 18 MV Resp Motion Error

Y-axis: > 1% DD and 1 mm DTA
X-axis: Response time (msec)
Prediction error varies with ...

- Response time (latency)
- Algorithm
- Position information frequency
- Signal irregularity/non-stationary behavior
  - No error for periodic signals
Motion compensation strategies
- Continuously receive position information
- Beam on if position < threshold
- Beam hold if position > threshold
Gated control

- Similar to action threshold but applicable to periodic motion
- Continuously receive position information
- Beam on if position < threshold
- Beam hold if position > threshold
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)
Target tracking is not rocket science
Target tracking is rocket science
Dynamic motion compensation examples

Robotic linac
Courtesy Accuracy

DMLC
Dynamic motion compensation for IMRT
Tracking patient-derived motion
Tracking patient-derived motion

Displacement vs. time

Tracking error vs. time

Target
Beam
Beam (RT corr)
PDF of corrected and uncorrected motion
Comparison of motion compensation methods
Summary
Summary

- 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