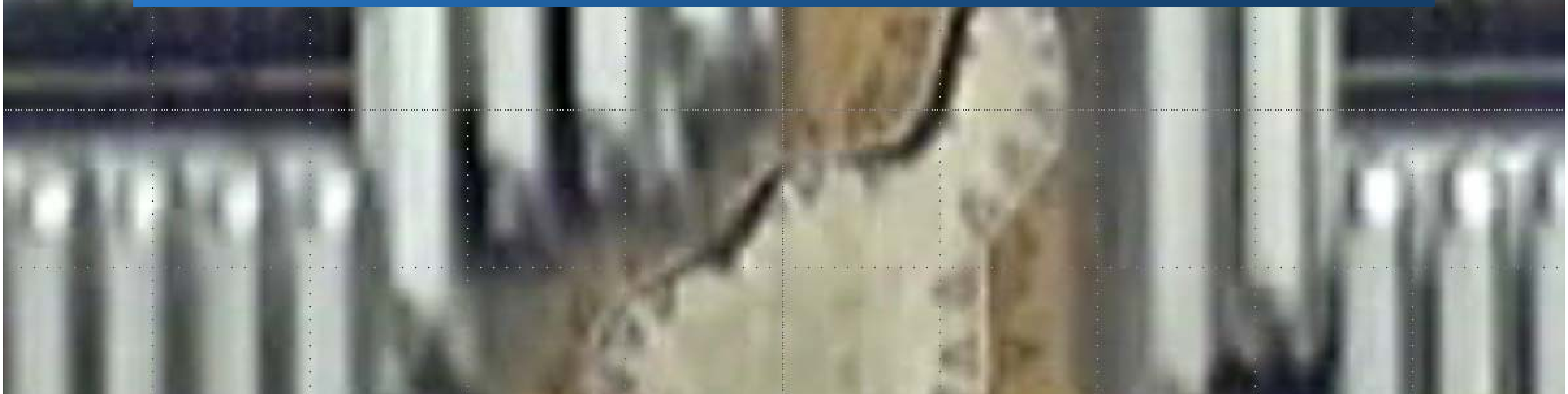
The integration of position monitoring and targeted radiotherapy control systems



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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

- 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

Position/motion detection device	Motion-compensation strategy	Dynamic beam patient-alignment technologies
Optical/video X-ray/fluoroscopy Ultrasound MRI Spirometer EPID Electromagnetic Combination …	Passive Gated Dynamic	Robotic Couch Block DMLC

Previous talks

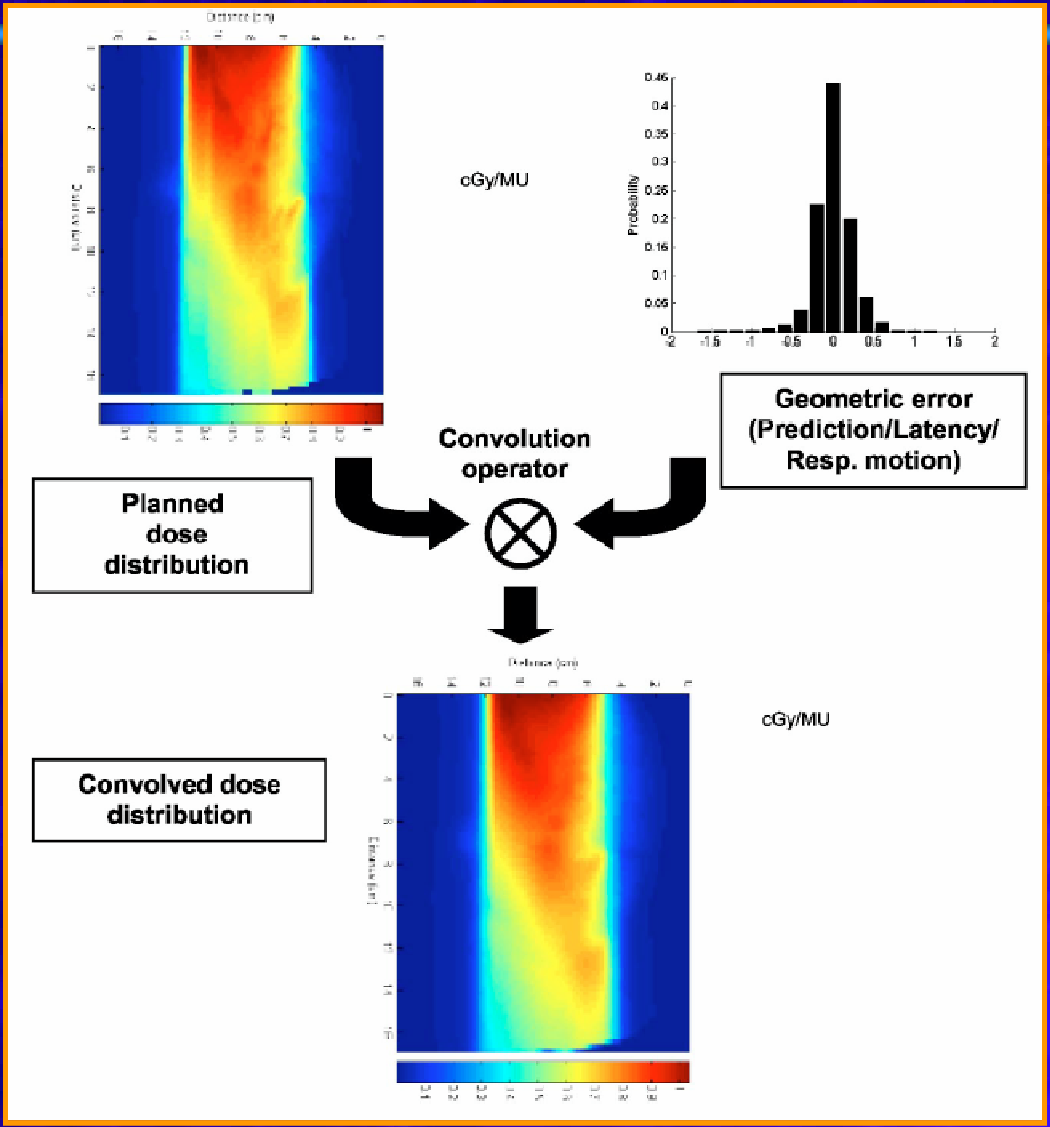
This talk

Clinical rationale

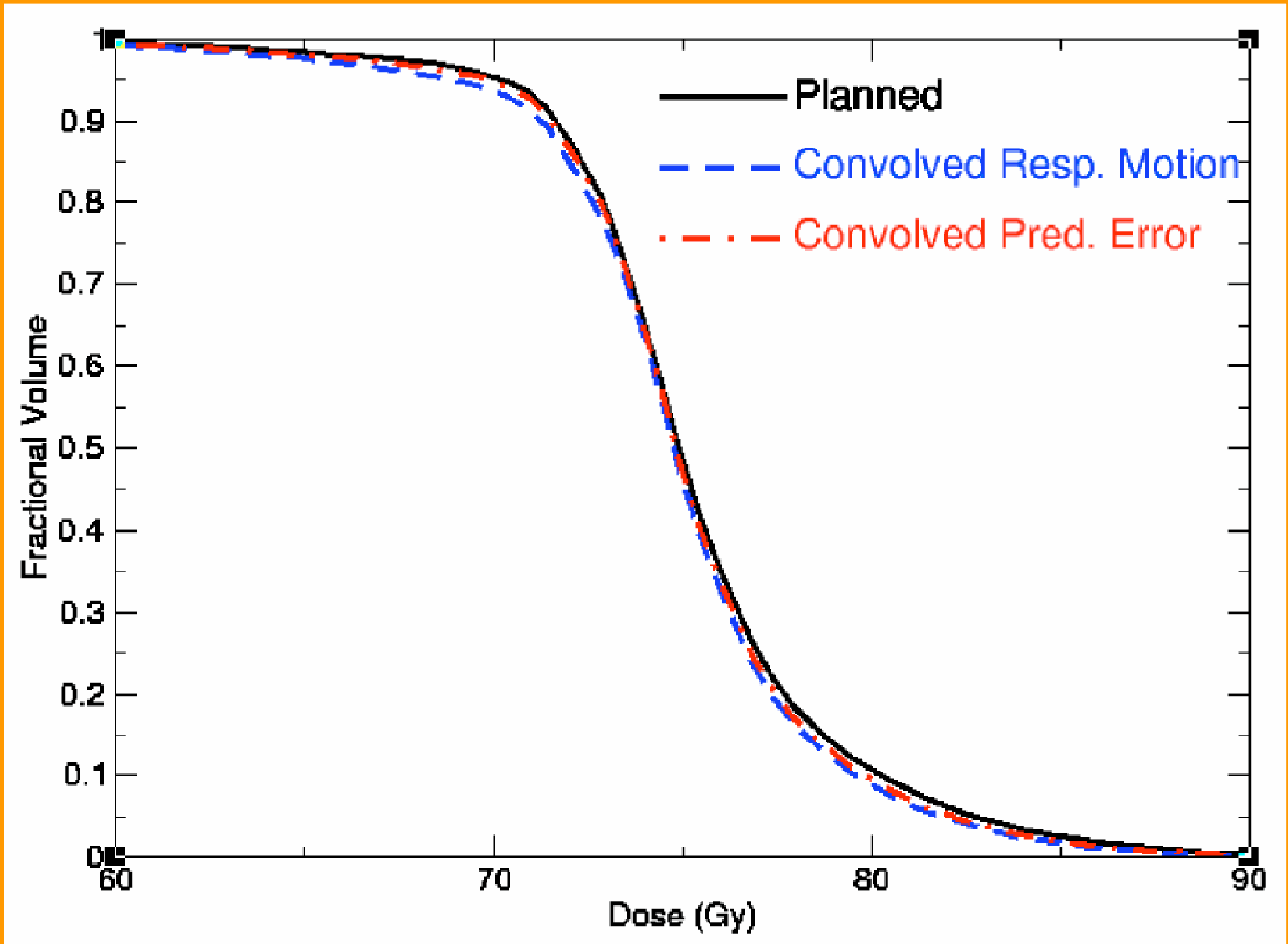
Clinical rationale

- 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



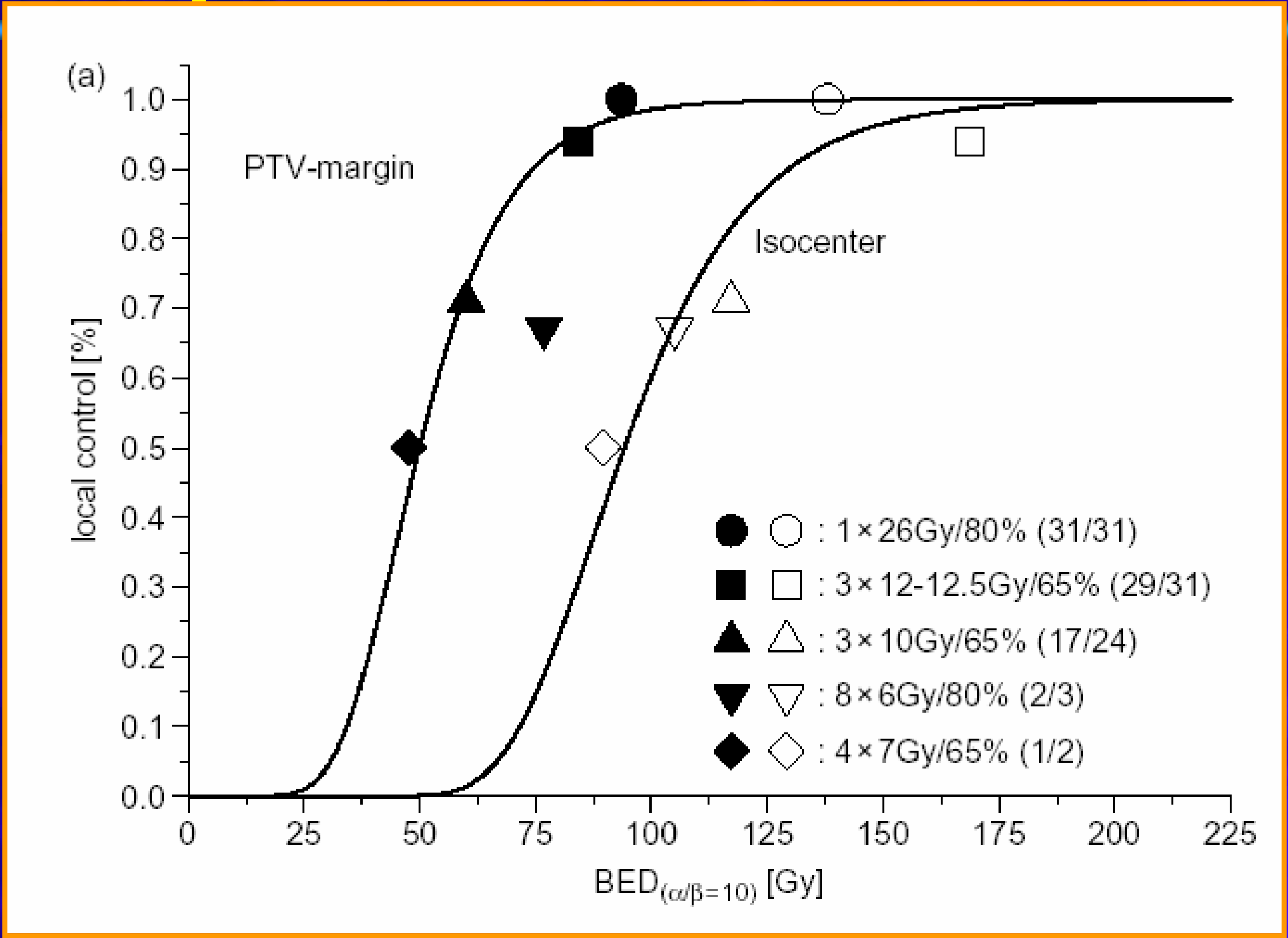
Geometric error translates to dosimetric error



Clinical rationale

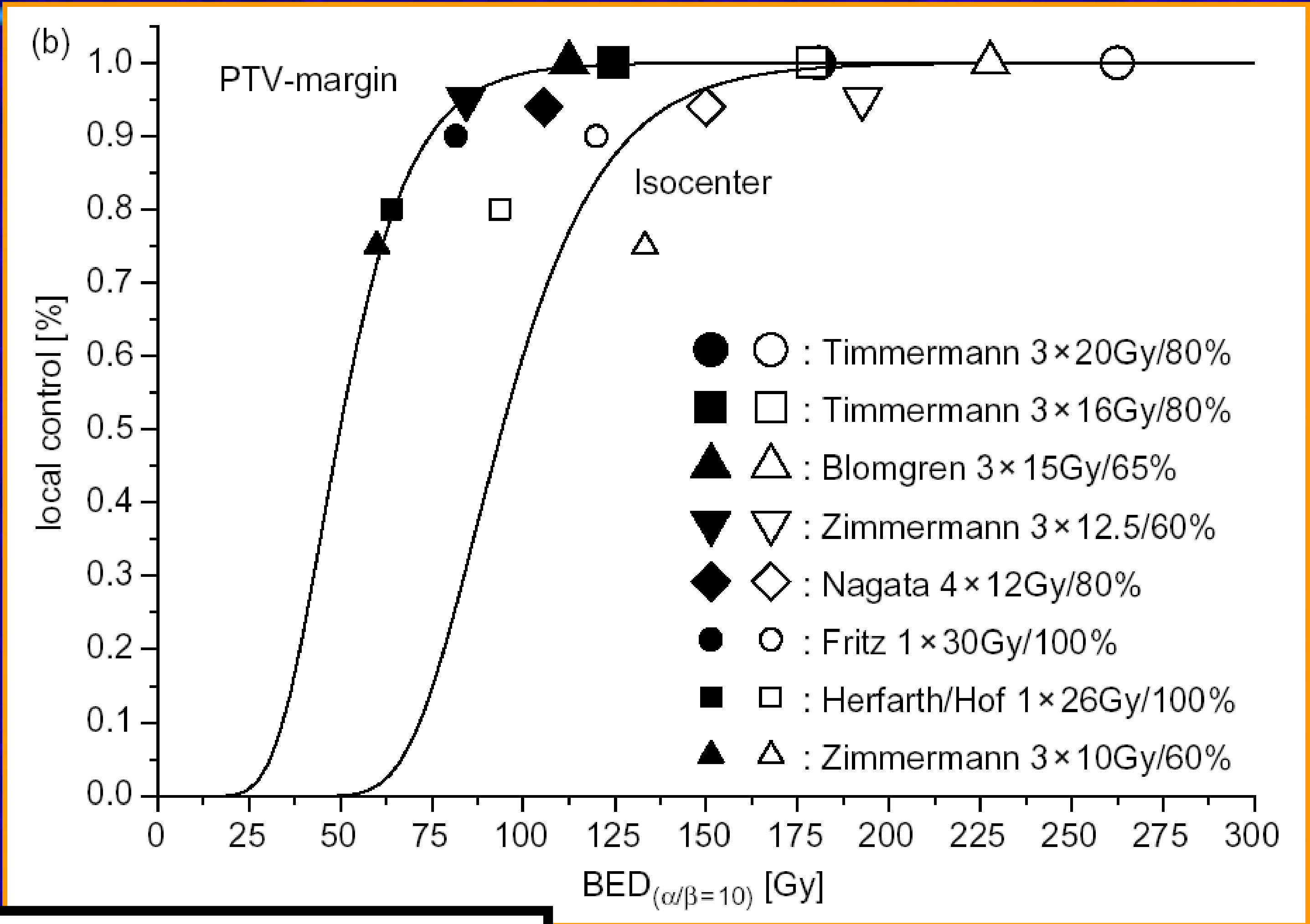
- An RTOG retrospective analysis of 1290 NSCLC patients demonstrates that every 10-Gy increase in BED results in an 18% decrease in the risk of death
- Martel *et al*. estimate that 85 Gy is needed to achieve 50% local progression-free survival at 30 months
- The cost of dose escalation is normal tissue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

Improved targeting will allow improved tumor control



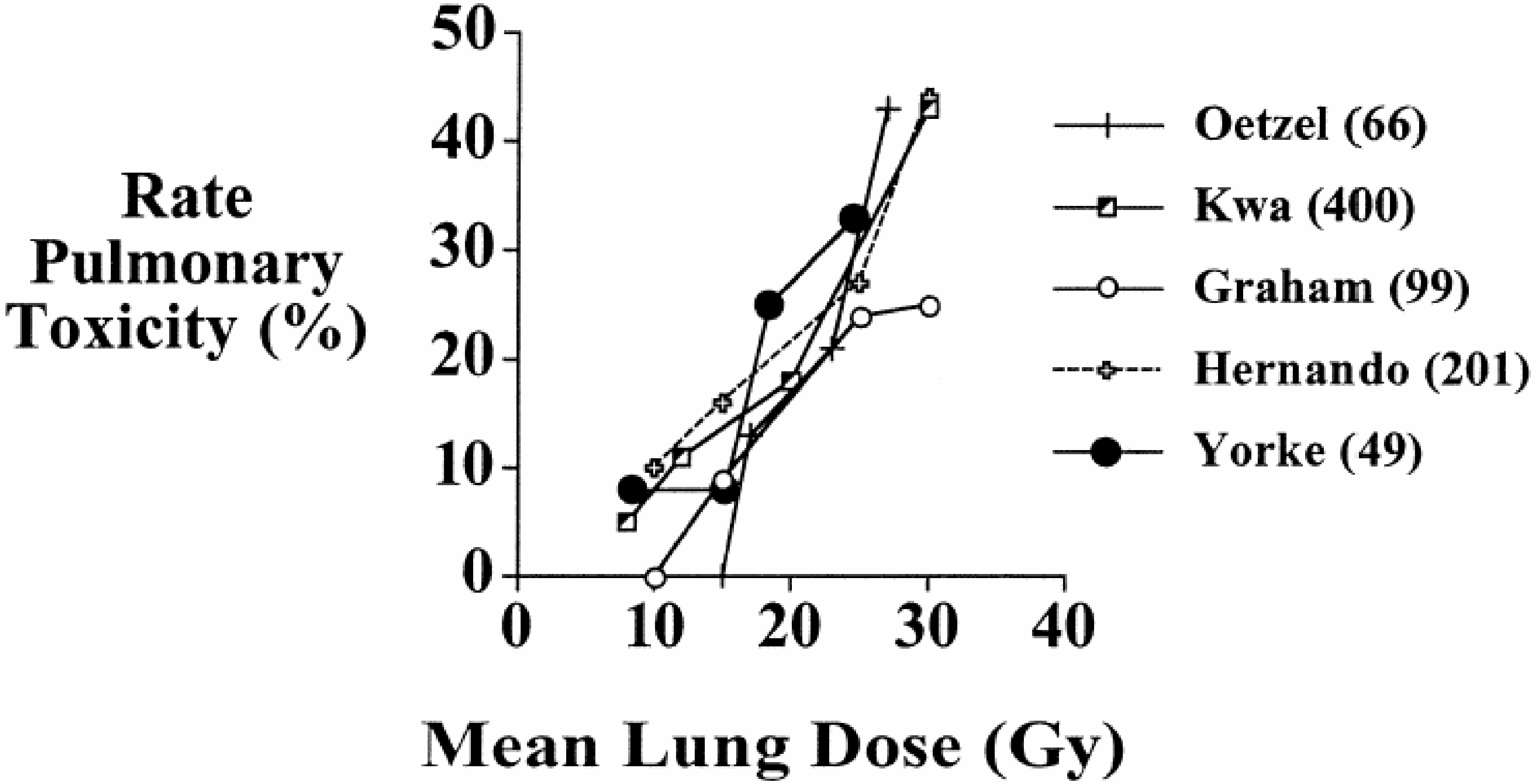
Wulf, Rad Onc, 2005

Improved targeting will allow improved tumor control



Wulf, Rad Onc, 2005

Improved targeting will allow reduced treatment toxicity



Marks, IJROBP editorial, 2002

Clinical rationale

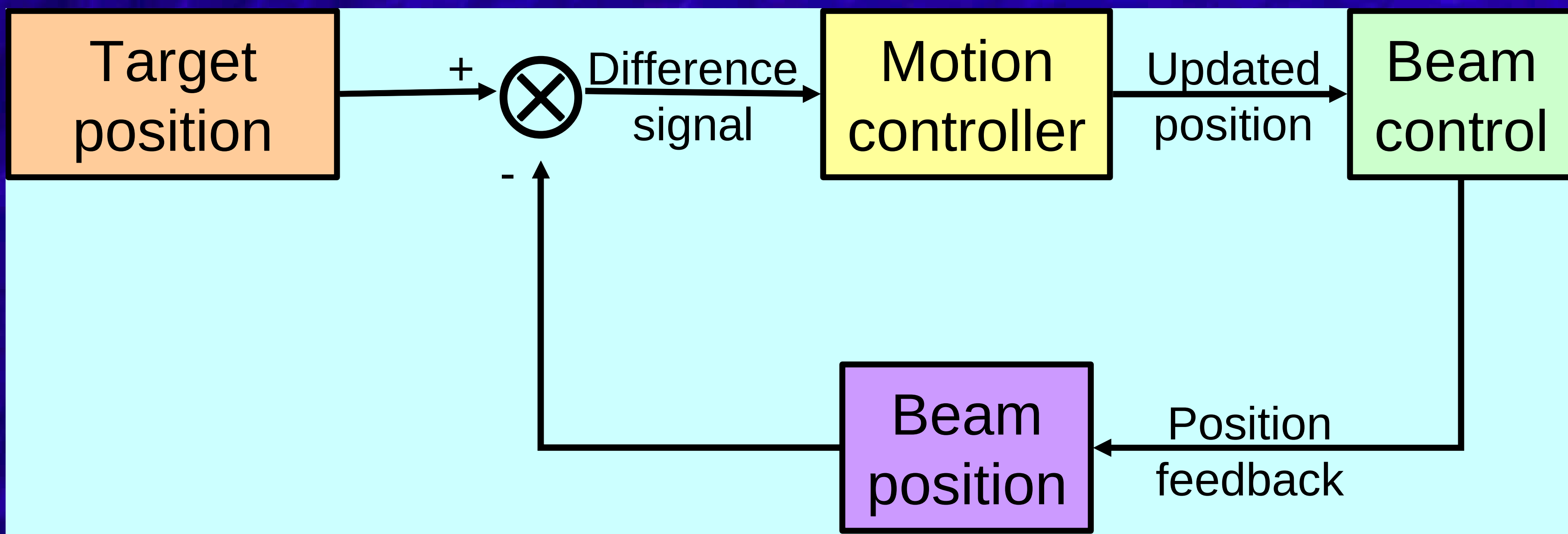
- Simultaneously increase tumor dose and reduce normal tissue dose?
  - Increase treatment accuracy
- Other methods
  - Improve dose calculation accuracy
  - Improve IMRT
  - Increase degrees of freedom in delivery
  - Normal tissue displacement
  - Particles
  - Synergistic biologic modifiers
  - …

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

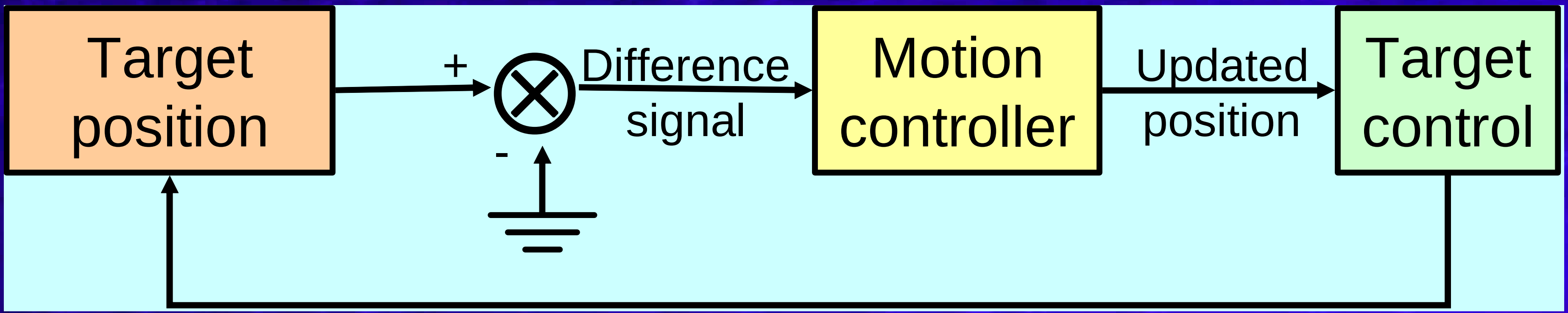
Open loop systems



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

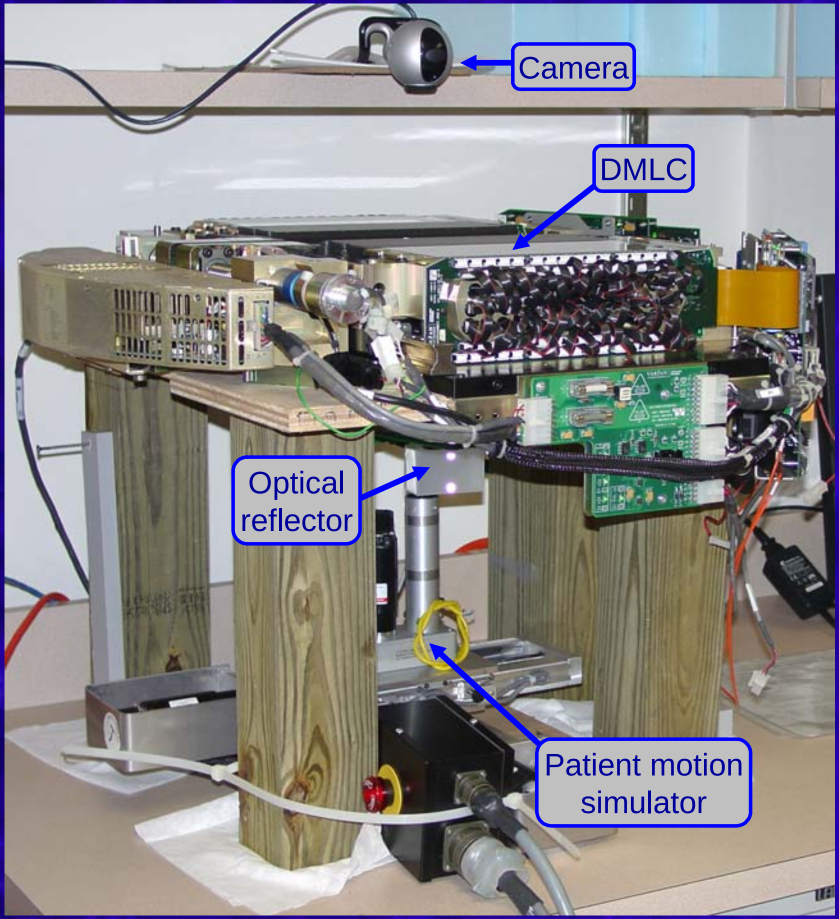


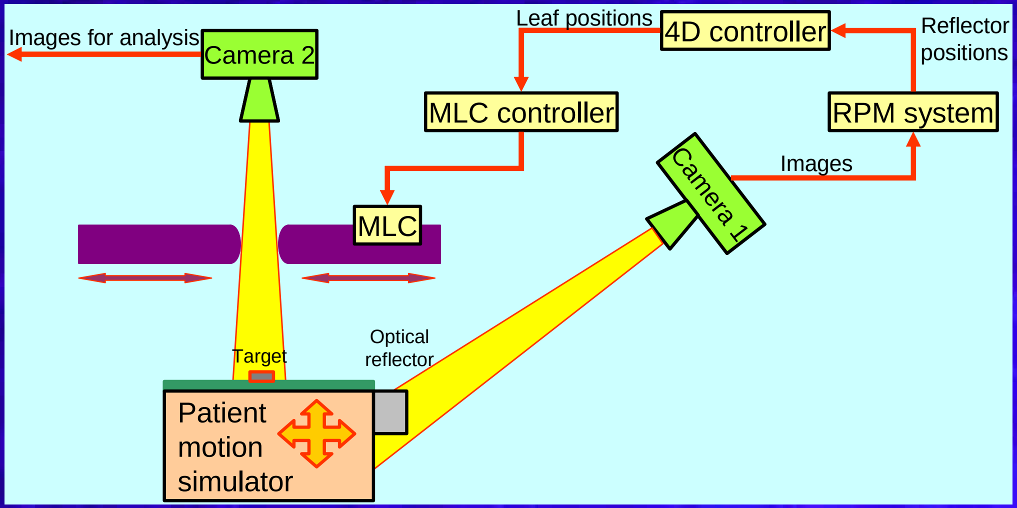
Closed loop system

- 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





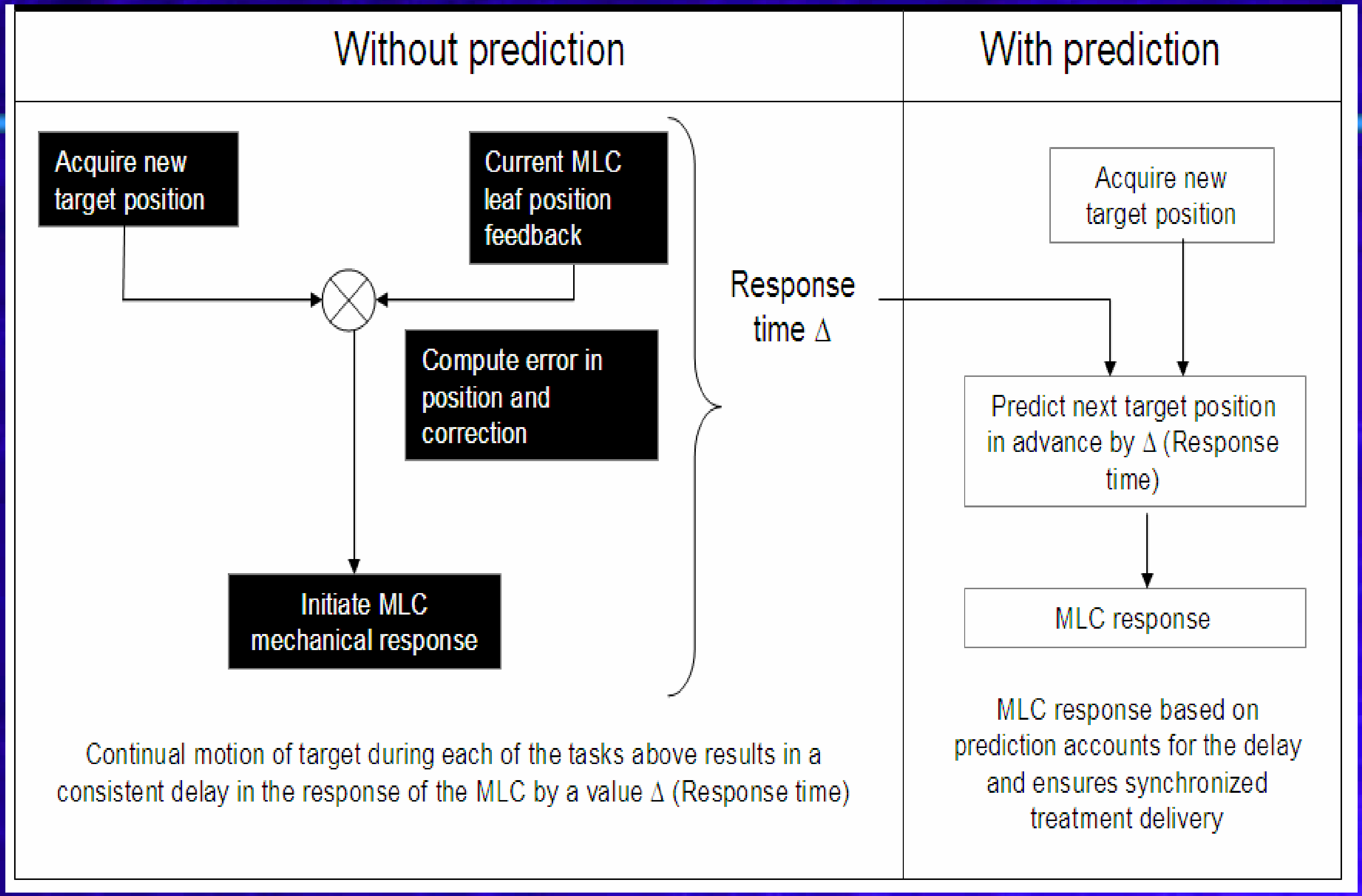
Motion prediction

For any given sequence $\{x\} = x_{act}(t_n)\big|_{n=1,m}$ at a given time instant t_n, prediction provides an estimate $x_{pred}(t_{n+\Delta})$ of $\{x\}$, ahead by an interval Δ. The prediction $x_{pred}(t_{n+\Delta})$ 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:

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

- Well defined problem with clear metric and few constraints on solution method
  - Metric: Predicted – actual position
  - Constraint: Calculate << Δ

Motion prediction

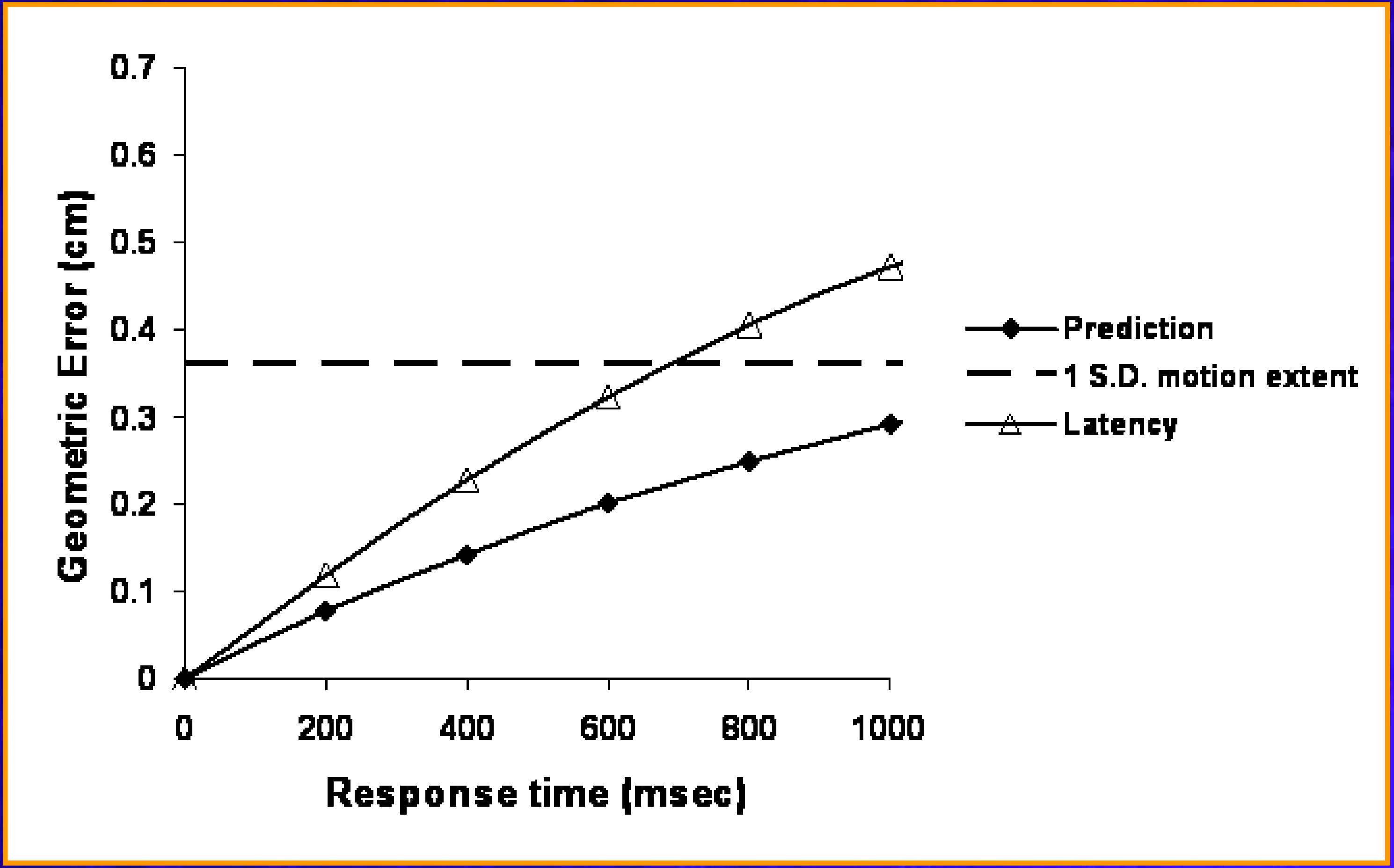


- No prediction: Residual error due to response time
- Prediction: Residual error due to signal/model

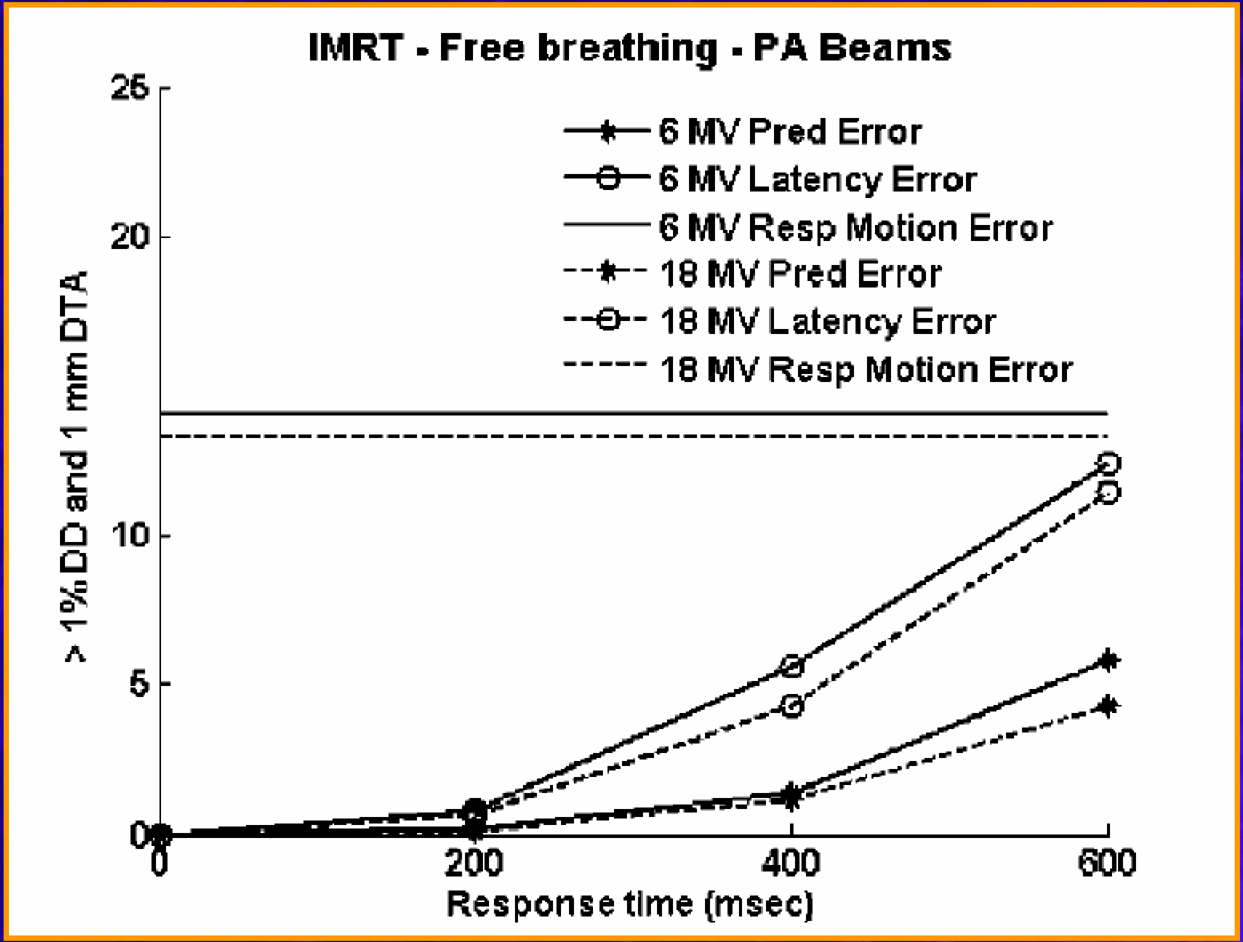
Motion prediction algorithms

- None
- Parametric modeling
- Kalman/adaptive filters
- Neural networks
- …

Error increases with response time Prediction error < latency error

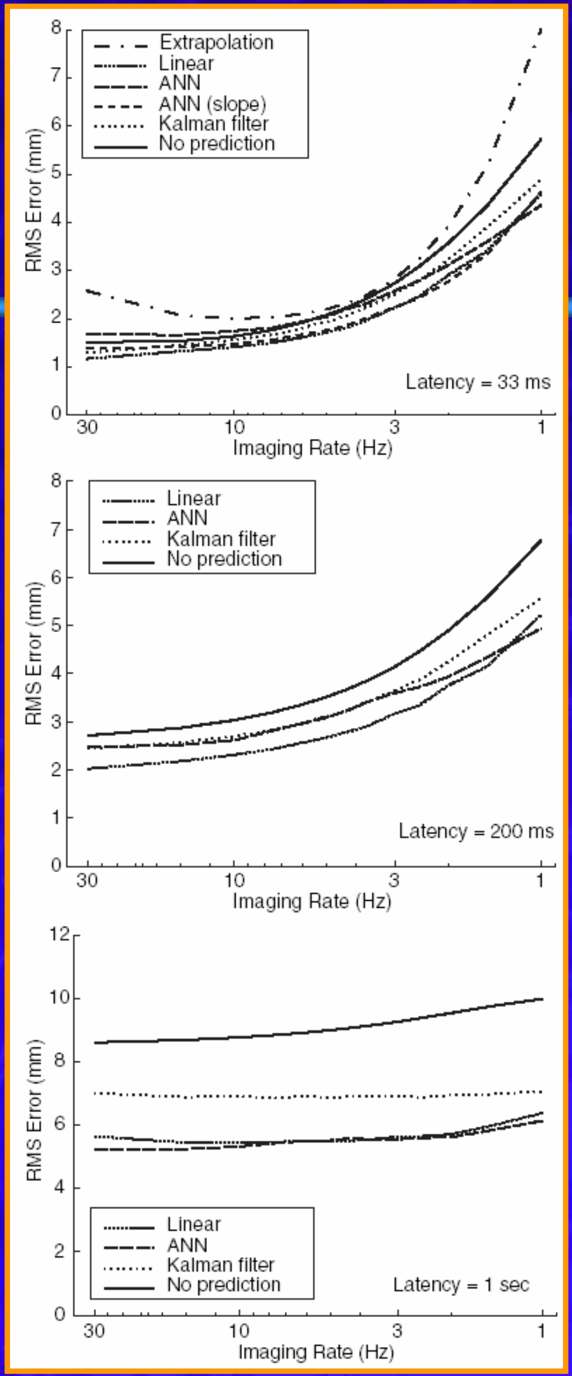


Dosimetric error increases too!



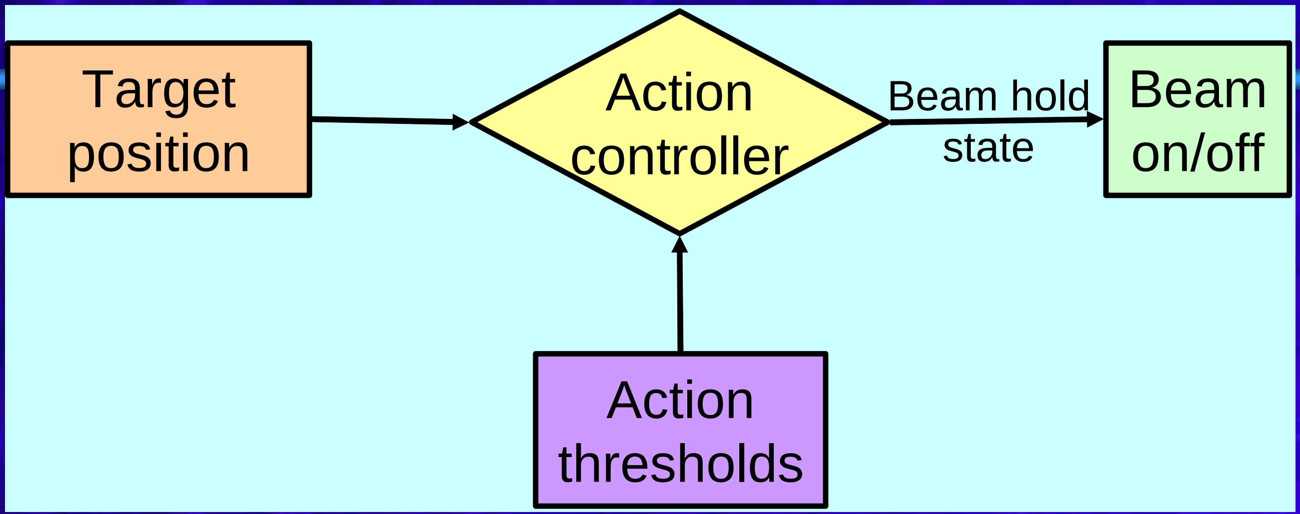
Prediction error varies with …

- Response time (latency)
- Algorithm
- Position information frequency
- Signal irregularity/non-stationary behavior
  - – No error for periodic signals



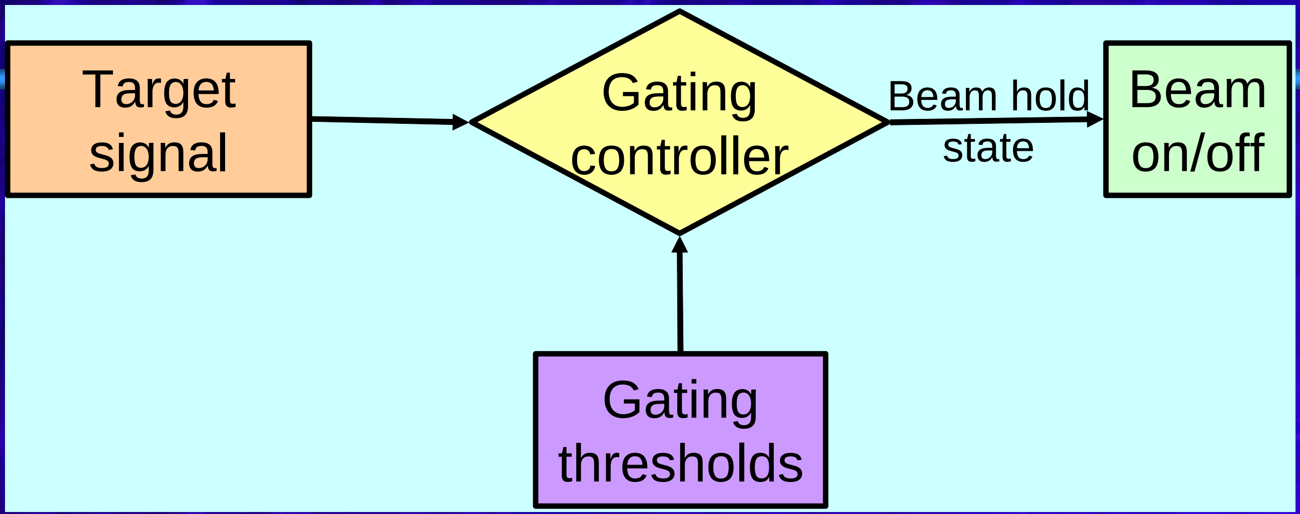
Motion compensation strategies

Action threshold



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

Gated control

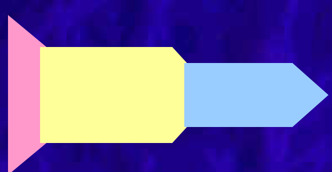


- Similar to action threshold but applicable to periodic motion
- Continuously receive position information
- Beam on if position < threshold
- Beam hold if position > threshold

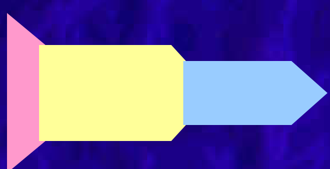
Dynamic motion compensation

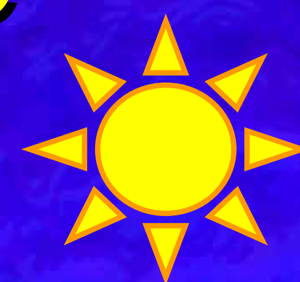
- Open loop- move beam
  - Robotic control of the linear accelerator (clinically available)
  - Block motion (used clinically at one center)
  - DMLC (proof of principle but not clinical)
- Closed loop- move patient
  - Couch motion (proof of principle but not clinical)

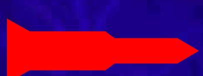
Target tracking is not rocket science



Target tracking is rocket science







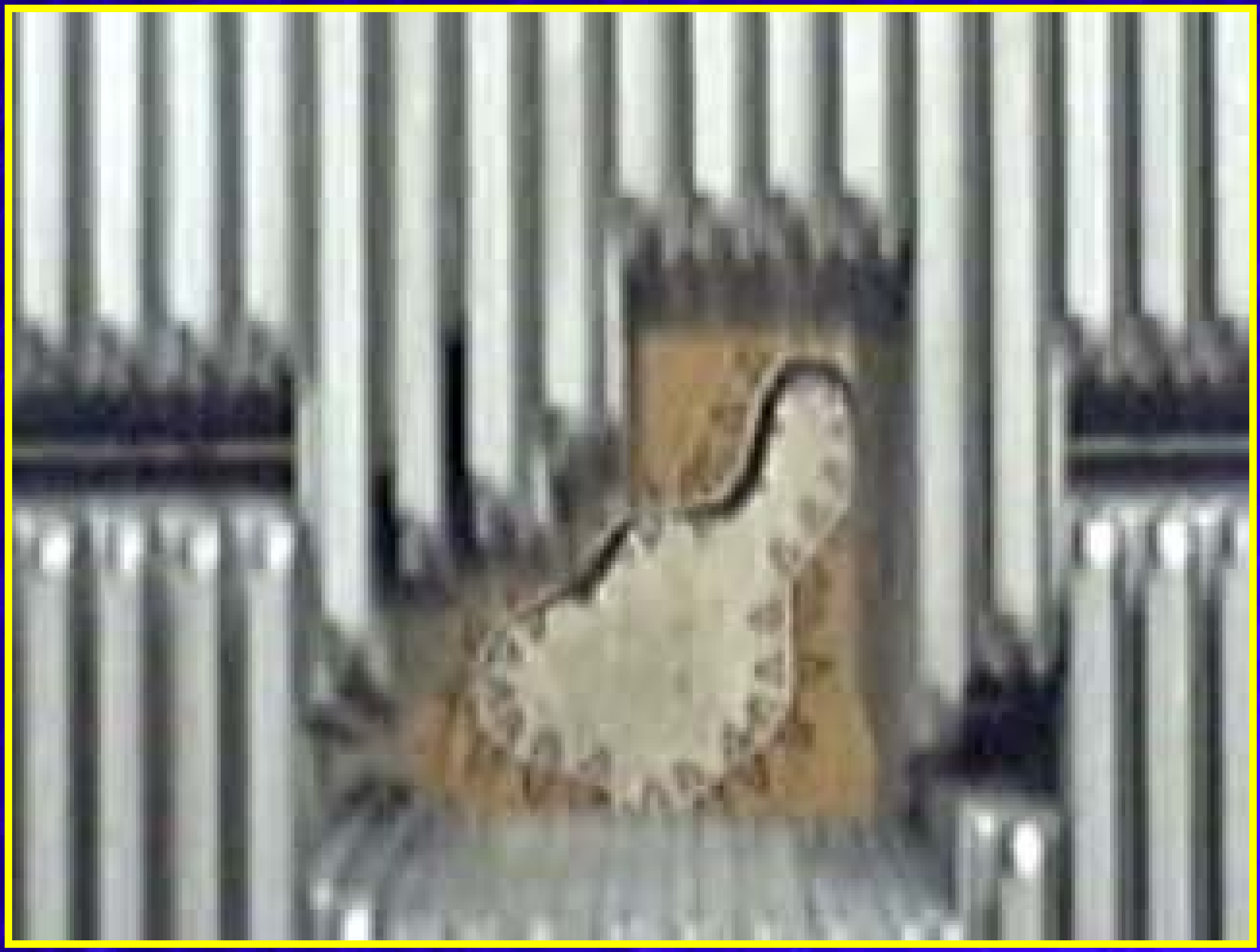
Dynamic motion compensation examples

Robotic linac

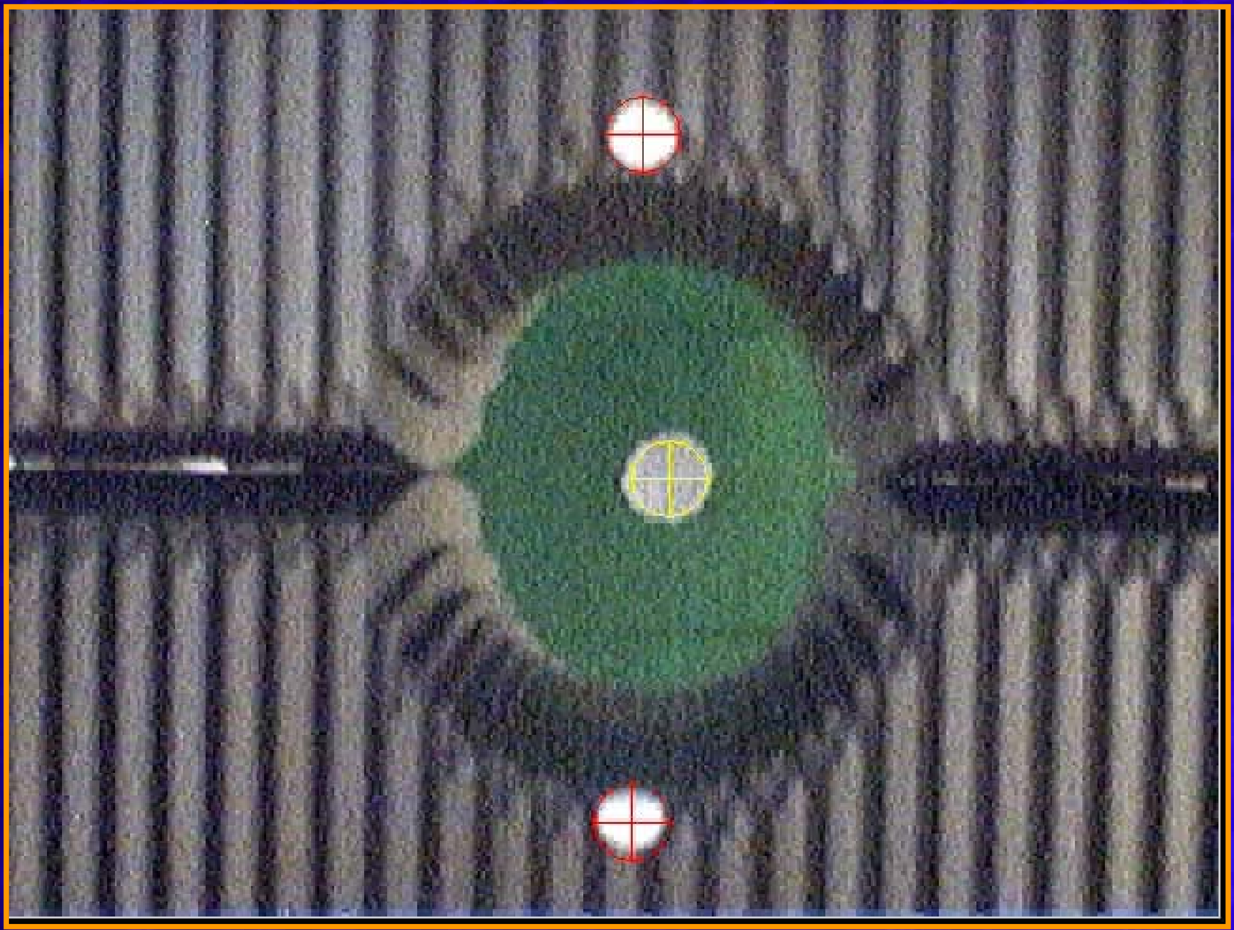
Courtesy Accuracy

DMLC

Dynamic motion compensation for IMRT

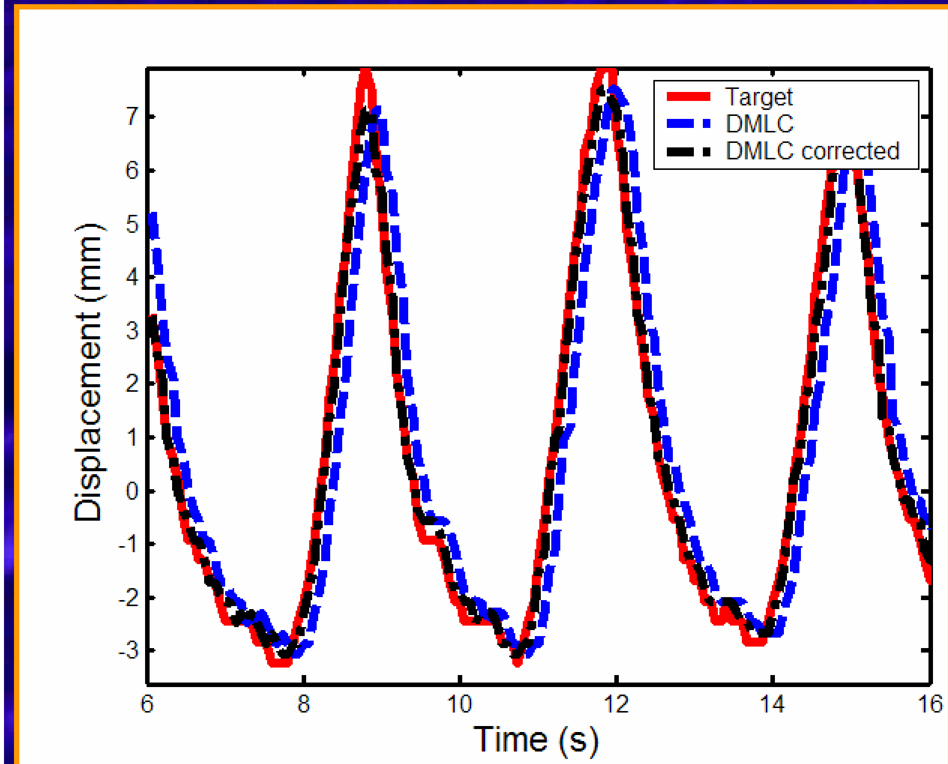


Tracking patient-derived motion

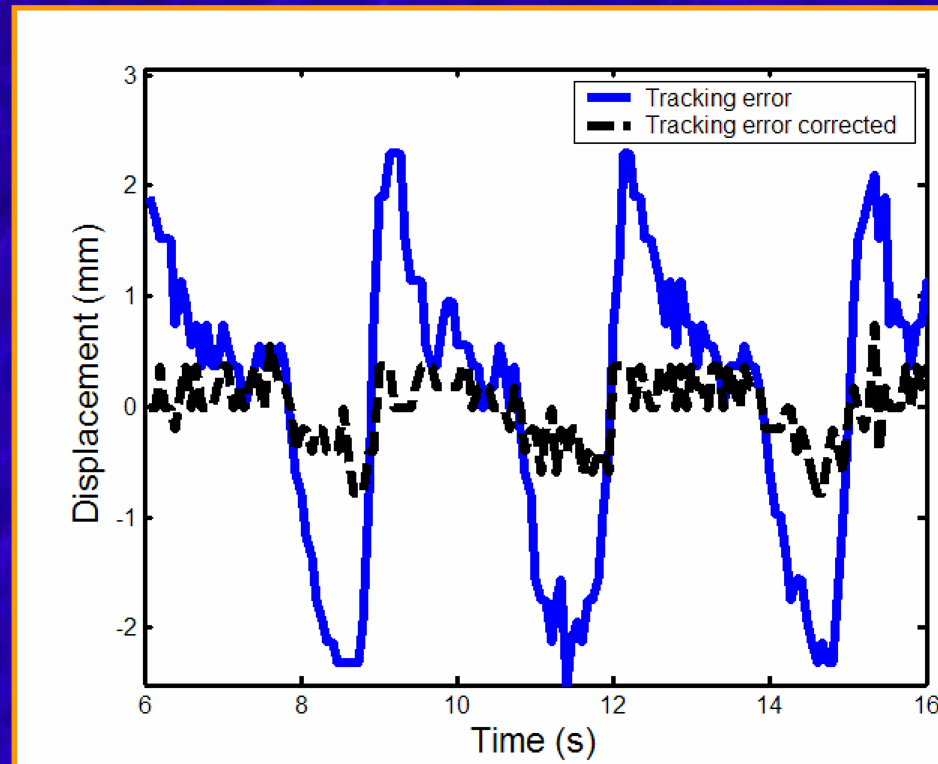


Tracking patient-derived motion

Displacement vs. time

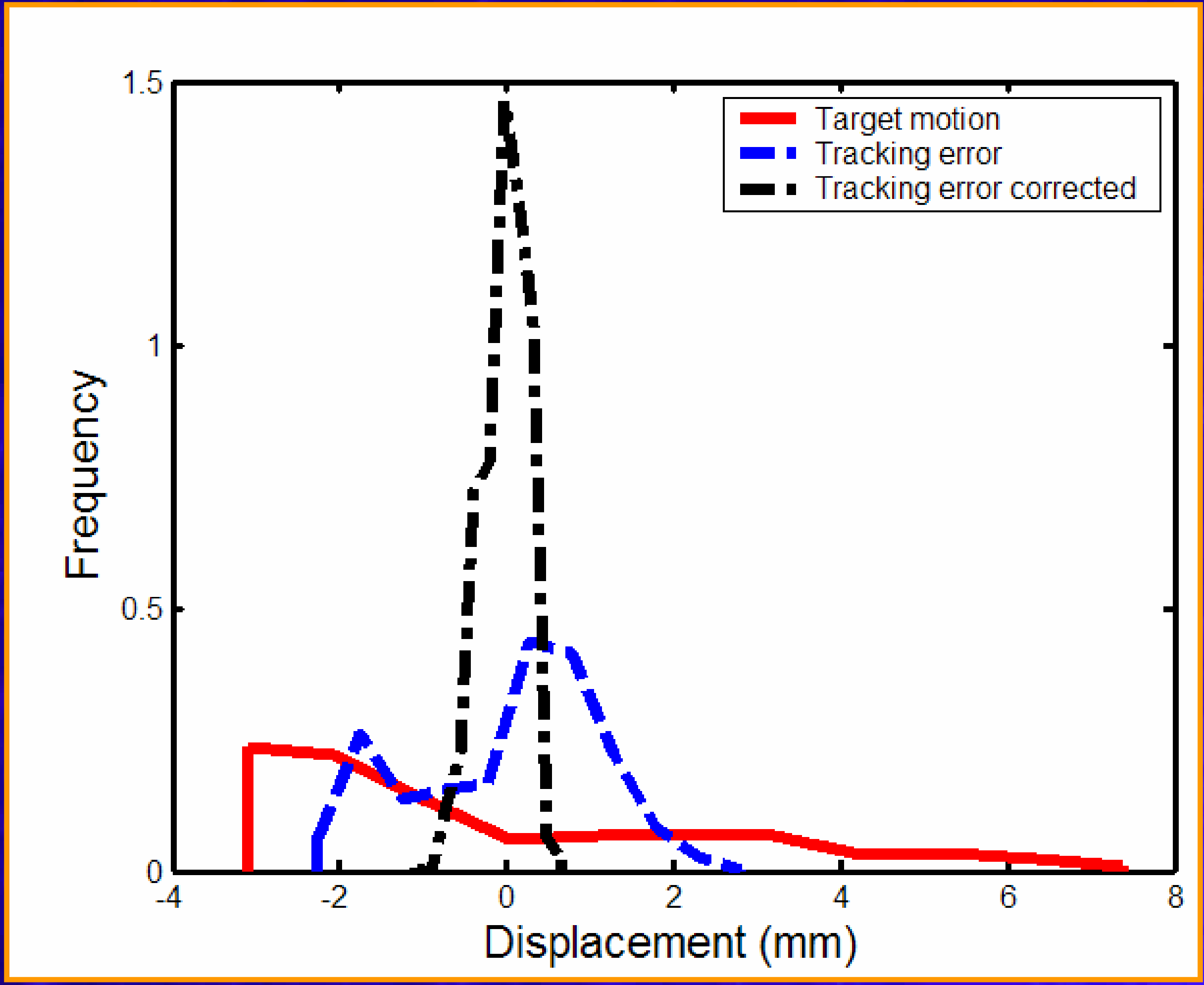


Tracking error vs. time

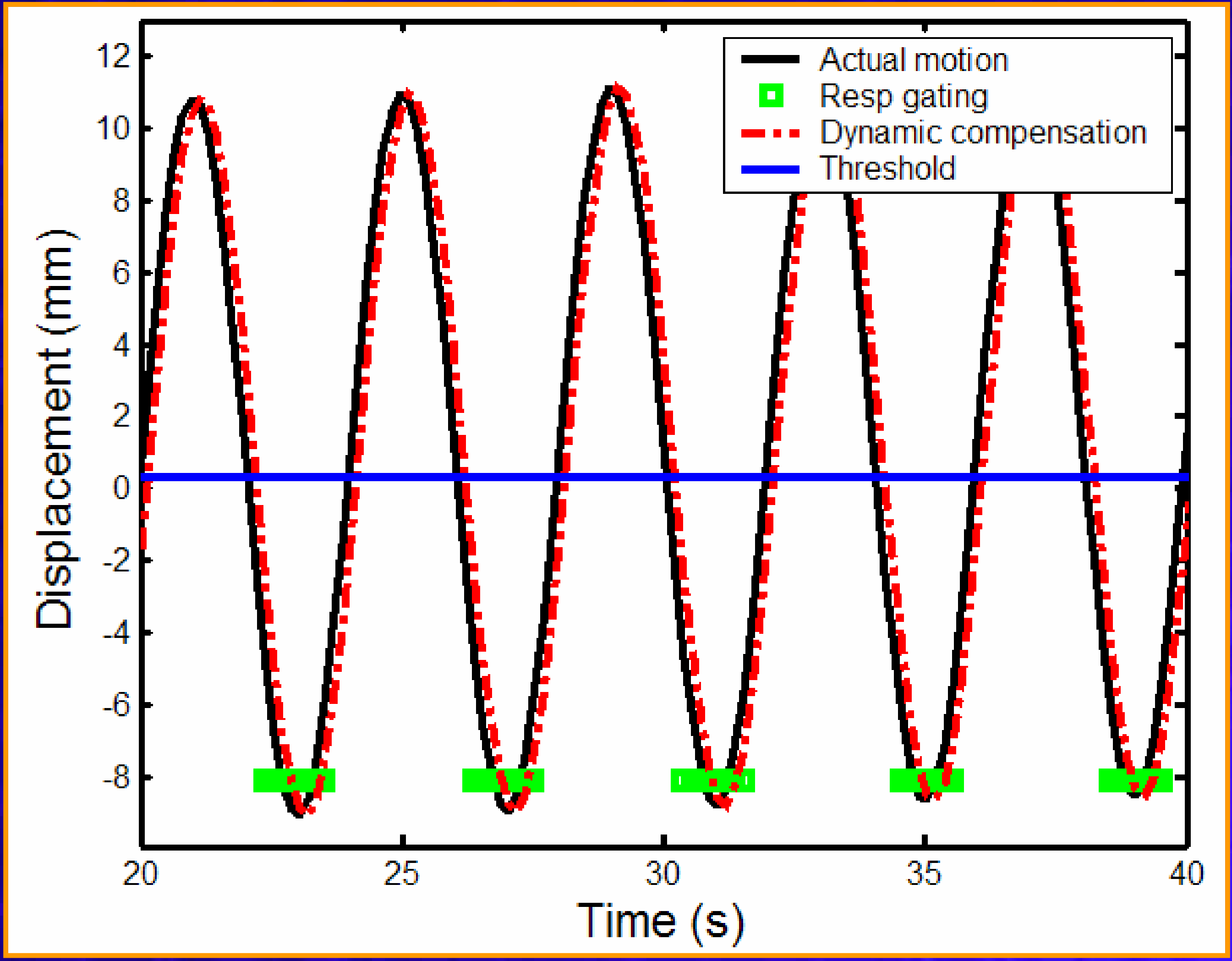


—Target
—Beam
—Beam (RT corr)

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