Real-time adaptive radiotherapy

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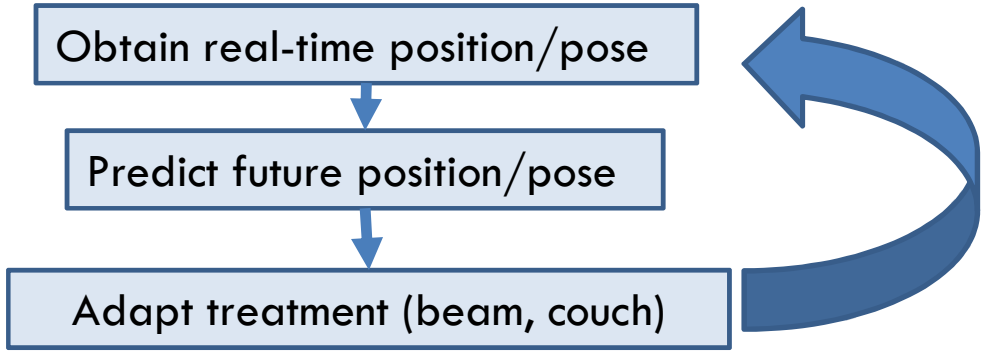
Overview

- Definitions/context
- What's in the box?
- How well does it work?
- Future?

Real-time adaptive definition

- To adapt radiotherapy delivery to account for intra-treatment anatomic change - during treatment
  - May include inter-fraction variation implicitly

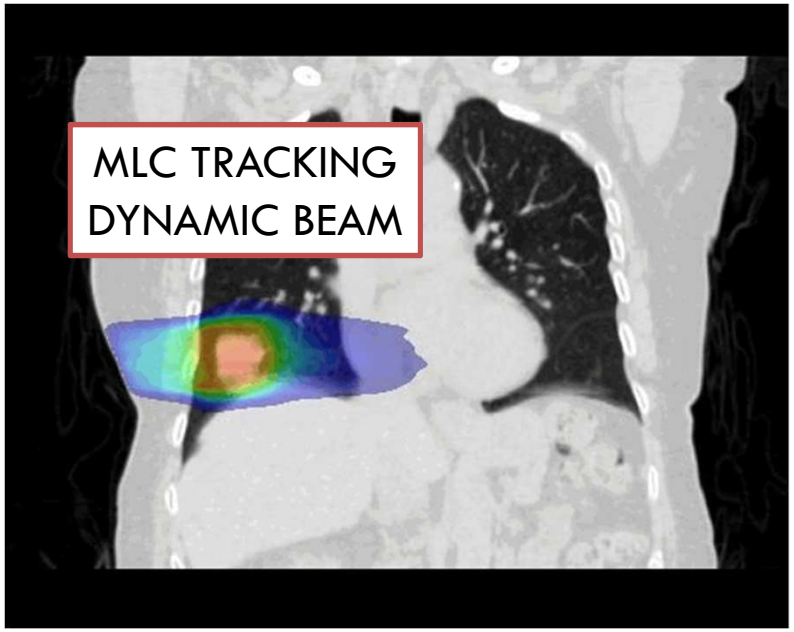


Some more definitions

- ***Real-time***: the latency or response time of motion is less than the timescale of significant changes in the position during the response time
- ***Latency:*** time lag between target motion and the complete execution of the system response
- ***Temporal prediction:*** estimation of target position at some time in the future ~latency
- ***Tumour trailing:*** delivery adapts to baseline shifts
- ***Tracking:*** increasingly used to refer to monitoring motion, has/is used to refer to adaptation

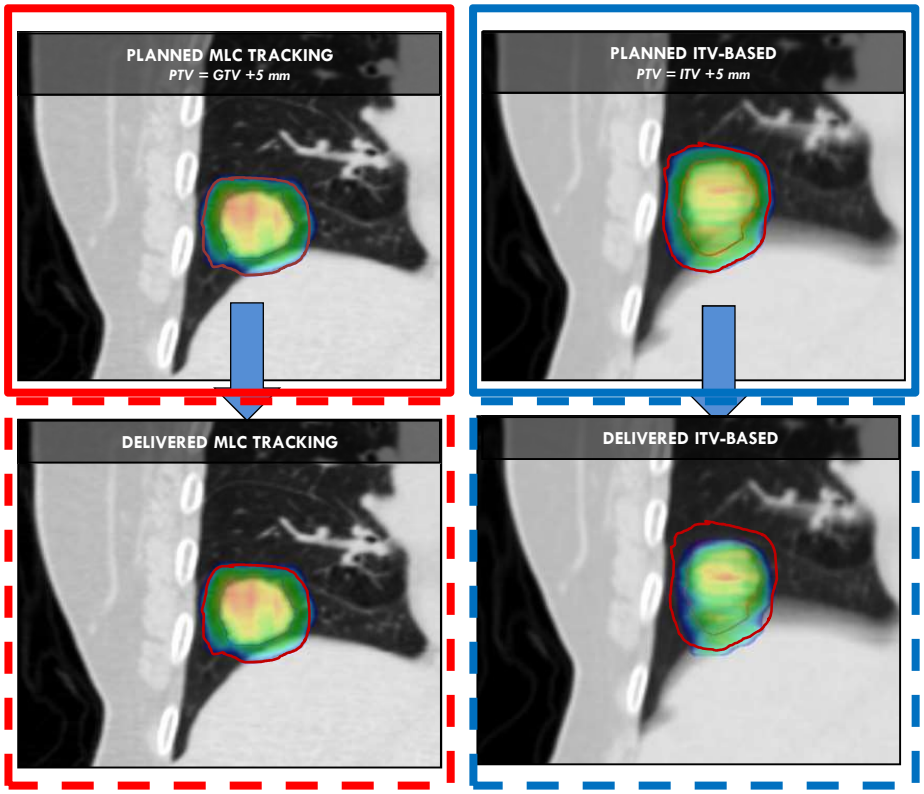
Clinical drivers for real-time adaptation

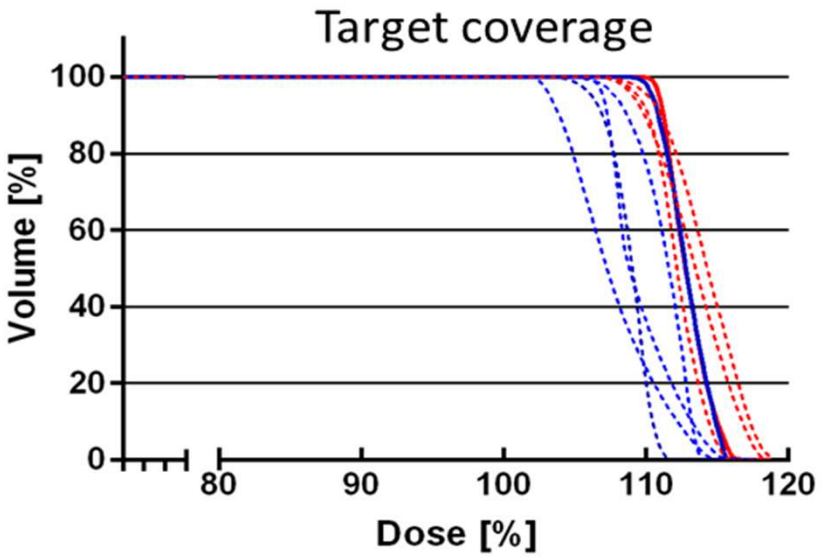
- Safety
  - ⇒ Patient-connected
  - ⇒ Deliver planned dose
- Efficient workflow / Automation
  - ⇒ Improve consistency
- Compact dose / Accuracy
  - ⇒ Reduce OAR dose



Lung SABR dose accuracy: Individual

PTV = red contour; dose cloud >95% dose





Lung tracking reduces PTV/MLD

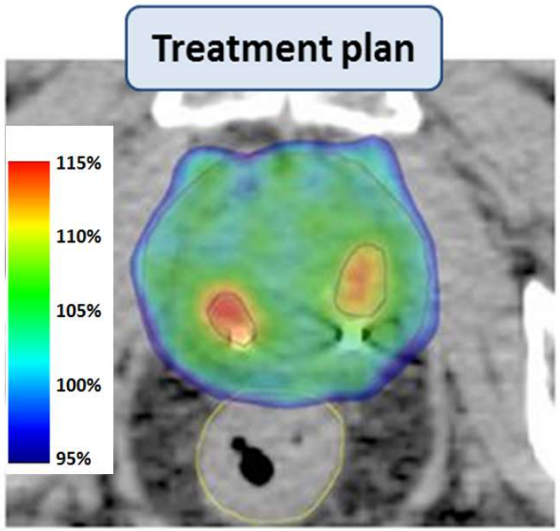
System	Peak-to-peak motion (cm)	PTV reduction	MLD reduction	Reference
Cyberknife	0.2 – 2.3	16 - 49%	Nr	Chan et al 2013
Vero	0.2 – 2.6	16 - 53%	Nr	Depuydt et al 2014
MLC tracking	0.3 -1.8	2 - 47%	7 - 38%	Booth et al ESTRO 2019

Notes

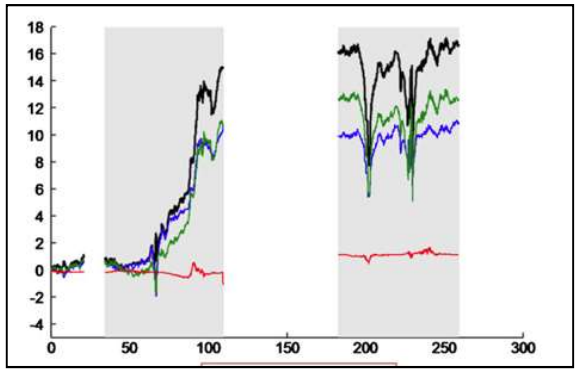
- Guides towards safety for retreatment, larger tumours, central tumours, higher target doses

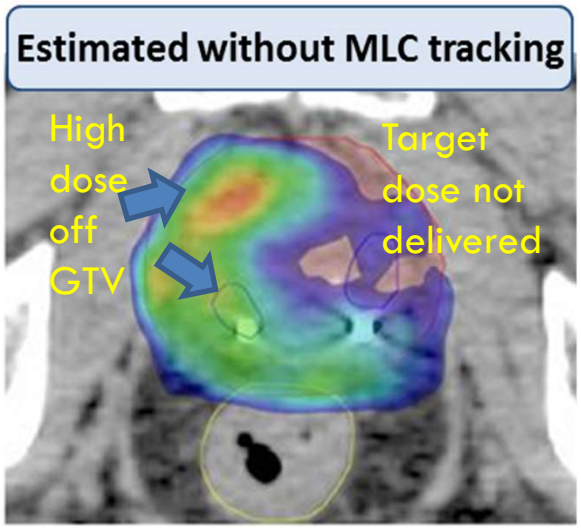
MLC tracking meets the challenge of dose painting

MLC tracking for dose painting moving targets (prostate, liver, pancreas)



High dose GTV defined from mMRI + PSMA PET

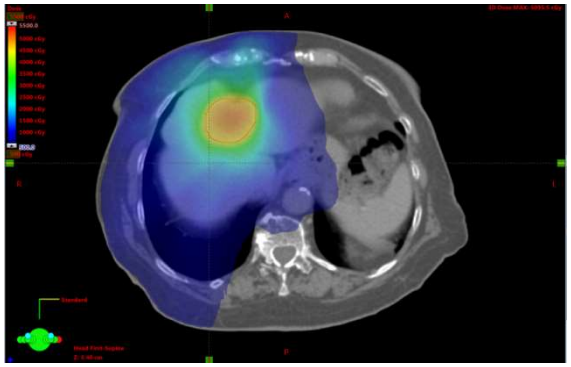




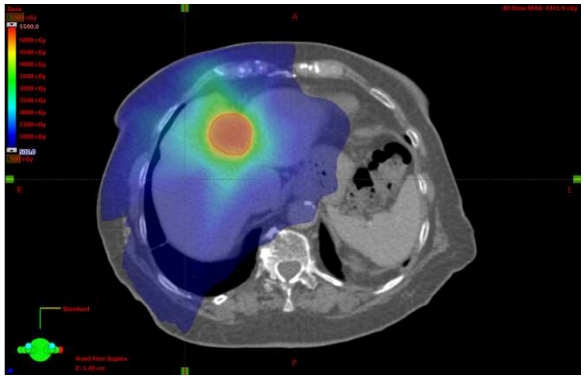
Colvill IJROBP 2015

Isotoxic Liver SABR prescription

- Liver SABR
  - Goal: 50Gy/5#
  - Target dose constrained by normal liver tolerance
- Gargett etal simulated gating/tracking
  - 13/20 cases had constrained target dose
  - 11/13 cases reached target dose with real-time adaptation
  - Further dose escalation possible



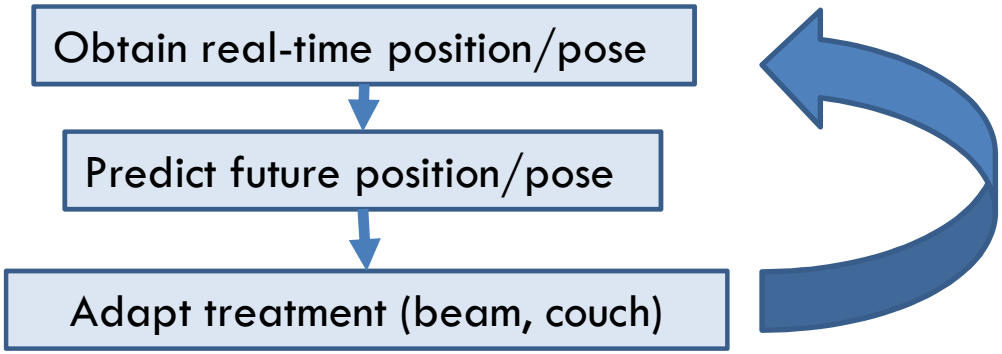
Standard
Free-breathing
42.5Gy/5#



Motion
management
50Gy/5#

Gargett *et al* RadOnc 2019

Real-time adaptive action loop

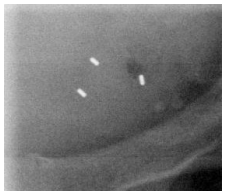


Real-time tumour monitoring systems

NORTHERN SYDNEY CANCER CENTRE

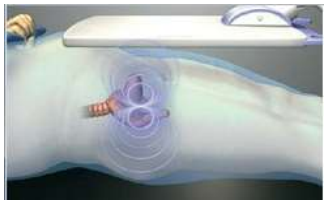
Implanted fiducial markers

X-ray



Electromagnetic

Calypso & Micropos

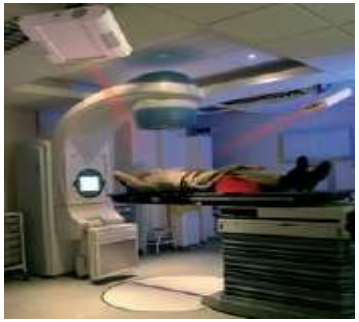


Radioisotope

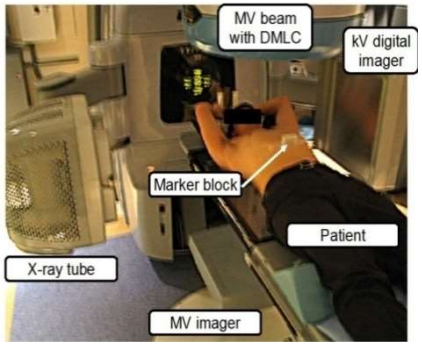
Navotek

Optical surface markers

VisionRT



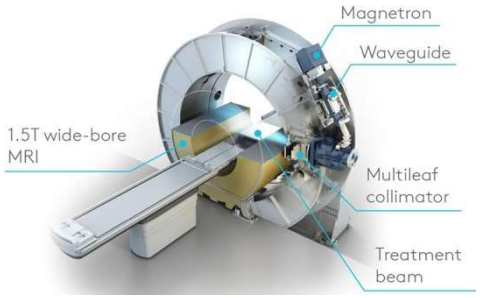
kV/MV/ Optical



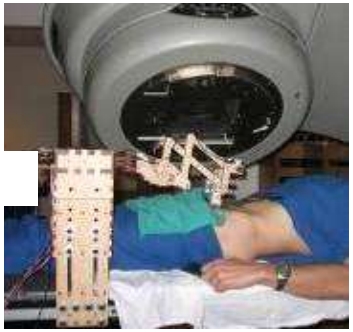
and a combination of them …

Volumetric

MRI linac



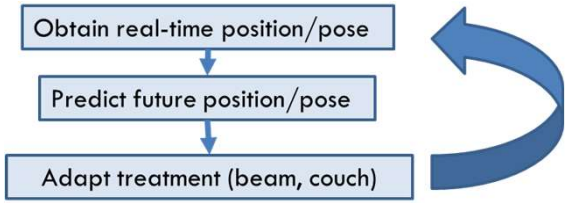
Ultrasound



Slide courtesy of Paul Keall

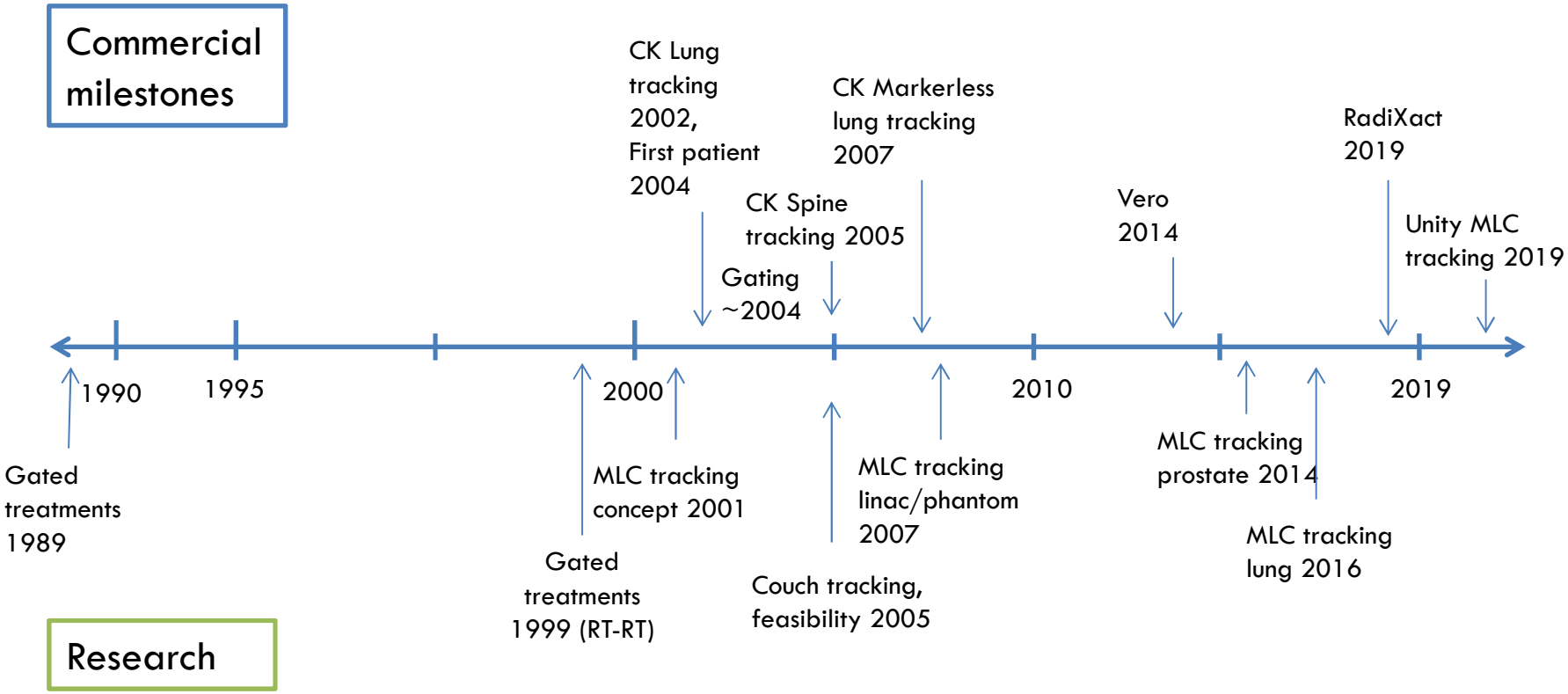
Overview of Technologies

- Motion monitoring (tracking) method
  - Type of information
    - Point, shape, volume
    - Surrogate, target/OAR
  - Frequency of information



- Adaptation method
  - Gating, Robotics, MLC tracking, Couch tracking, Gimbal tracking, Combinations
  - Generally incorporates the prediction component

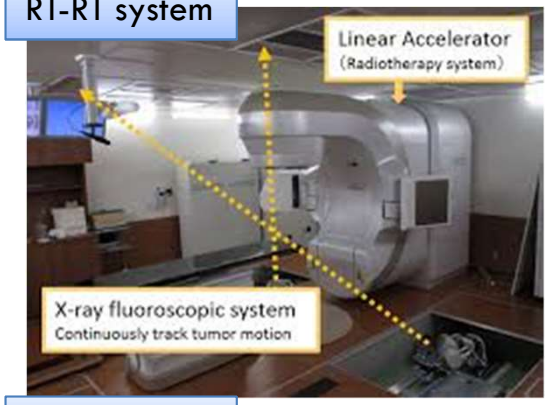
History of real-time adaptation



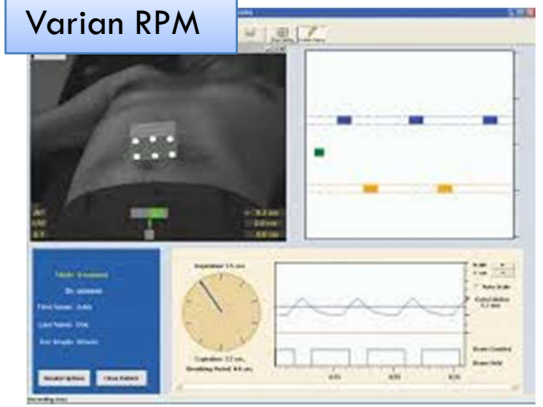
Gating

- Gating stops the treatment when the target moves outside a pre-defined tolerance eg 2mm
- Available clinically with a range of motion triggers
  - First papers from 1989 with research systems
    - Abdominal compression sensors, RT-RT
- Commonly applied to SABR techniques, DIBH
- Duty cycle is the proportion of time beam in on and is a compromise to residual motion
- Reference: TG76 (2006), currently in revision

RT-RT system



Varian RPM



Robotics: AccuRay Cyberknife

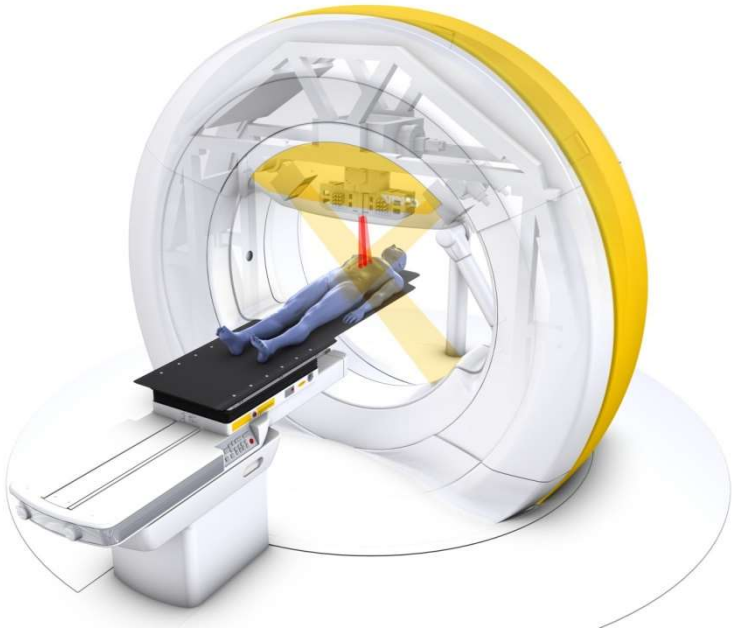
- Utilises dual kV and optical
- Robotic arm sychronises linac targeting with detected motion
- Motion model correlates optical surface with target motion, updates model regularly
- Synchrony system detects direct tumour location (markerless)
- Planning on single phase of 4DCT

Couch Tracking

- Couch position adapts to synchronise with motion
  - Single target
  - 6DoF
  - Range of couch motion
- Not commercialised, no patients treated

Gimbal tracking (VERO)

- Detects motion using dual kV and optical surface
- Tracks with gimbal ring gantry and couch
- Utilises a motion model for correlation of external to internal motion
- No longer in production



MLC tracking

- MLC adapts shape to synchronise with motion
  - Real-time optimisation of leaf position
    - Area of under dose and over dose
  - Unique ability to track deformation and multiple targets
  - Conformity linked to leaf speed, width
  - Accuracy dependent on plan complexity
- Planning on single phase of 4DCT, no ITV

Deformation

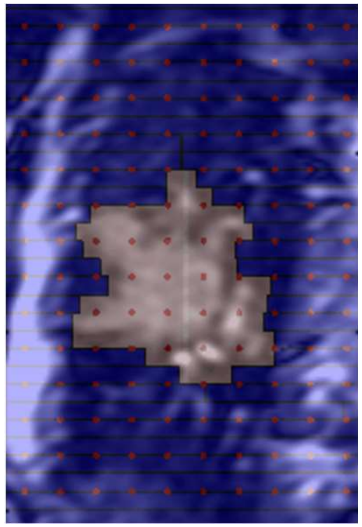
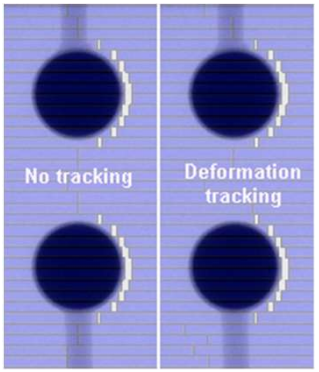


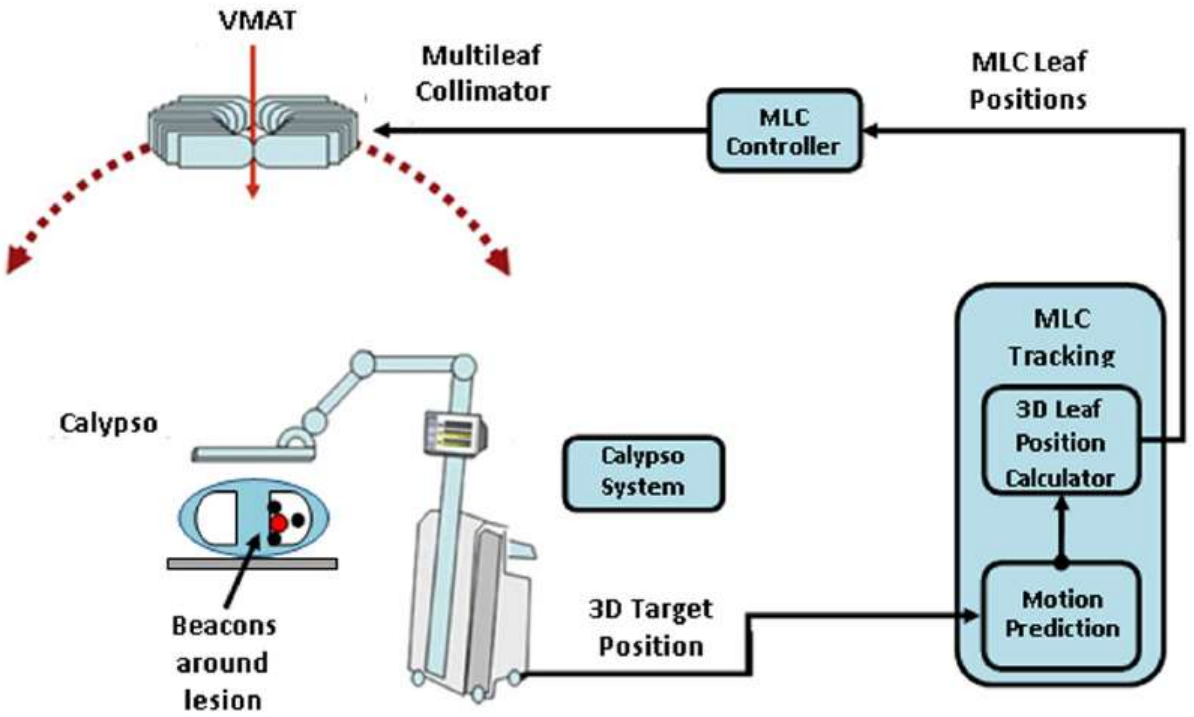
Image-based tracks DVF



Lung and node
Prostate and node (ethics filed)

Ge et al 2014

Example MLC tracking control loop



Clinical status of MLC tracking

Prostate Oct 2013 – June 2015
Calypso-guidance

- 28 patients (858 fractions)
- V7.4 MLC controller

Lung SABR July 2015 – Oct 2018
Calypso-guidance

- 17 patients (70 fractions)
- V7.5 MLC controller
- Prediction on

Prostate SABR Nov '16 – Jul '18
KIM-guidance

- 10 patients (50 fractions)

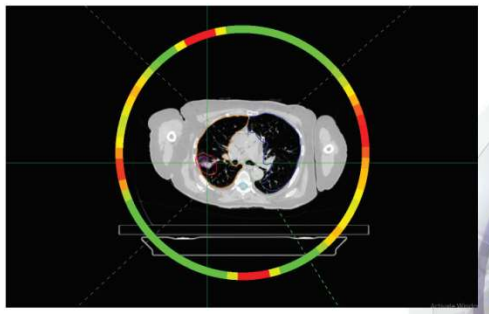
All with University of Sydney MLC tracking software (latency 220ms); All with Varian Trilogy linac, Millennium MLC

MR-guided MLC tracking

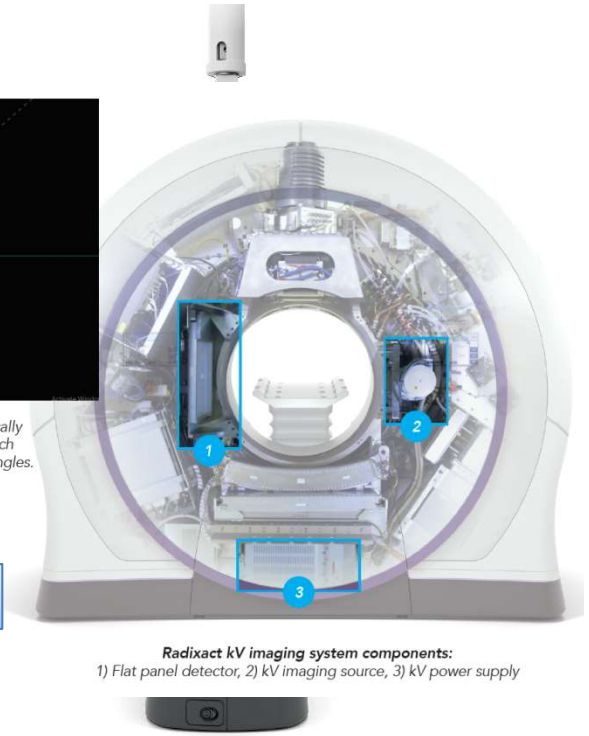
- MRI volumetric tracking
- Superb soft tissue contrast
- An MLC tracking algorithm developed at Royal Marsden/DKFZ for deformable targets (Fast et al 2014)
- Implemented on Elekta Unity (Glitzner et al 2019)
  - Latency of 347ms/4Hz and 204/8Hz.
- Potential for real-time functional imaging

Combination - RadiXact

- Radixact detects motion from kV and surface
- Utilising Synchrony to track lung, liver, pancreas…
- Treats with helical beam
- RadiXact adapts with jaw, binary MLC and couch
- Latency 70ms



Imaging angle section window: *Color wheel automatically indicates best imaging angles. Green dashed lines, which can be interactively moved, indicate selected imaging angles.*

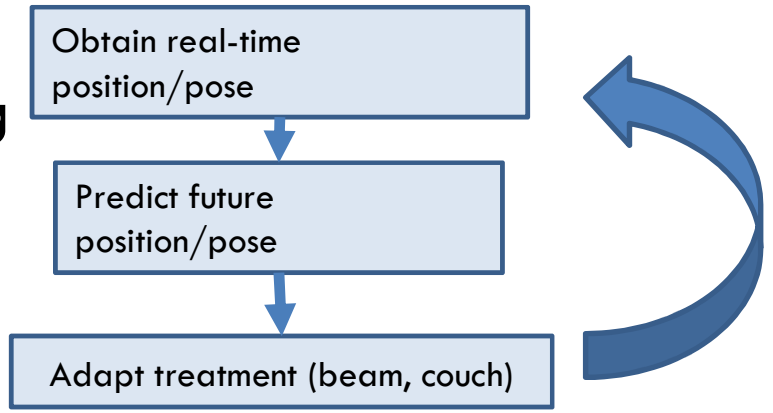


Radixact kV imaging system components:
1) Flat panel detector, 2) kV imaging source, 3) kV power supply

Schnarr et al 2018

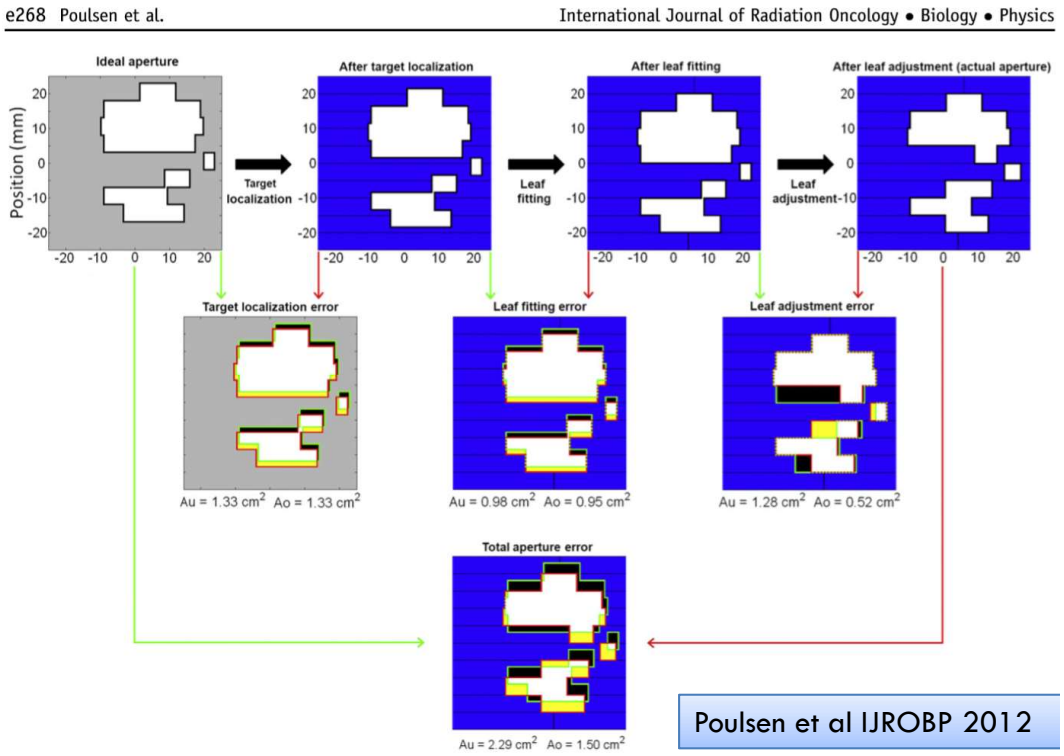
Uncertainty for real-time adaptive RT

- 4DCT & lack of 4D planning
- Tumour delineation
- Surrogate vs direct tumour tracking
- Latency vs Prediction accuracy
- MLC tracking accuracy
  - Real-time monitoring accuracy
  - Leaf fitting (leaf width)
  - Leaf adjustment (leaf speed)



Understanding MLC tracking

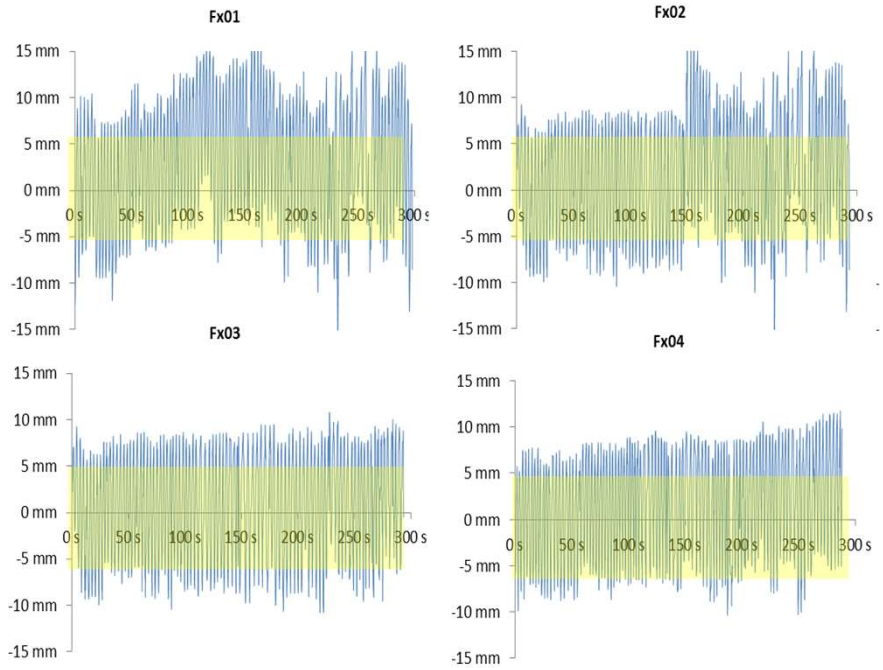
- Target localization error
  - caused by system latency and uncertainties in the monitoring system
- Leaf fitting error
  - occurs when the desired MLC shape is fitted onto the closest physically possible MLC shape and is caused by the finite leaf width.
- Leaf adjustment error
  - the difference between the actual and the requested leaf positions and is caused by the finite leaf speed.



Poulsen et al IJROBP 2012

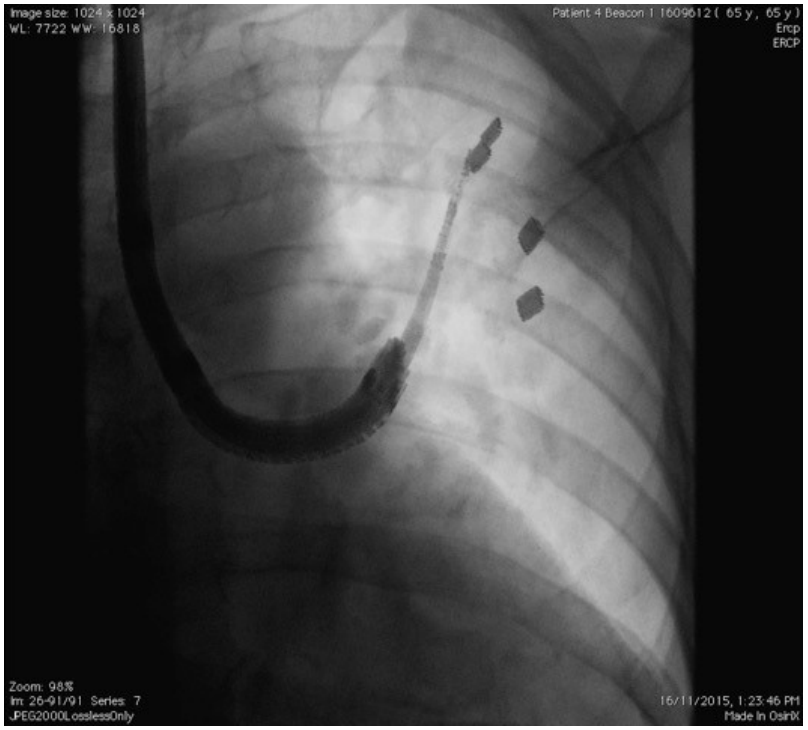
Clinical Challenges from 4DCT

- Planned on exhale phase of 4DCT
  - 4D treatment with 3D planning
- 4DCT can under estimate motion
  - Leads to potential geographic miss
- 4DCT can over estimate motion
  - Leads to larger PTV, higher lung dose
- ?4D planning
- ?Improved 4DCT image quality

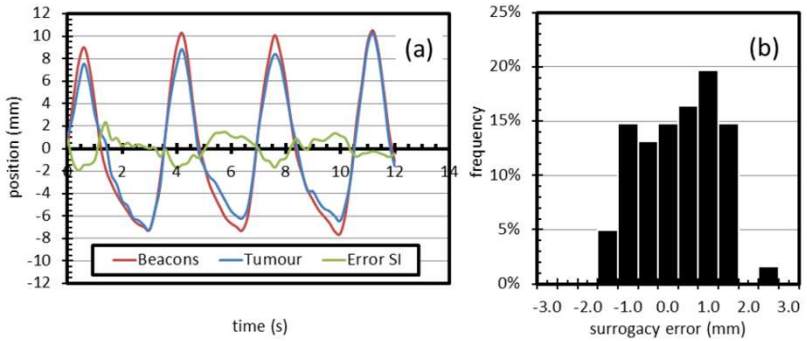


MLC tracking lung Patient 2: beacon motion in SI direction during treatment

Clinical challenges with fiducials

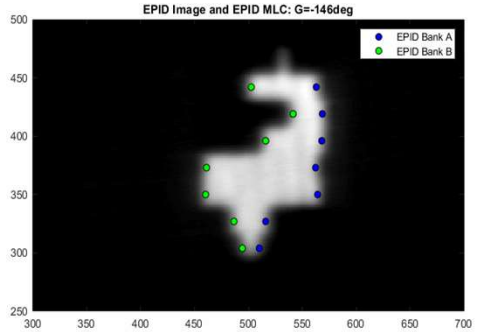


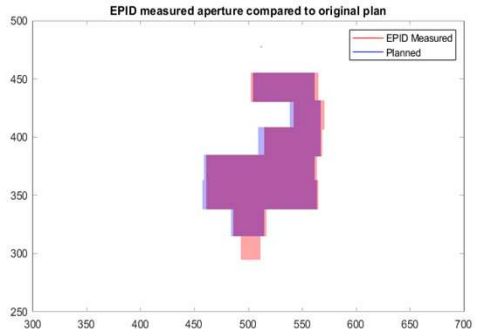
1. Potential toxicity with **implantation**
   - Bronchoscopic under II guidance: 0/17 toxicity
   - Benchmarking markerless tracking (Shieh et al 2017)
2. Fiducials provide a **surrogate** for tumour position
   - Surrogacy at 4DCT and treatment (fluoro)



QA of real-time adaptive system

- Published guides for Cyberknife/Synchrony and MLC tracking
- System integrity
  - End to end test with hidden target and known motion(s)
  - Latency measurement
- Real-time QA
  - Interlocks for unexpected conditions ie target outside tracking area, comms error, large/fast motion
  - Potential for EPID-based aperture check or back-projected dose estimation
- Retrospective dose reconstruction





Future Outlook

- Emerging technologies
  - Faster data processing / algorithms
  - Artificial intelligence
    - Automation
    - Bridge gaps in information
  - Evolution of geometric margins towards probabilistic
  - Real-time dose prediction ⇒ dose-guided adaptation
  - Real-time functional imaging ⇒ biology-guided adaptation

Summary

- Real-time adaptation available for 30 years (gating) and 20 years (tracking)
  - currently first generation: adapting to rigid motion of target
- Real-time adaptation well aligned to emerging technologies
  - Automation, machine learning, real-time volumetric imaging
  - Implicitly includes 'plan of the day' / inter-fraction change
- Next generations will consider:
  - Deforming anatomy (tumour and OAR)
  - Dose/biology-guidance