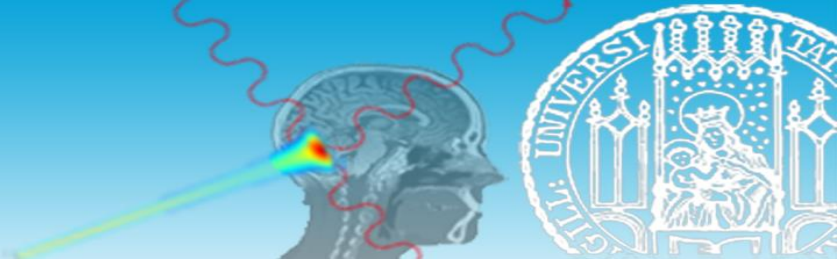
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

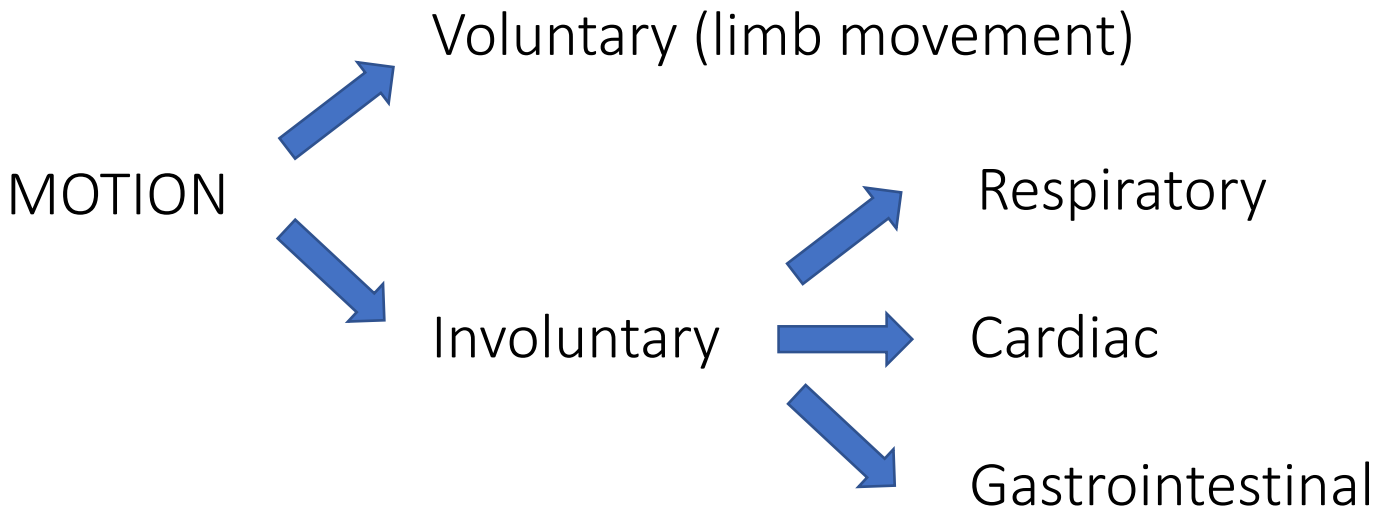


Real-time tumor tracking with MLC

Advanced motion compensation in modern radiotherapy Seminar – 23/06 - Francesca Neri

Tumor Motion

Intrafraction tumor motion during external radiotherapy is an issue that challenges the treatment accuracy.



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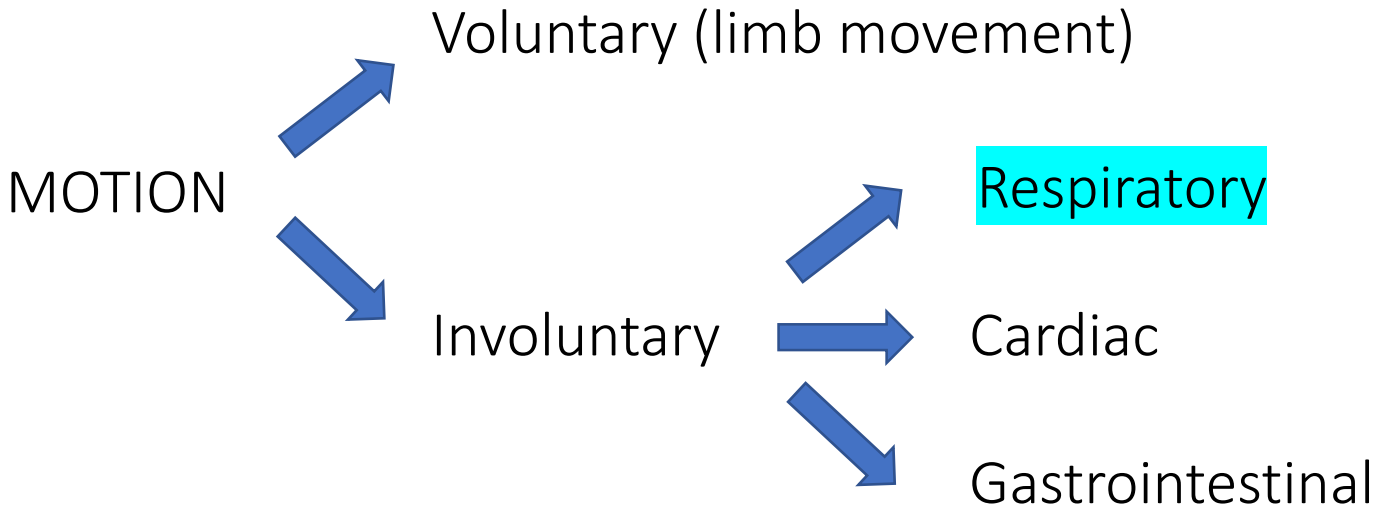


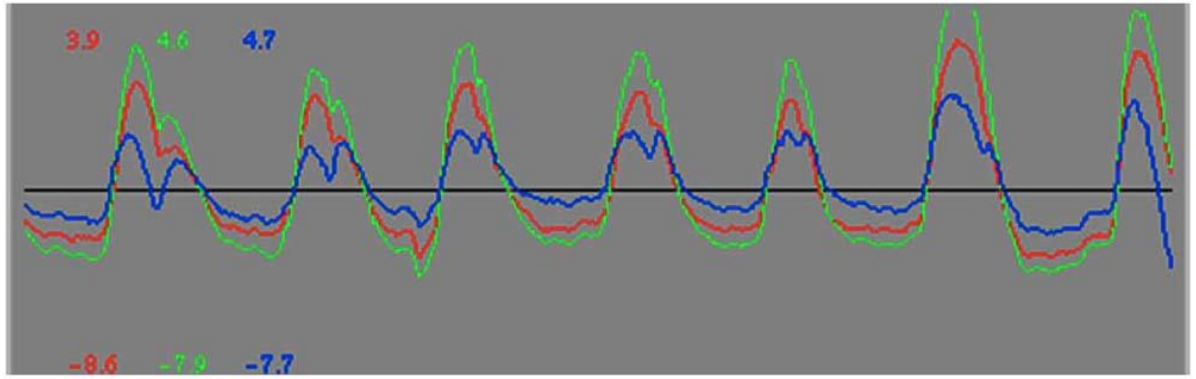
-Mainly affects thorax and abdomen tumor sites
-Relevant for hypofractionated treatments

Breathing Motion

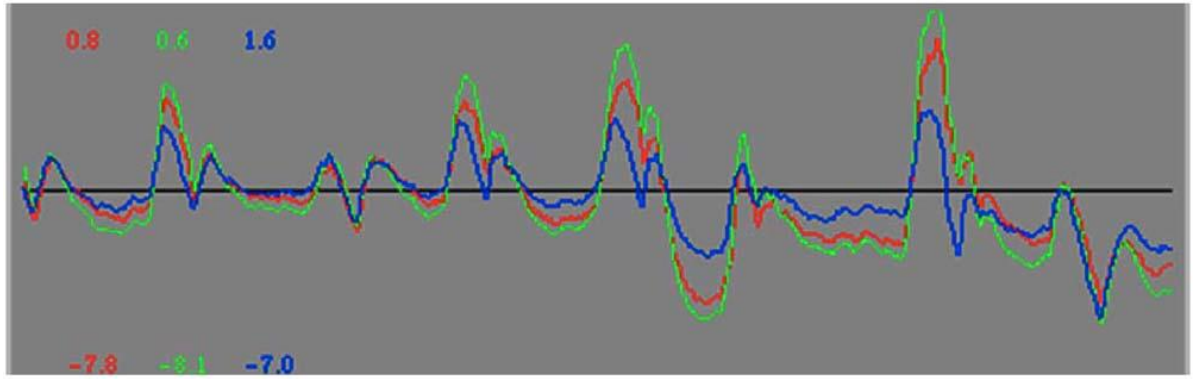
Patients' breathing patterns can vary in magnitude, period and regularity during imaging and treatment sessions.

Motion varies between patients

individual approach to respiratory management



(a)



(b)

Figure 1: Variations in respiratory patterns from the same patient. [1]

Motion Management

Motion management approaches:

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

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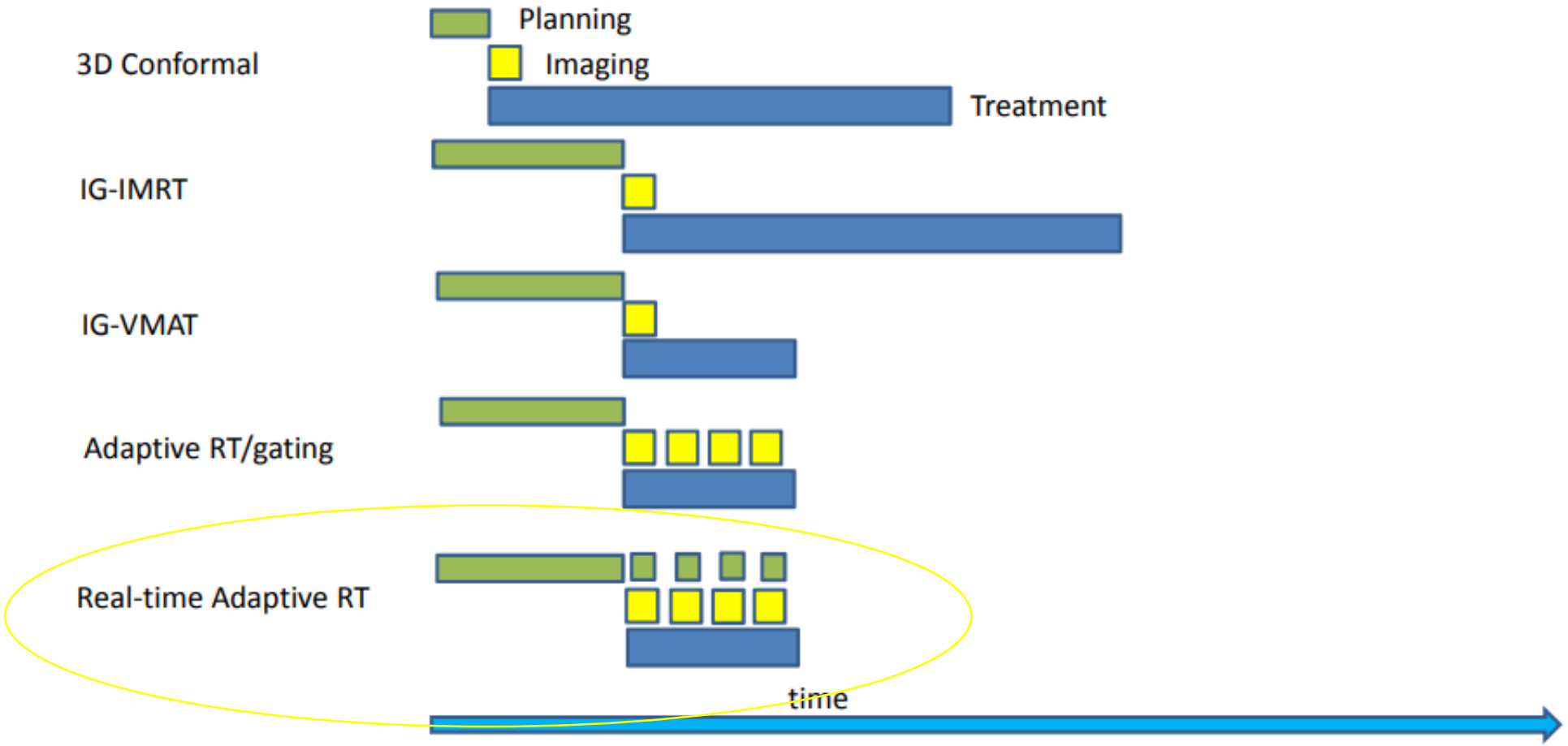
Motion Management



Real Time Tumor Tracking

Tumor motion signals are used in a feedback loop to dynamically update beam and compensate for motion.

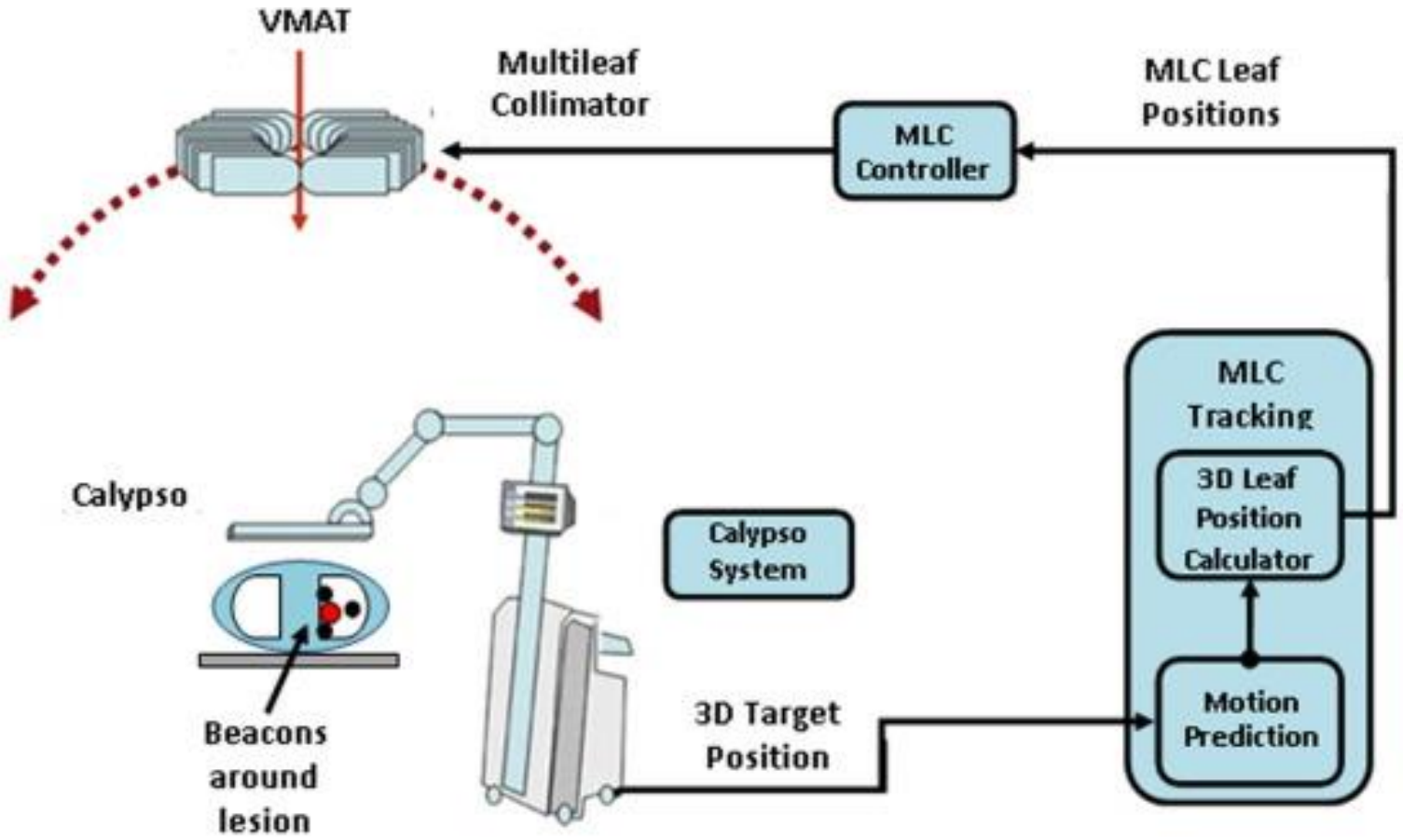
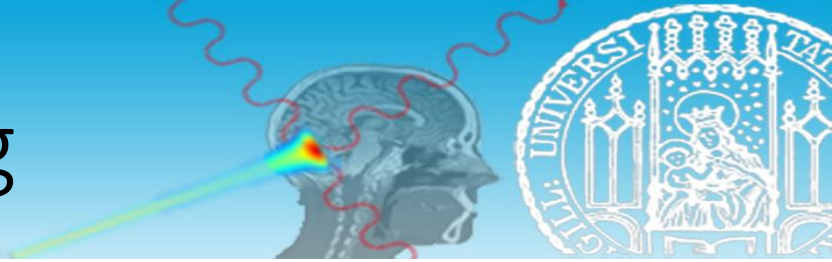


Figure 2: Schematic of the MLC tracking control system. Electromagnetic transponders send real-time localization to the MLC tracking system which updates the MLC pattern and sends the new leaf positions to the MLC controller [2].

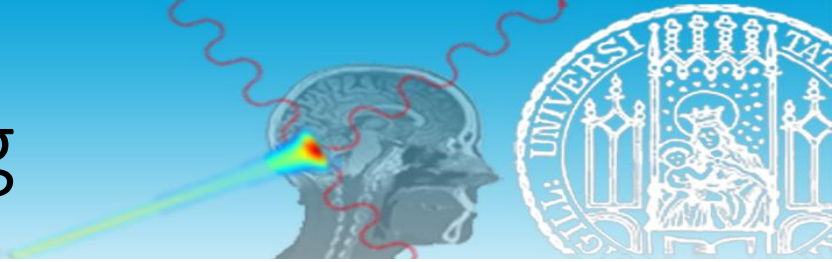
Real Time Tumor Tracking



Successful tumor tracking:

1. Tumor position identification in real time
2. Tumor motion anticipation (compensate system lag)
3. Beam repositioning
4. Dosimetry adaptation

Real Time Tumor Tracking



1. Tumor position identification in real time:

- Direct target visualization
- Implanted fiducial markers (electromagnetic transponders implanted into the target tissue)
- Target position with surrogate signals (correlation)

Real Time Tumor Tracking

1. Tumor position identification in real time

Imaging Modality

IONIZING
(X-rays from keV to MeV range)

Relevant parameters:
Image resolution, acquisition rate, cumulative dose

NON-IONIZING

Cameras, Radiofrequency systems (EM transponders), Ultrasounds, MRI

Real Time Tumor Tracking

2. Tumor motion anticipation :

- System latency (computational time for image acquisition, data processing, mechanical response)

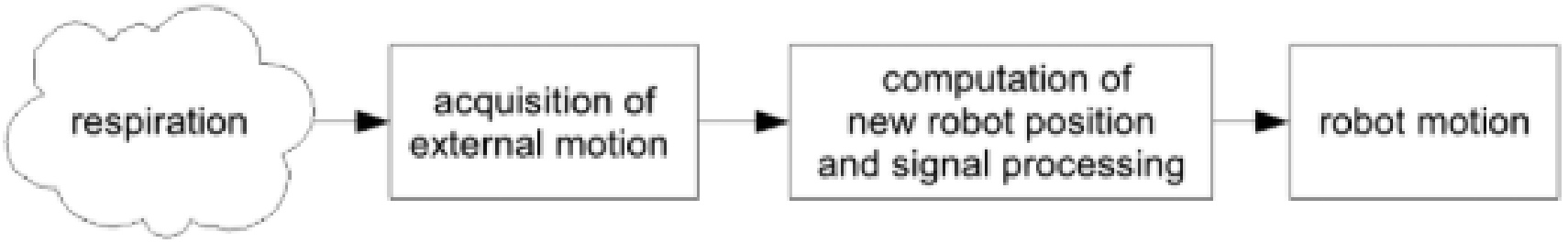


Figure 3: Sources of latency scheme [3].

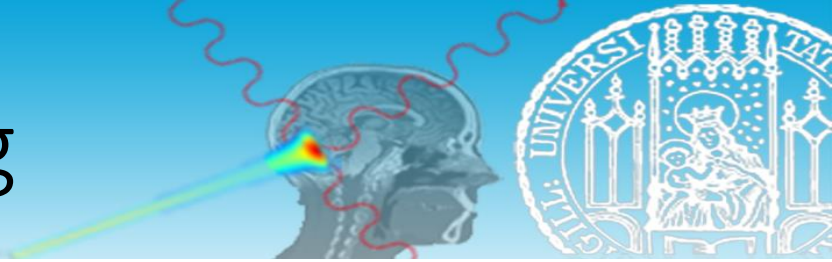
Real Time Tumor Tracking

2. Tumor motion anticipation :

- Predictive algorithms for motion models

To minimize the impact on prediction algorithms, TG-76 recommends that overall system lag for real-time tumor tracking should not exceed 500 ms [1].

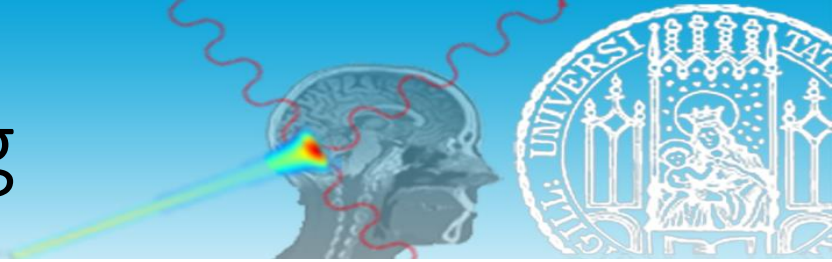
Real Time Tumor Tracking



3. Beam repositioning:

- Moving linac head (gimbaled, robot mounted)
- Moving couch
- Dynamic Multi Leaf Collimators (MLC)

Real Time Tumor Tracking



3. Beam repositioning:

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Real Time Tumor Tracking

4. Dosimetry adaptation:

The TPS calculates dosimetry from a static configuration, while During breathing, the target and structure locations are continuously changing.

Real time dose reconstruction and QA

Dynamic MLC Tracking

The real time adaptation of the multileaf collimator (MLC) aperture, allows to conform the planned treatment to the moving target.

The reduction of dose to adjacent healthy tissue maintaining a full target coverage is especially relevant for highly conformal, hypofractionated treatment protocols [4].

Dynamic MLC Tracking

DMLC motion to align with the moving target

2008, Sawant et al. [5]

– Good tracking accuracy < 1 mm for in plane motion

– Lower efficiency for high frequency motion perpendicular to leaf direction.

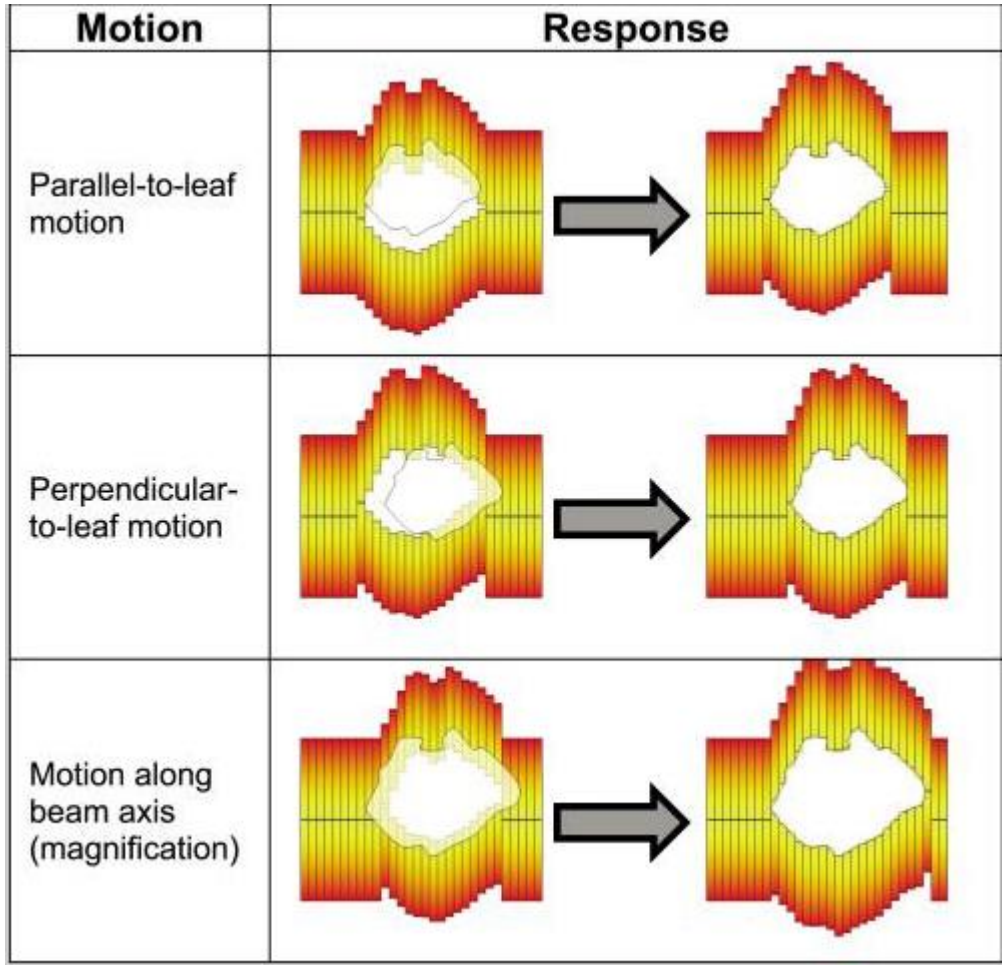


Figure 4: Schematic illustration of the various types of target motion as seen in the beam's view and the desired change in MLC configuration to account for each type of motion [5].

Dynamic MLC Tracking

The algorithm obtains real-time information of target location from an independent position monitoring system and dynamically calculates MLC leaf positions to account for changes in target position [5].

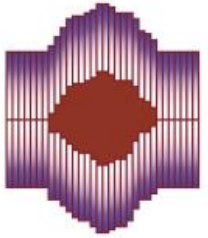
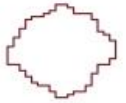
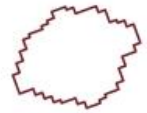
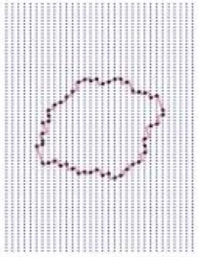
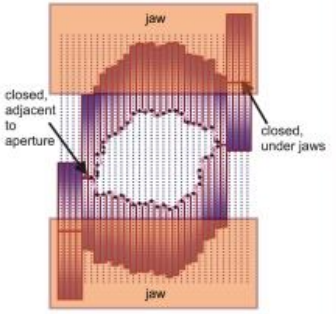
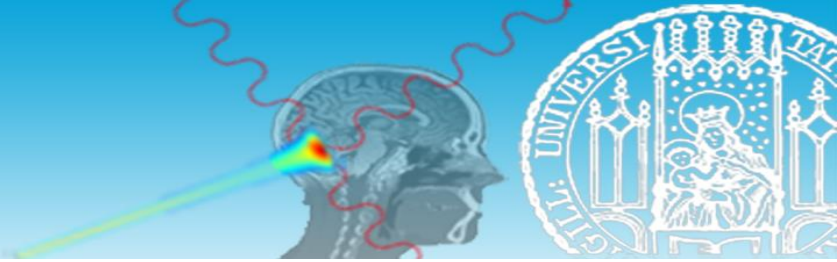
1	Read initial leaf positions from MLC file.	
2	Extract the "shape" defined by the points corresponding to MLC leaf tips.	
3	Transform this shape to match real-time target position/shape (estimated from a real-time position monitoring system).	
4	Determine the intersection points of MLC leaf trajectories with the transformed shape.	
5	Send MLC leaves to the points of intersection. Closed leaf pairs adjacent to open aperture(s) are positioned at the midpoint of nearest open leaf pair. Peripheral closed leaf pairs are sent beneath the nearest jaw.	

Figure 5: Schematic illustration of the key steps in the tracking algorithm [5].

DMLC Timeline



- First human clinical implementation of dynamic MLC relied on electromagnetic transponder implants.

- First human treatment for prostate cancer patient.

Reported 30% increase of dose in rectal volume without MLC tracking [6].

- First lung cancer treatment with MLC tracking: PTV reduced from 18.7 cm^3 to 11 cm^3 (healthy tissue sparing) [2].

DMLC Timeline

CyberKnife

- First clinical system designed to employ real time motion correction by detecting and compensating for intrafractional motion.
- Hybrid tumor monitoring
  – Breathing camera for continuous monitoring
  –Stereoscopic X-ray system based on fiducials tracking
  – Correspondence model
- Move entire linac mounted on robot.

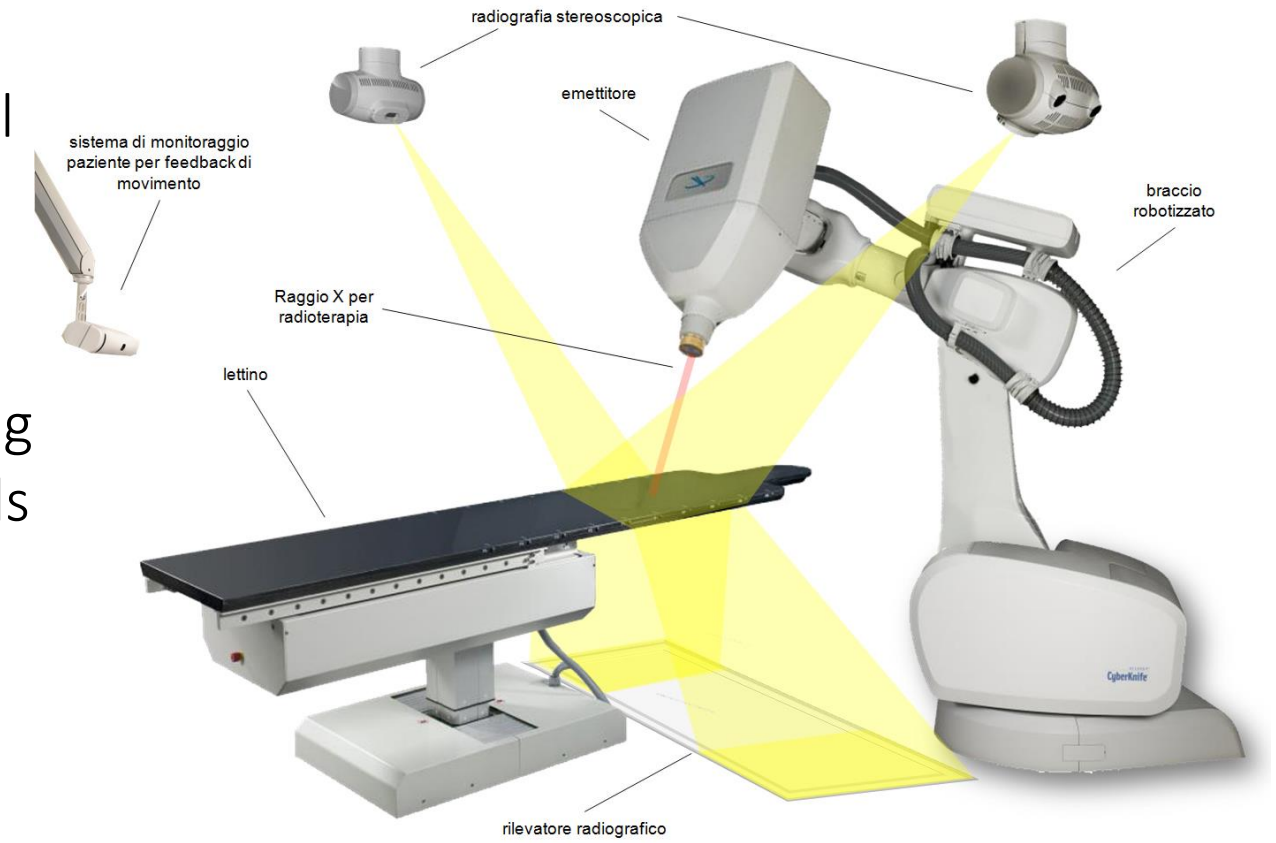


Figure 6: Schematic illustration of the CyberKnife robot.

DMLC Timeline

Vero

- No longer commercially available

- Gimbaled linac with MLC
- Ring gantry
- MV EPID imaging & orthogonal kV imaging

– direct tumor tracking

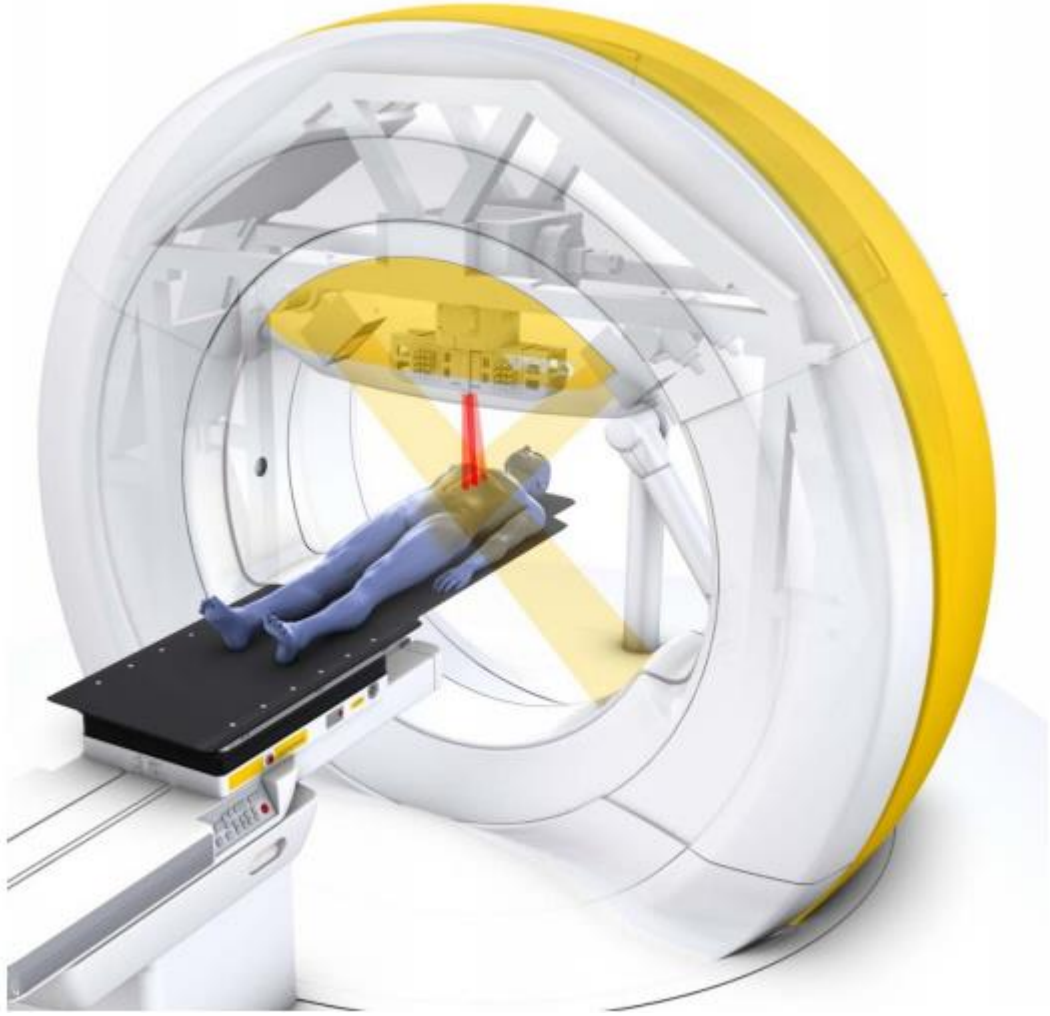


Figure 7: Schematic illustration of the Vero linac.

DMLC Timeline

Integrated MRI

- Technically challenging

- Improved soft tissue contrast
- No need for fiducials
- Non ionizing

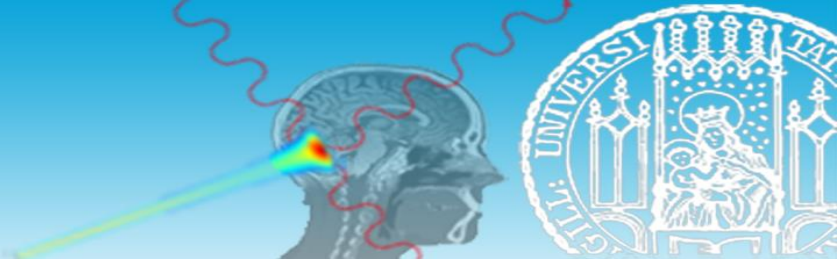
Figure 8: Image of the Elekta Unity integrated MRI linac system [8].

DMLC Performance

The efficacy of MLC tracking is limited by:

- the target localization modality (spatial and temporal resolution)
- system lag times
- the mechanical performance of the MLC.

Target Localization



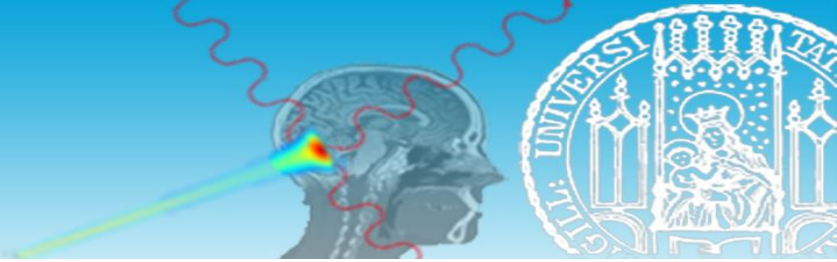
- the target localization modality (spatial and temporal resolution):

Current target localization strategies rely on X-ray imaging, often in combination with implanted fiducials.
The combination of different sources (kV MV systems) and detectors allow for 2D, 3D and 4D imaging.

Limits:

- imaging dose
- Implanted markers challenges (invasive method, positional changes,…)

Target Localization



- the target localization modality (spatial and temporal resolution):

Research on less invasive and non-ionizing target localization relying on soft tissue contrast (ultrasound imaging and MRI)

- 2016 Real-time MLC tracking based on a noninvasive US:

First Evaluation of the Feasibility of MLC Tracking Using Ultrasound Motion Estimation, Martin Fast et al., Med Phys.

- 2019 markerless dynamic tumor tracking (MLDTT) :

Performance of Makerless Tracking for Gimbaled Dynamic Tumor Tracking, Marc Ziegler et al., Zeitschrift für Medizinische Physik.

System Lag

- system lag times

Latencies occur inevitably in the signal processing . The systematic latency of the systems are described in literature.

Table 1.1: Components of the latency of a system based on a Varian MLC (kV tracking), the VERO, TomoTherapy MAD, and CyberKnife systems.

	VERO	MLC	MAD	CyberKnife
position acquisition	25 ms	309 ms[(a)]	30 ms	25 ms[(d)]
position calculation	2 ms	20 ms	—	15 ms[(d)]
gimbals/MLC/robot control cycle	20 ms	52 ms	45 ms	75 ms[(d)]
other	—	38 ms[(b)]	100 ms[(c)]	—
total	47 ms	420 ms	175 ms	115 ms

Figure 9: Tabulated latency components [3].

System Lag

- system lag times

The presence of a time delay requires that the tumor position be predicted in advance.

- 2018 Performance investigation of prediction algorithms and tracking system improvements:

Potential Improvements of Lung and Prostate MLC Tracking Investigated by Treatment Simulations, Jackob Toftegaard et al., Med Phys.

- 2019 Model approach for tracking lung tumor motion:

Dynamic MLC Tracking Using 4D Lung Tumor Motion Modelling and EPID Feedback, Rostampour N. et al., J Biomed Phys Eng.

Mechanical Performance

- the mechanical performance of the MLC

Conventional MLCs have mechanical constraints which may impact the tracking efficiency. Need for high speed MLCs.

- 2016 Performance investigation of prediction algorithms and tracking system improvements:

Performance Evaluation of a High-Speed Multileaf Collimator in Real-Time IMRT Delivery to Moving Targets , Fang Li et al., Med Phys.

DMLC Tracking Evaluation

- Tracking accuracy:

Results indicate that real-time delivery of radiation with dynamic MLCs brings to significant geometric and dosimetric advantages and allow effective management of intrafraction motion.
DMLCs can significantly reduce margins required and therefore decrease dose to OARs.

- Efficient workflow:

The technique also provides decreased time to deliver treatment compared to gating, because of continuous targeting.

DMLC Tracking Research

The dose using ionizing imaging methods can be decreased with the research and application of novel non ionizing imaging methods.

DMLC tracking can be combined with other technologies such as real time treatment couch adaptation to improve motion management.

- 2017 Study of hybrid couch-MLC tracking for improved tracking performance:

An Experimentally Validated Couch and MLC Tracking Simulator Used to Investigate Hybrid couch-MLC Tracking, J. Toftegaard et al., Med Phys.

Research Papers

- Search engine: Google
- Keywords: «Real Time Tumor Tracking», «Dynamic MLC Tracking», «MLC Tracking»
- Focus on collective articles or books which describe time evolution of the technique
- Cross check on Pubmed and Researchgate (Research Interest score)
- Firstly looked at important early publications
- Secondly focussed on 2016/2020 articles

Legend

[1]: Keall PJ et al., The management of respiratory motion in radiation oncology report of AAPM Task Group 76, Med Phys., 2006
[2]: Jeremy Booth et al., The first patient treatment of electromagnetic-guided real time adaptive radiotherapy using MLC tracking for lung SABR, Radiother Oncology, 2016
[3]: Floris Ernst, Compensating for Quasi-periodic Motion in Robotic Radiosurgery, Springer, 2011
[4]: MLC tracking: from bench to bedside, Radiotherapy and Oncology, 2017
[5]: Sawant et al., Management of Three-Dimensional Intrafraction Motion Through Real-Time DMLC Tracking, Med Phys, 2008
[6]: Keall PJ et al. The first clinical implementation of electromagnetic transponder-guided MLC tracking. Med Phys. 2014.
[7]: Booth JT, Caillet V, Hardcastle N, O'Brien R, Szymura K, Crasta C, et al. The first patient treatment of electromagnetic-guided real time adaptive radiotherapy using MLC tracking for lung SABR. Radiother Oncol. 2016;121(1):19–25.
[8]: https://www.elekta.com/radiotherapy/treatment-delivery-systems/unity/