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Physics of radiation therapy

Imaging in radiotherapy and advanced treatment techniques

UNIL | Université de Lausanne

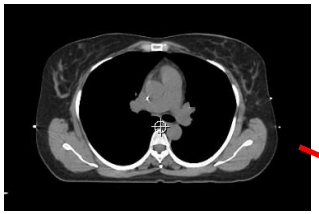
Outline

Introduction to image guided radiotherapy (IGRT)

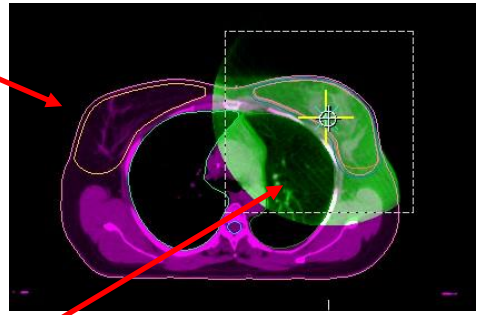
Basic principles
Reference and day imaging
Practical example: CyberKnife

Basic principles

D0: reference image



Planning CT (reference)



D1: first treatment session

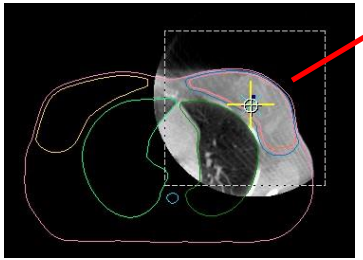
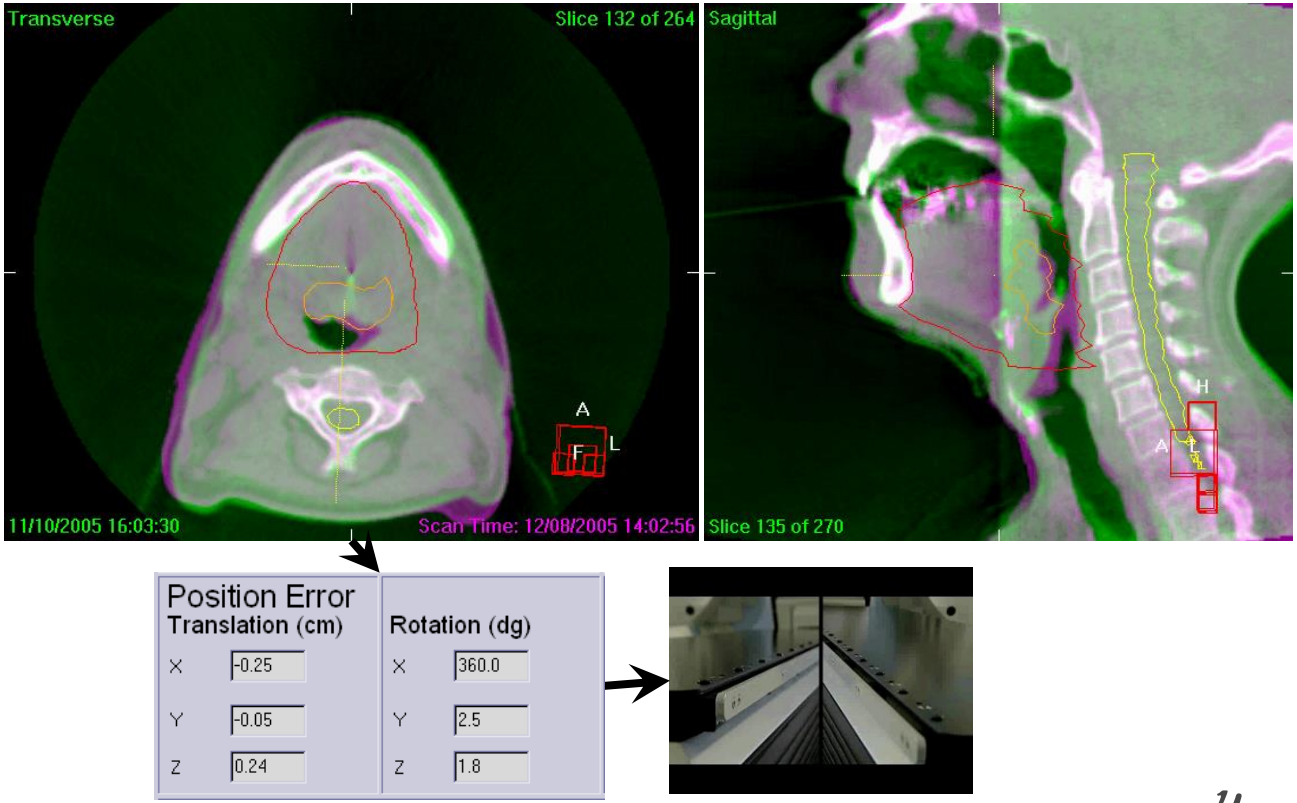


Image of the day (IGRT)

Registration



Reference imaging

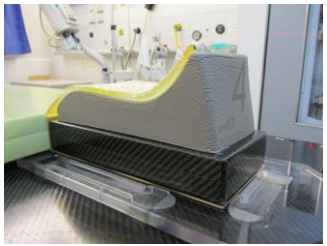
Reference imaging

CT scan:

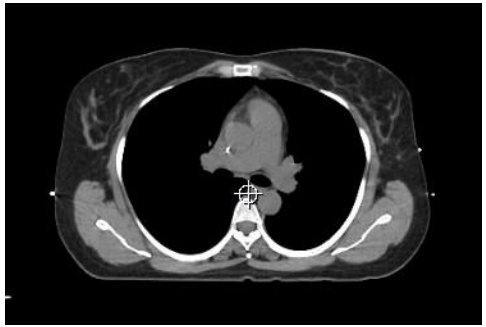
Define reproducible position of the patient for the treatment

Use for the treatment planning in the TPS

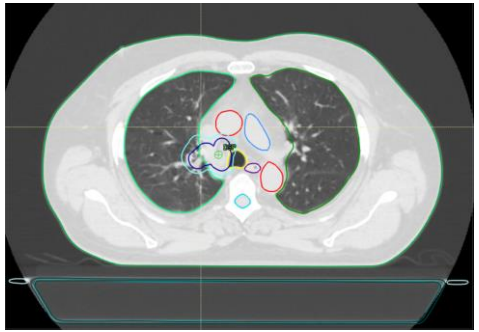
Use as reference image for registration before the treatment



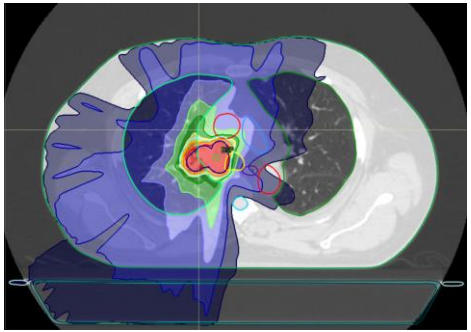
Reference imaging



Planning CT

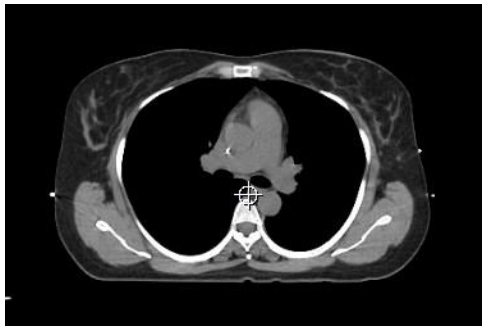


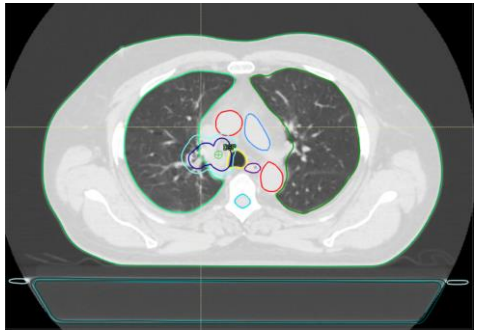
Contours delineation
(physcian)

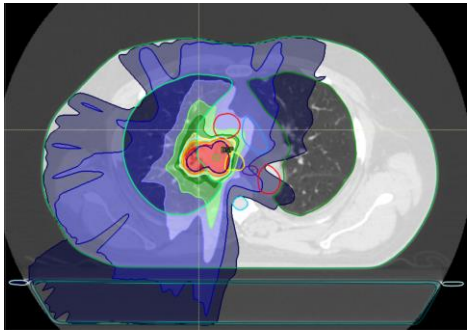


Planification
(medical physicist)

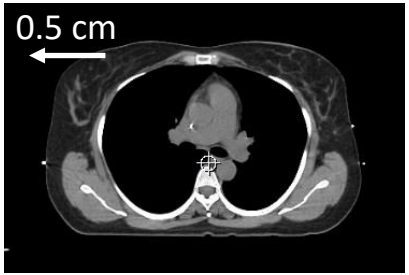
Reference imaging

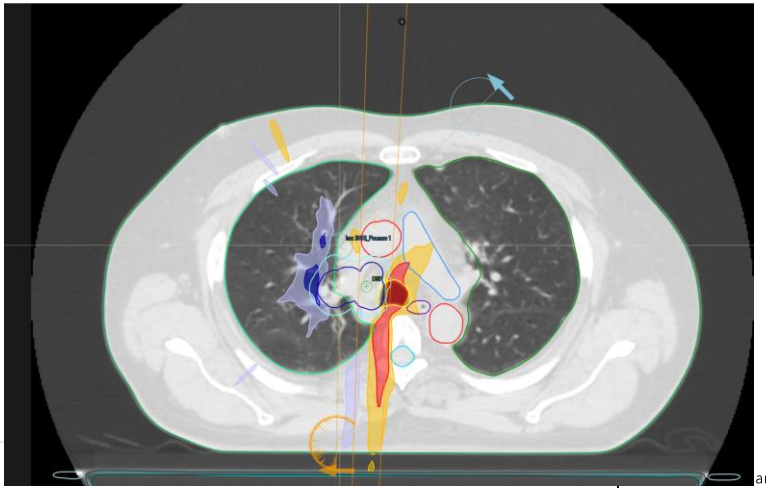






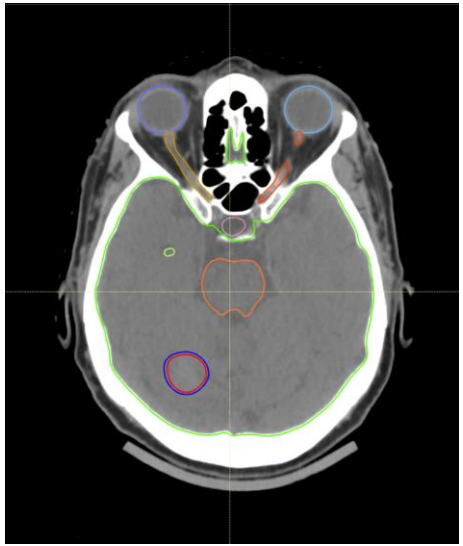
What is the impact of a 0.5 cm right displacement?



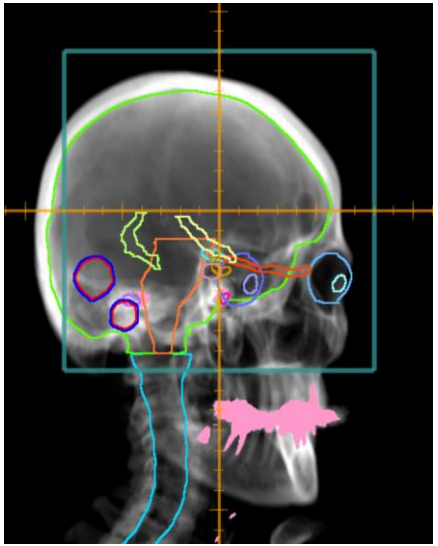


Reference imaging

Digitally reconstructed radiograph (DRR)



?

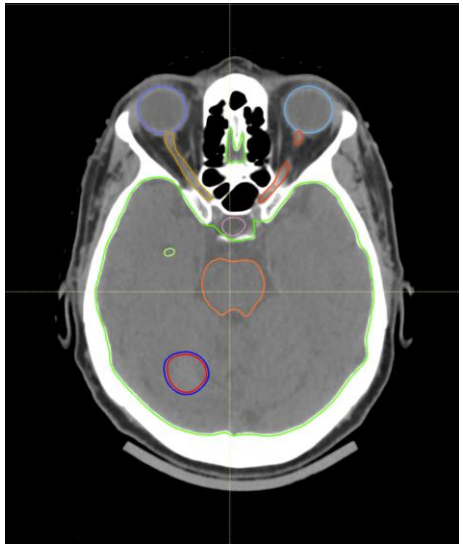


CT (3D)

DRR (2D)

Reference imaging

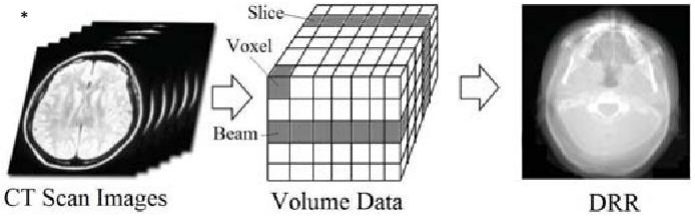
Digitally reconstructed radiograph (DRR)

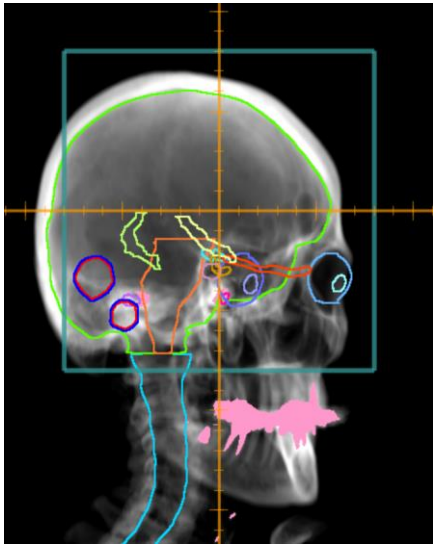


CT (3D)

$$I = I_0 \, e^{-(\mu_1 x_1 + \ldots + \mu_n x_n)}$$

μ = linear attenuation coefficient





DRR (2D)

* Montúfar, Jesús et al. "Perspective and orthogonal CBCT / CT digitally reconstructed radiographs compared to conventional cephalograms." (2016).

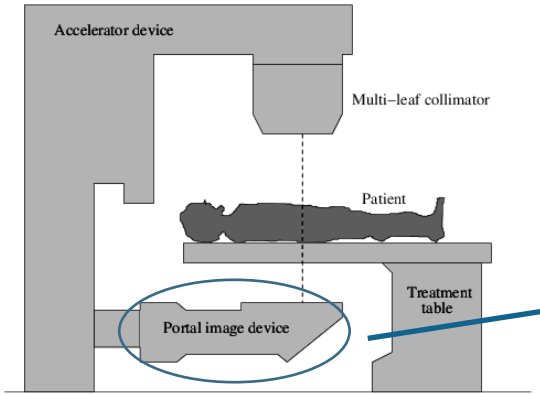
Day imaging

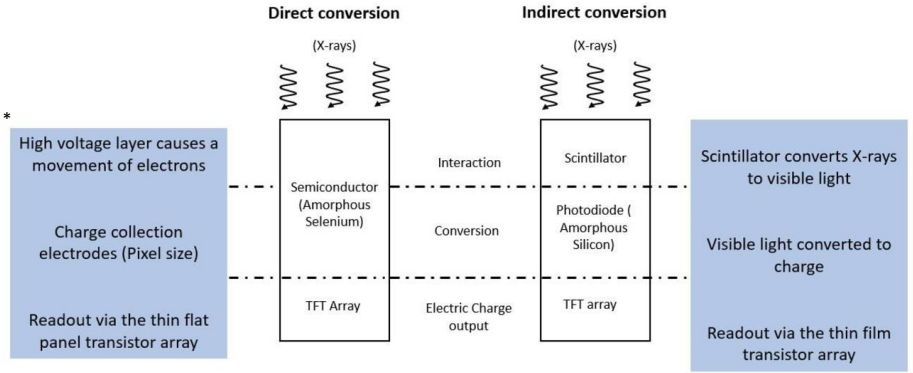
Portal imaging

Images obtained with treatment beam (MV energy range)

More X-rays at the detector = less absorption in the body = less dense tissue

$$I = I_0 e^{-\mu x}$$





*https://www.twi-global.com/technical-knowledge/faqs/digital-radiography

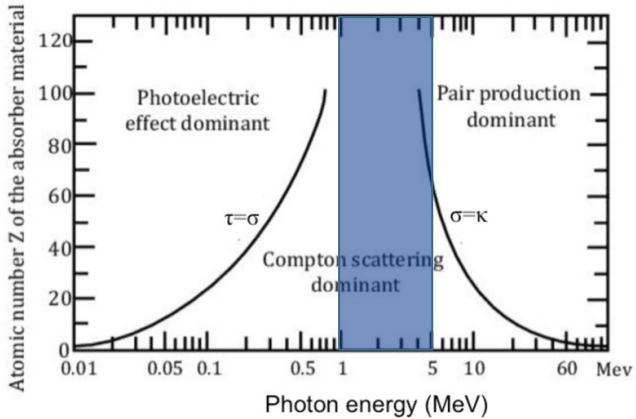
Portal imaging

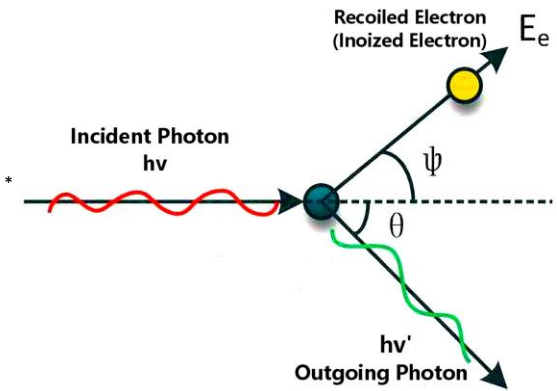
MV beam → Compton scattering dominant

Scattered photons = loss of information

- ≠ energy = ≠ tissue density
- ≠ direction = ≠ localisation of tissue

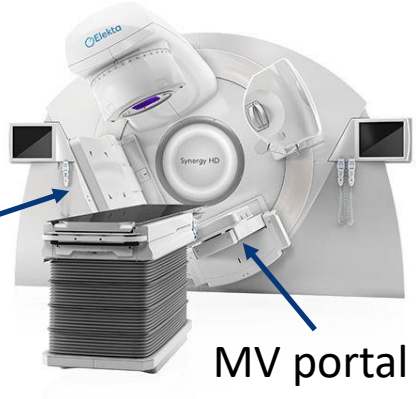
} loss of image quality





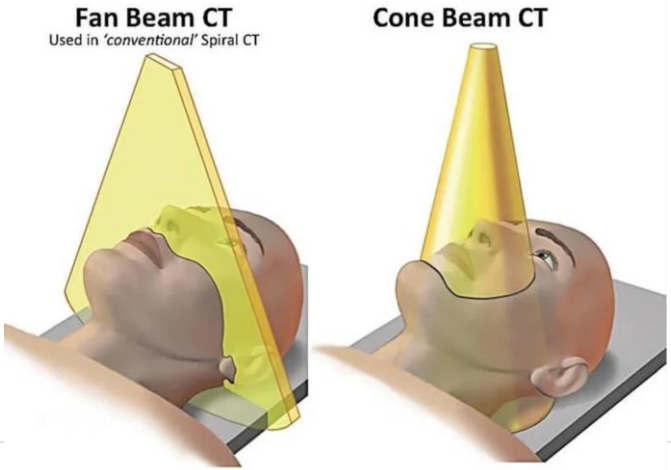
* https://doi.org/10.3390/cryst11050525

Cone beam CT



kV CBCT

MV portal imaging



CBCT

100-120 kV energy → better image quality than portal imaging

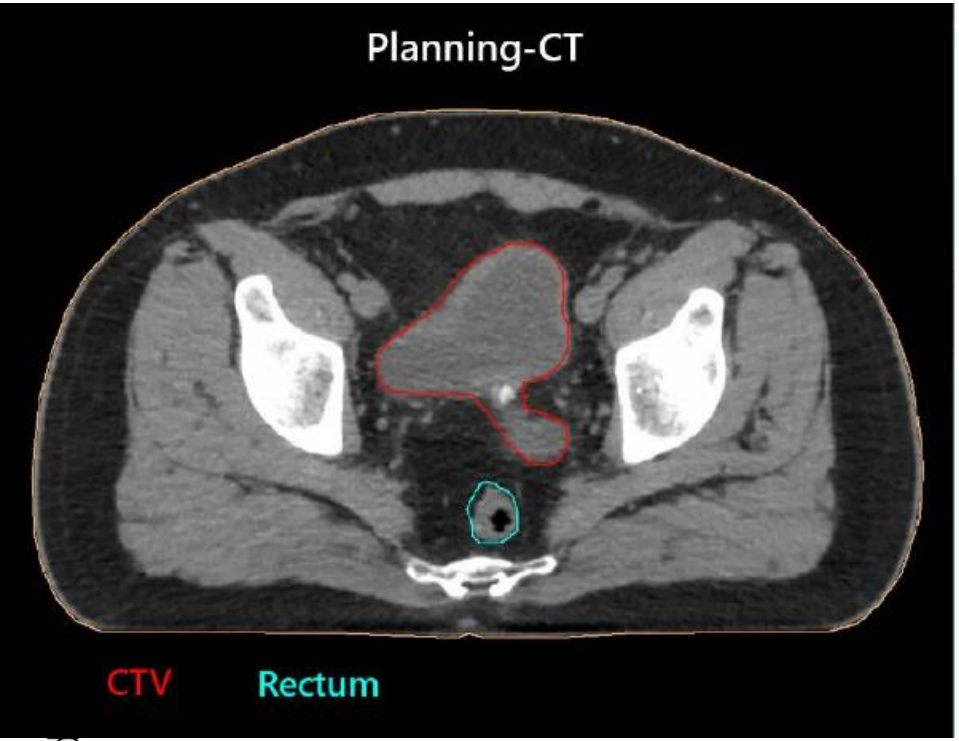
Cone beam shape (1 rotation):

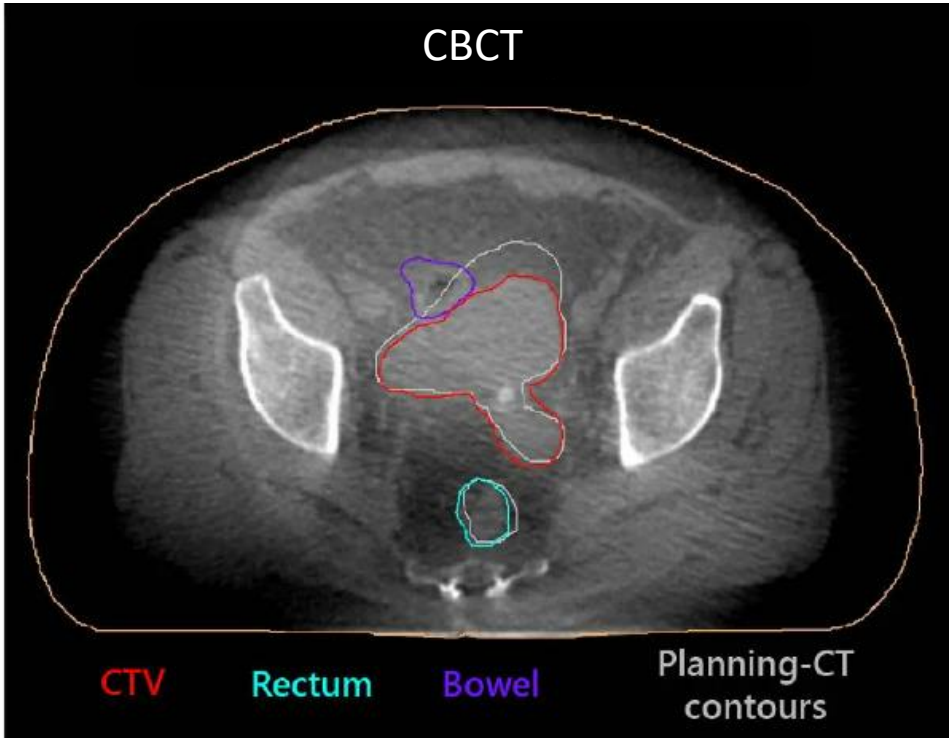
→ More scatter than conventional CT

→ Less dose than conventional CT

* https://www.online-sciences.com/technology/cone-beam-ct-vs-fan-beam-ct-cbct-advantages-disadvantages-uses/

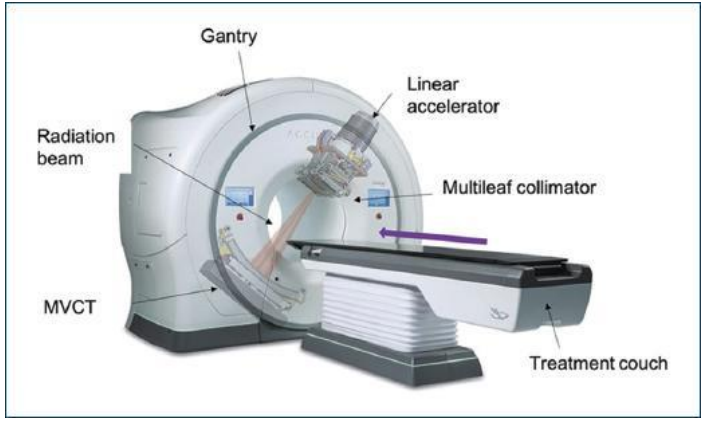
CBCT





*https://www.elekta.com/focus/netherlands-team-debuts-online-adaptive-radiotherapy-workflow-with-elekta-cbct-linac/

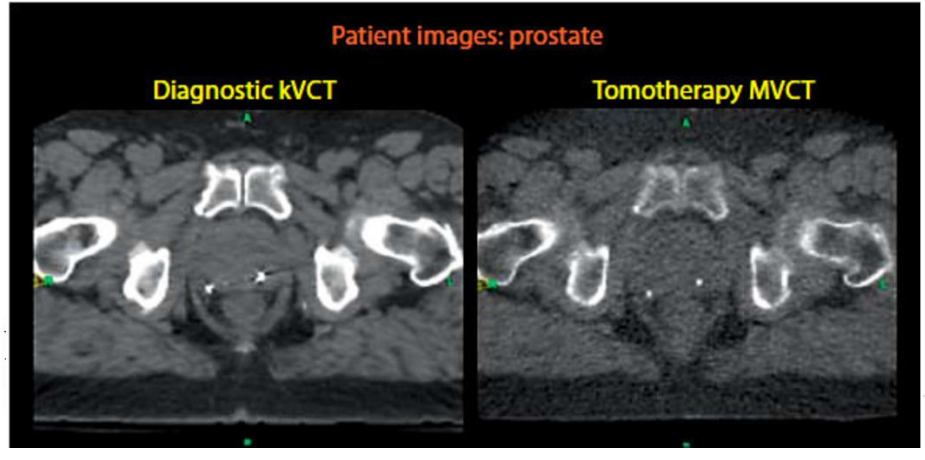
Megavoltage CT



MVCT

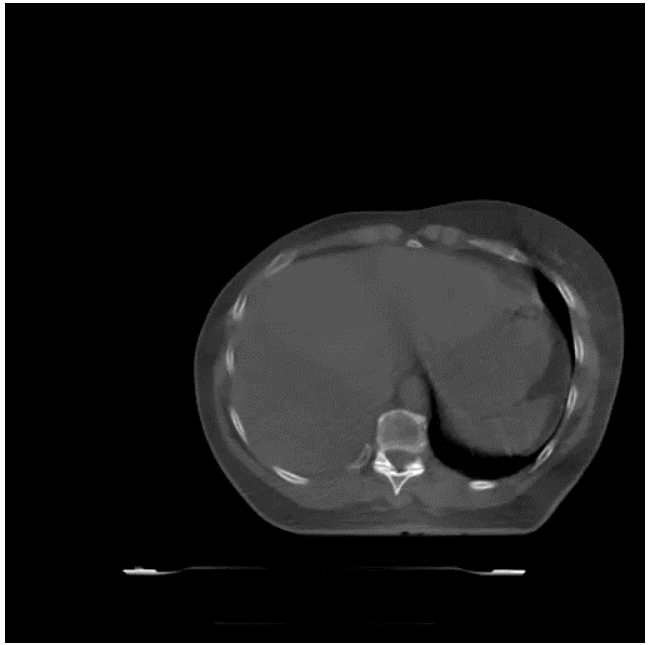
Tomotherapy/Radixact (Accuray)

3.5 MV fan-beam



*Kupelian, Patrick & Langen, Katja. (2011). Helical Tomotherapy: Image-Guided and Adaptive Radiotherapy. Frontiers of radiation therapy and oncology. 43. 165-80. 10.1159/000322420.

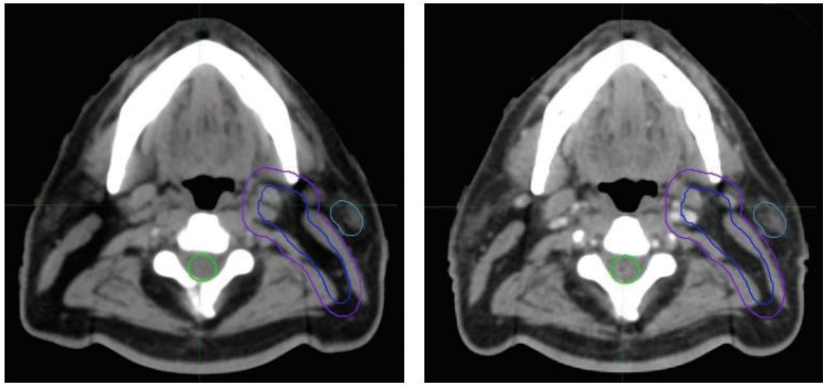
kVCT



Radixact (Accuray)

kV range → good contrast resolution

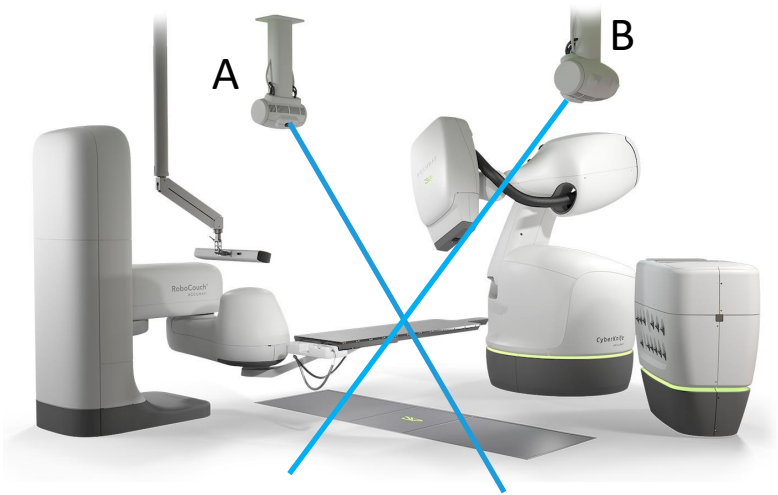
Fan-beam



ClearRT™ Planning CT

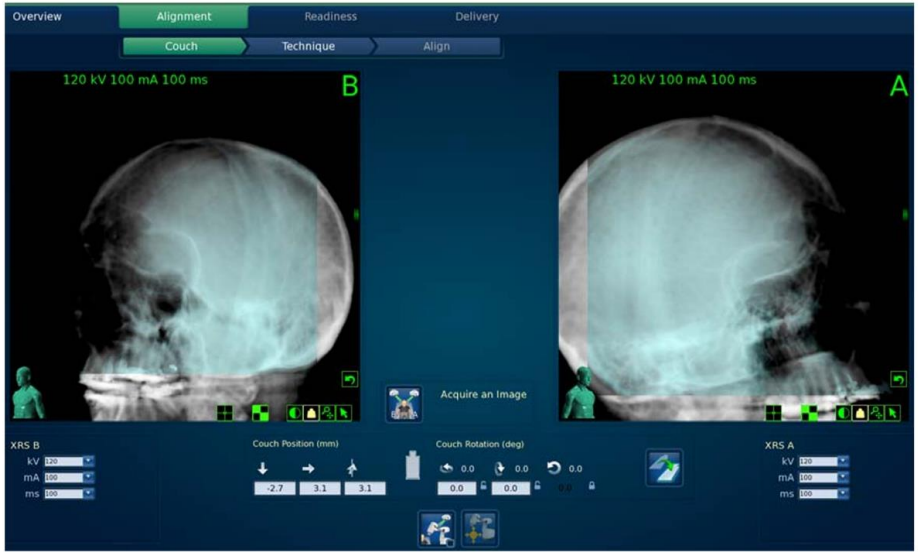
* https://www.accuray.com/clearrt/

CyberKnife IGRT

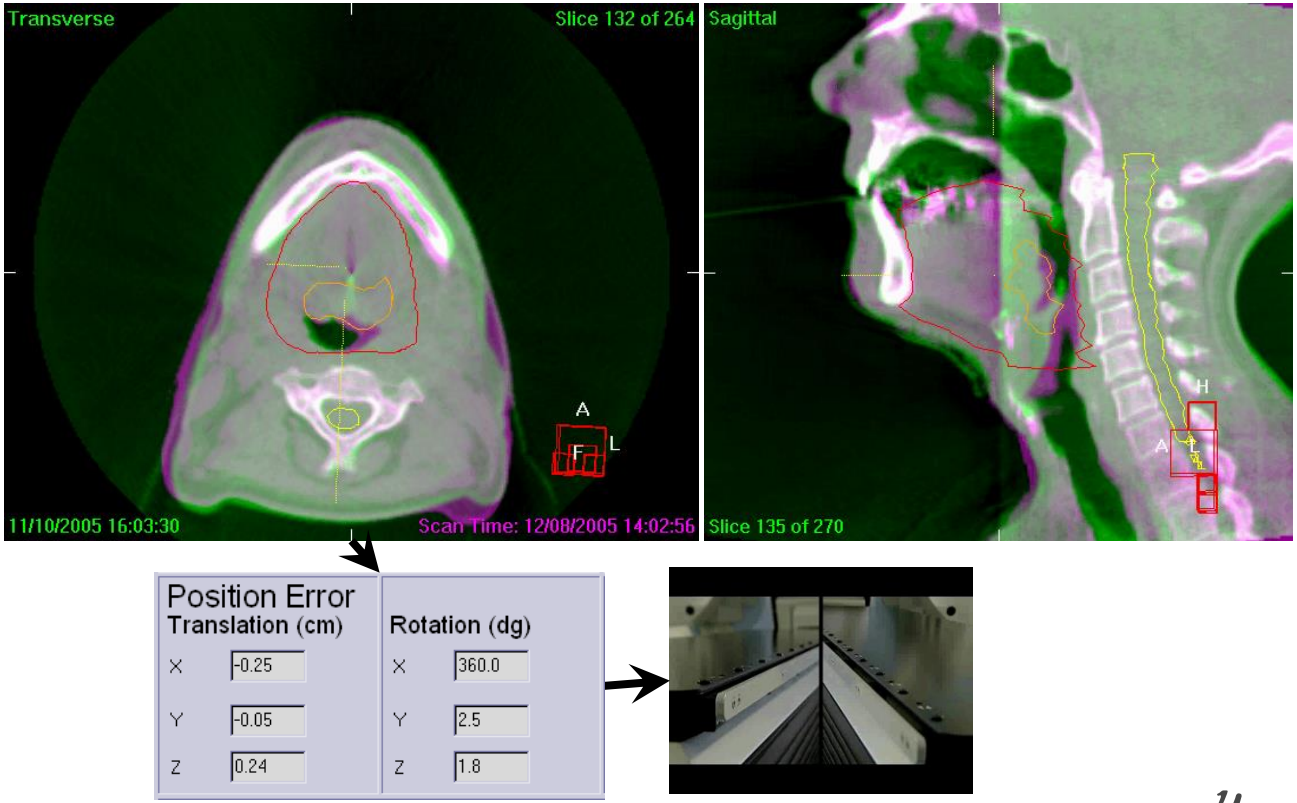


2 planar kV images

Comparison with DRR generated from planning CT



Registration



Quality assurance (QA)

Quality assurance of gantry-mounted image-guided radiotherapy systems

Recommendations No. 16

Chapter	Test	Frequency	Tolerance
2	**Safety**		
2.1.1	Interlocks	d	functional
2.1.2	Beam on indicators	w	functional
2.1.3	Anti-collision system	w	functional
3	**Geometric accuracy**		
3.1	kV Imaging field collimation	a	2 mm
3.2	Isocenter Quick check Full check:	d m	2 mm 2 mm
3.3	Beam and panel alignment	a	1 °
3.4	Image registration and couch correction accuracy:	w	2 mm /1°
4	**Image performance**		
4.1	**Planar imaging**		
4.1.1	Spatial accuracy:	a	2 mm
4.1.2	Spatial resolution	a	kV: 1.6 lp/mm MV: 0.6 lp/mm
4.1.3	Contrast	a	kV: 3 % 8 mm Ø MV: 1.2 % 7 mm Ø
4.1.4	Noise /contrast-to-noise ratio	a	10 % baseline
4.1.5	Uniformity	a	10 % baseline
4.1.6	kV imaging dosimetry	a	20 % baseline
4.2	**CBCT imaging**		
4.2.1	Spatial accuracy:	a	2 mm
4.2.2	High contrast / spatial resolution	a	0.1 lp/mm
4.2.3	Contrast / Low contrast visibility	a	10 % baseline
4.2.4	Noise	a	10 % baseline
4.2.5	Uniformity	a	< 2x baseline value
4.2.6	Sensitometry	a	Baseline
4.2.7	Slice thickness	a	50 % nominal
4.2.8	Artifacts	a	Absence
4.2.9	Imaging dosimetry	a	20 % baseline
5	**Data handling**		
5.1	Integrity	a	functional
5.2	Archiving and retrieving	a	functional

SSRMP recommendation for QA of IGRT systems

1. Geometric accuracy
2. Image quality

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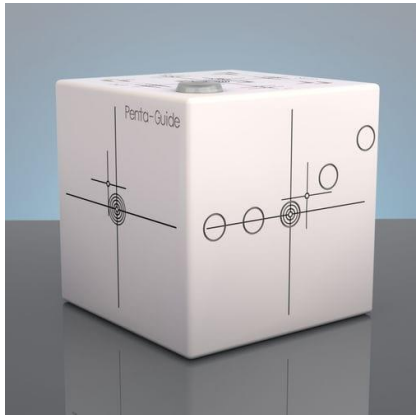
QA – Geometric accuracy

3	**Geometric accuracy**		
3.1	kV Imaging field collimation	a	2 mm
3.2	Isocenter Quick check Full check:	d m	2 mm 2 mm
3.3	Beam and panel alignment	a	1 °
3.4	Image registration and couch correction accuracy:	w	2 mm /1°



Geometric accuracy

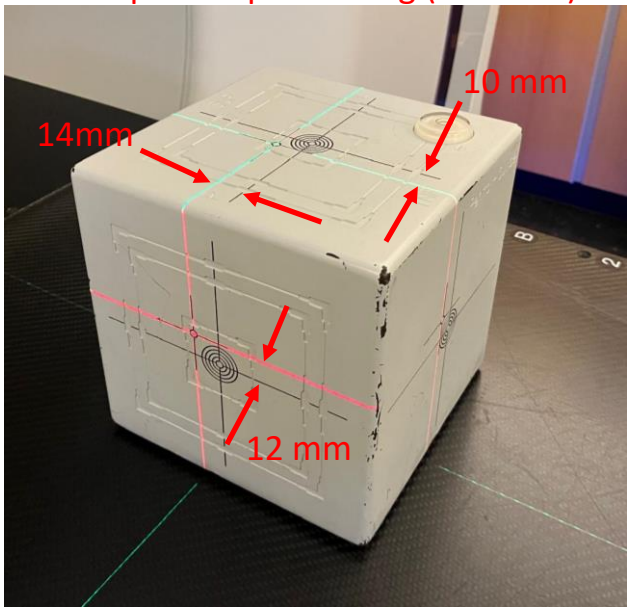
Coincidence of imaging and treatment isocenters

Image registration accuracy

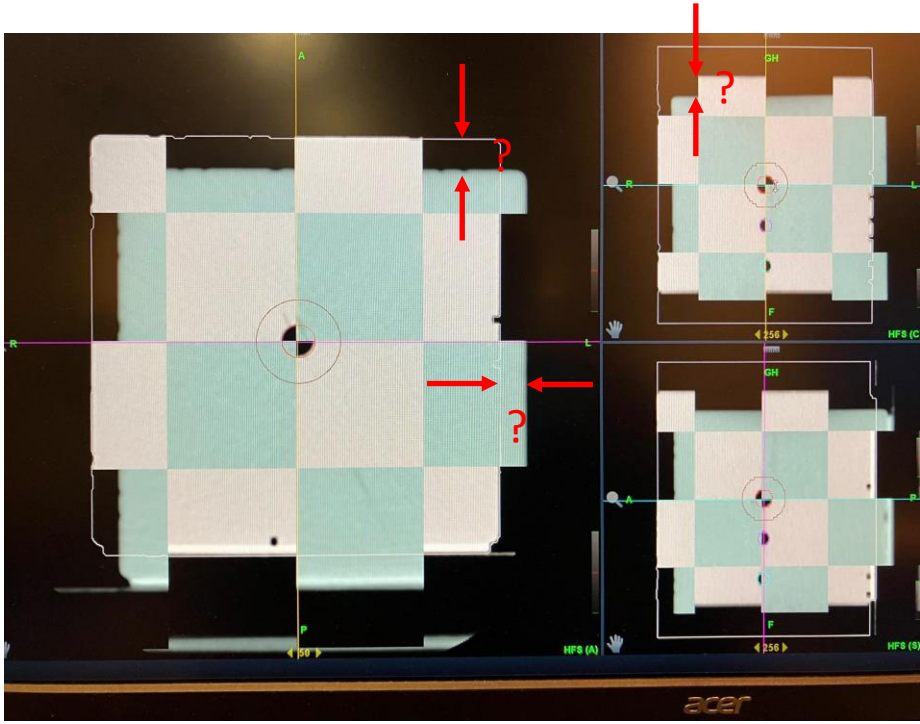
Couch correction accuracy

QA – Geometric accuracy

Green laser = virtual machine isocenter (fixed)
Red laser = patient positioning (movable)

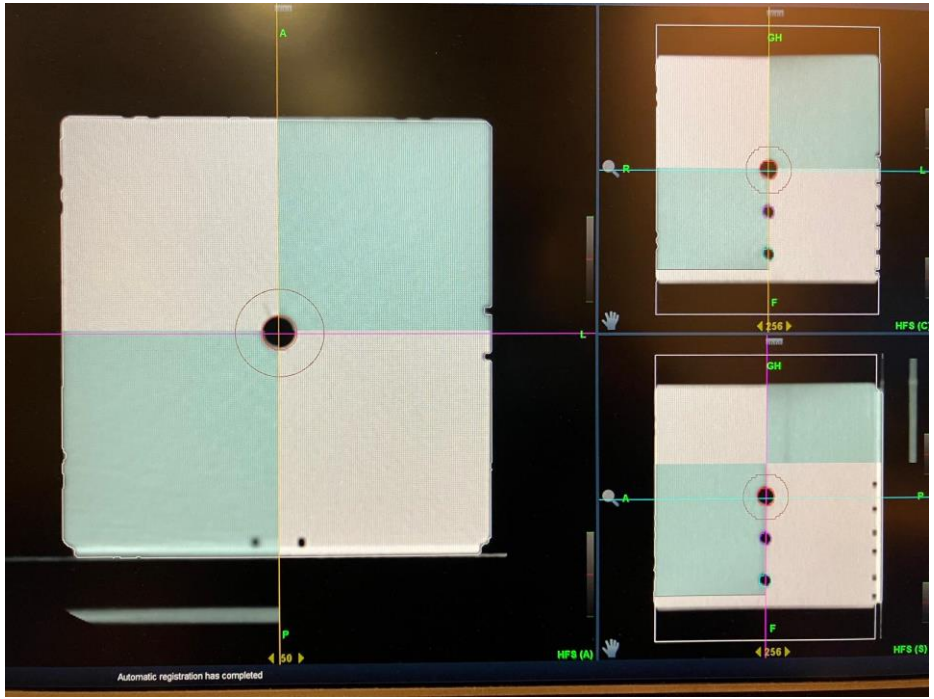


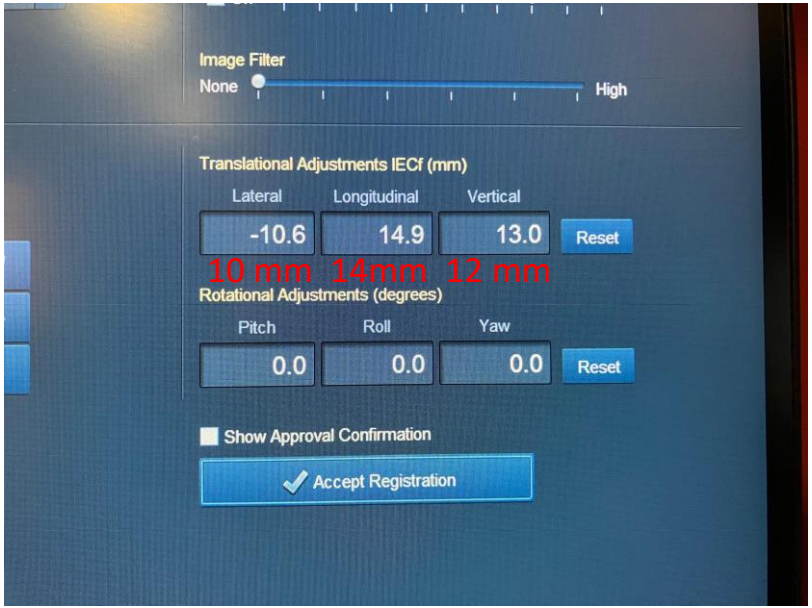
IMAGE



Pentaguide intentionally mispositioned
Known offsets from the isocenter

QA – Geometric accuracy

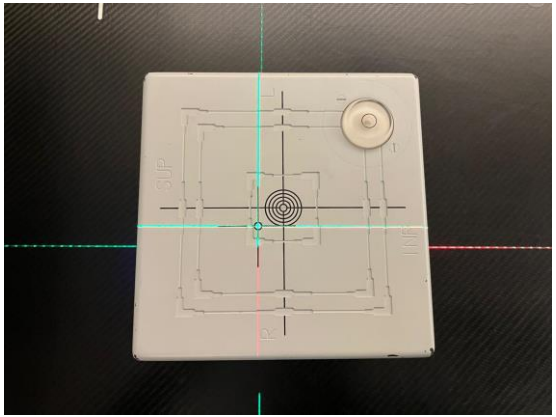


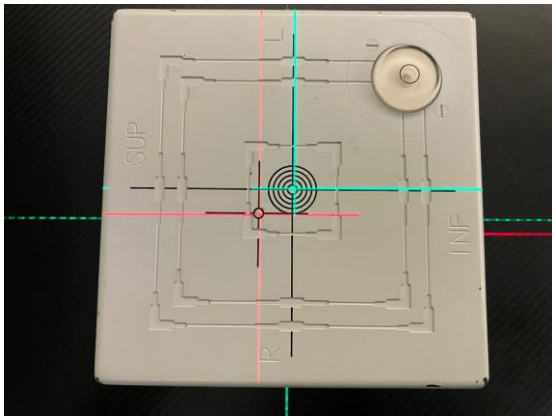


QA – Geometric accuracy

Before

After





Offsets are applied to the couch

→ Visual check

→ Registration accuracy

→ Couch correction accuracy

→ Coincidence of isocenters

QA – Imaging quality/dose

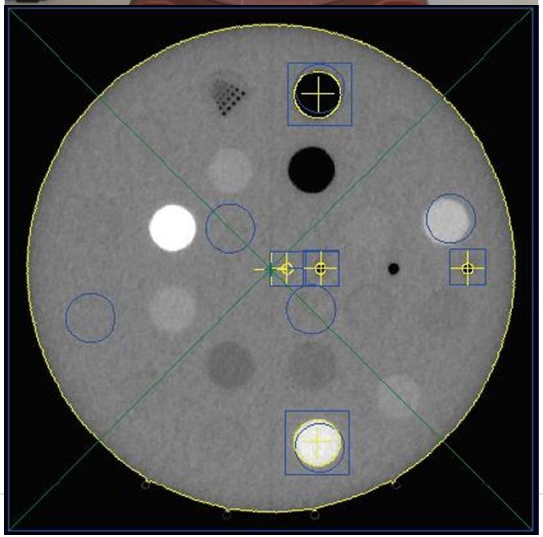


Image quality:

- *Contrast*
- *Noise*
- *Uniformity*
- *Spatial resolution*
- *Distance accuracy*

Imaging dose

Image quality parameters

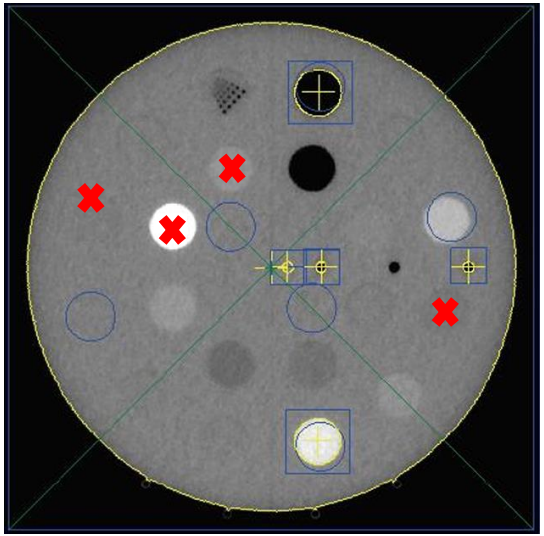


Image quality:

Contrast

Image quality parameters

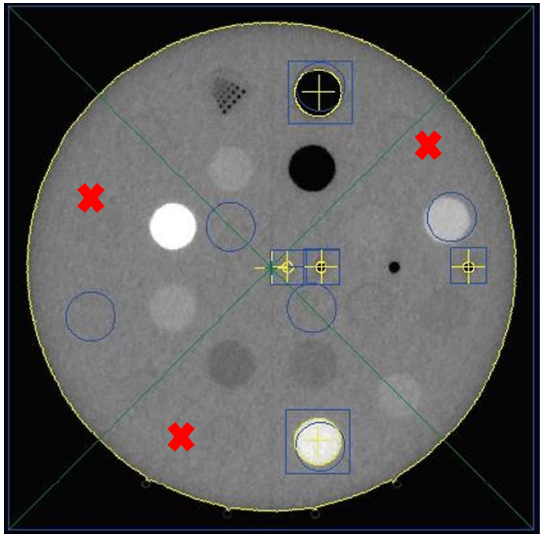


Image quality:

- Contrast
- Noise

Image quality parameters

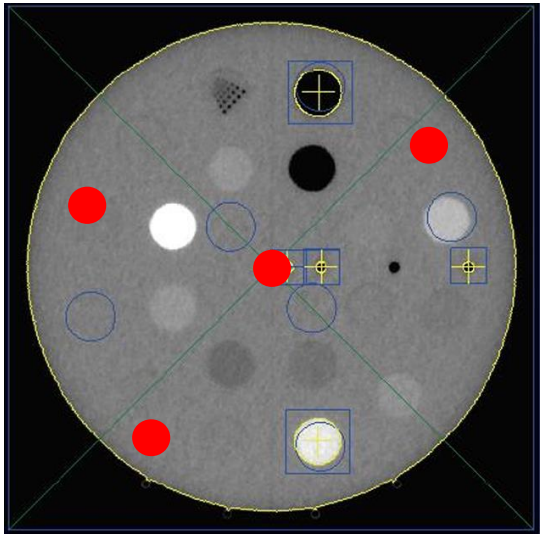


Image quality:

- Contrast
- Noise
- Uniformity

Image quality parameters

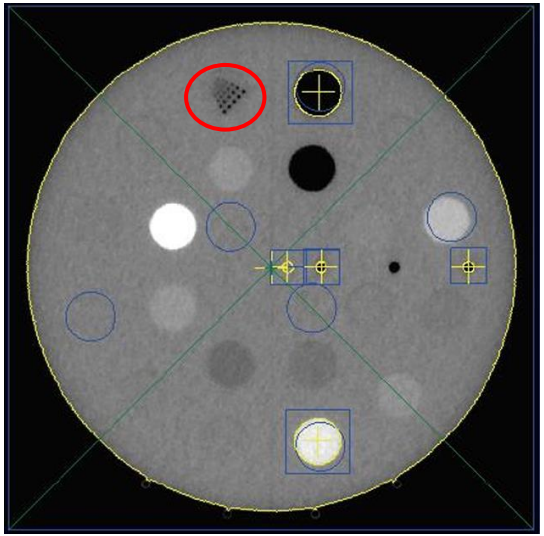


Image quality:

- Contrast
- Noise
- Uniformity
- Spatial resolution

Imaging dose

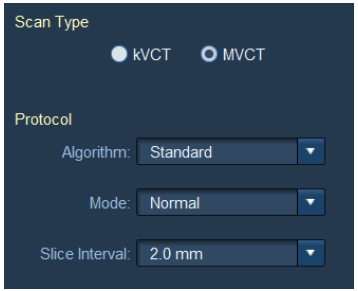


Image quality:

- Contrast
- Noise
- Uniformity
- Spatial resolution

Imaging dose

Standard imaging procedure:1.5 cGy

Practical example: CyberKnife Tracking systems

CyberKnife

CyberKnife

Stereotactic treatments:

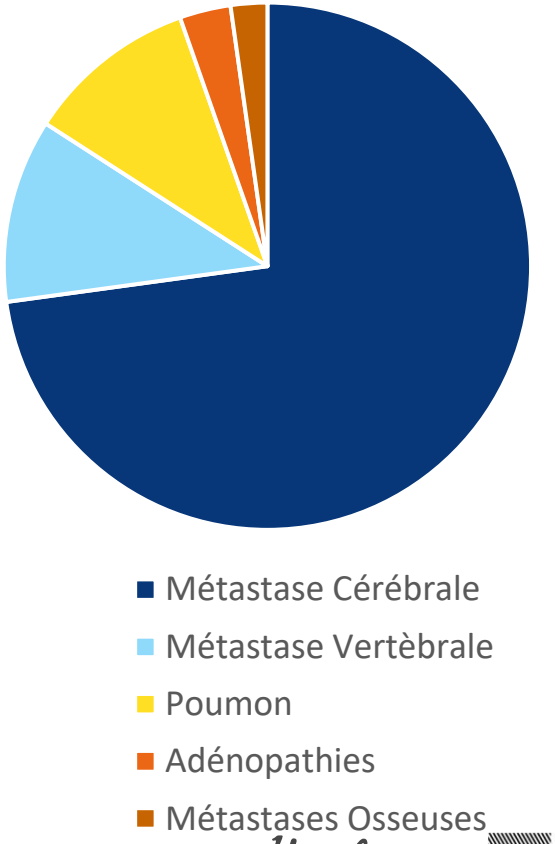
High dose per fraction

Reduced number of fractions (1-5)

Small volumes/small fields

IGRT/tracking system

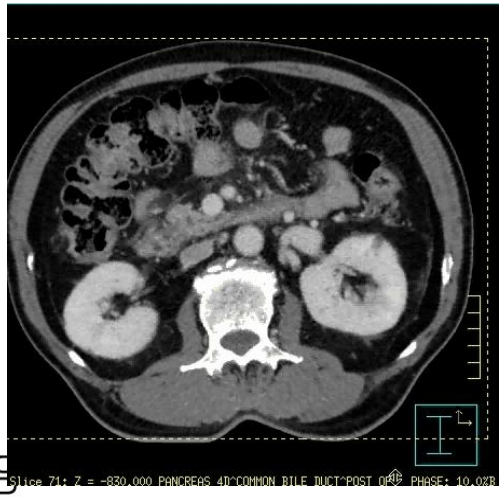
Brain, vertebra, lung



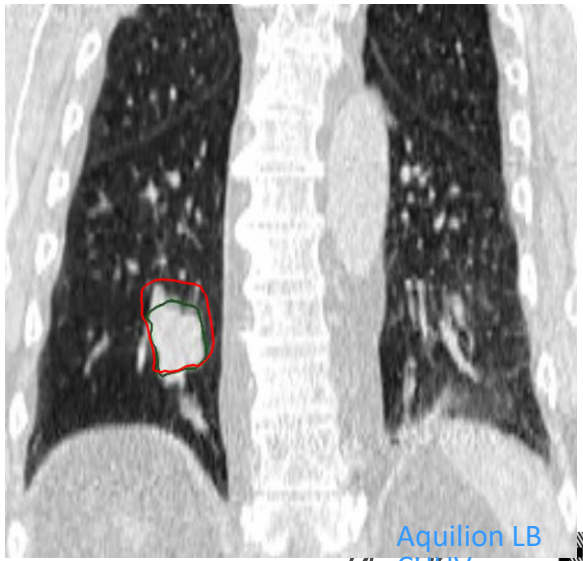
CyberKnife

"high level" IGRT = Tracking (images also taken *during* the treatment)

→ Registration *before* and *during* the treatment fraction

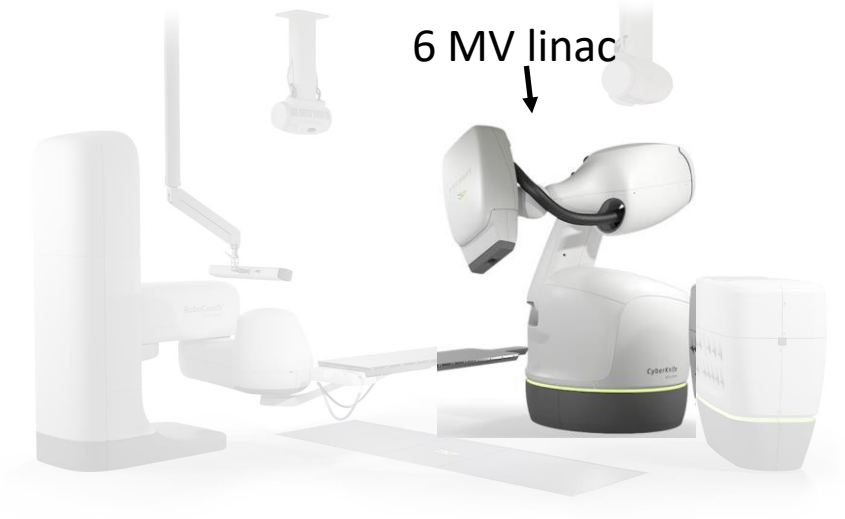


Courtesy of Philips Medical Systems



Aquilion LB

CyberKnife



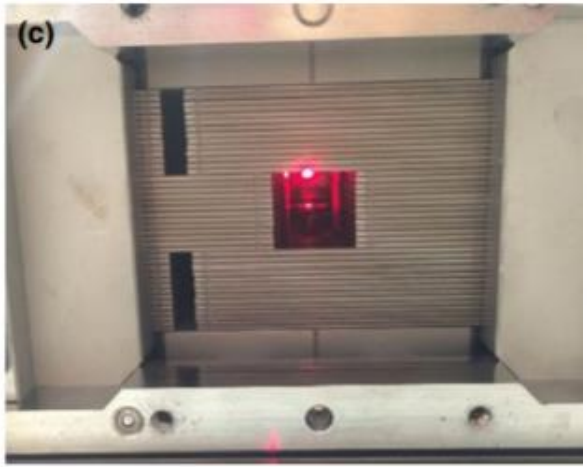
3 collimator types:

- *IRIS (12 diameters)*
- *Fixed (12 diameters)*
- *MLC (max 10x11.5 cm^2)*

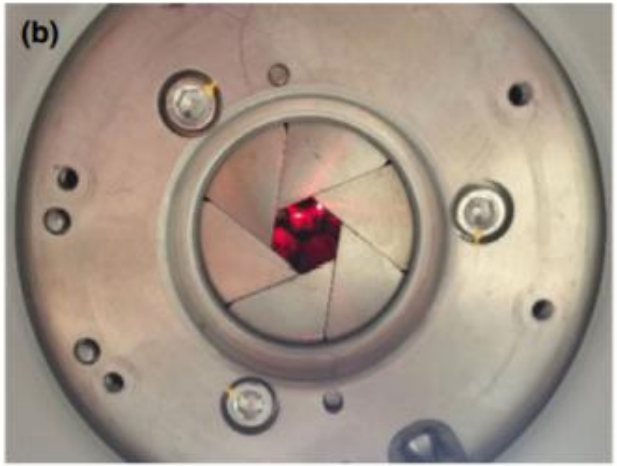
Nominal energy

- *6 MV*

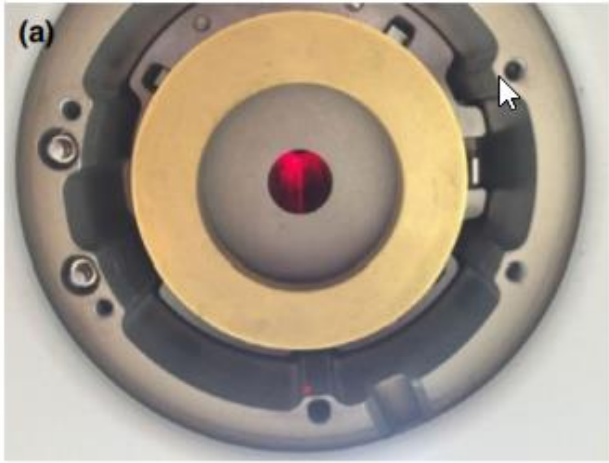
CyberKnife collimators



MLC

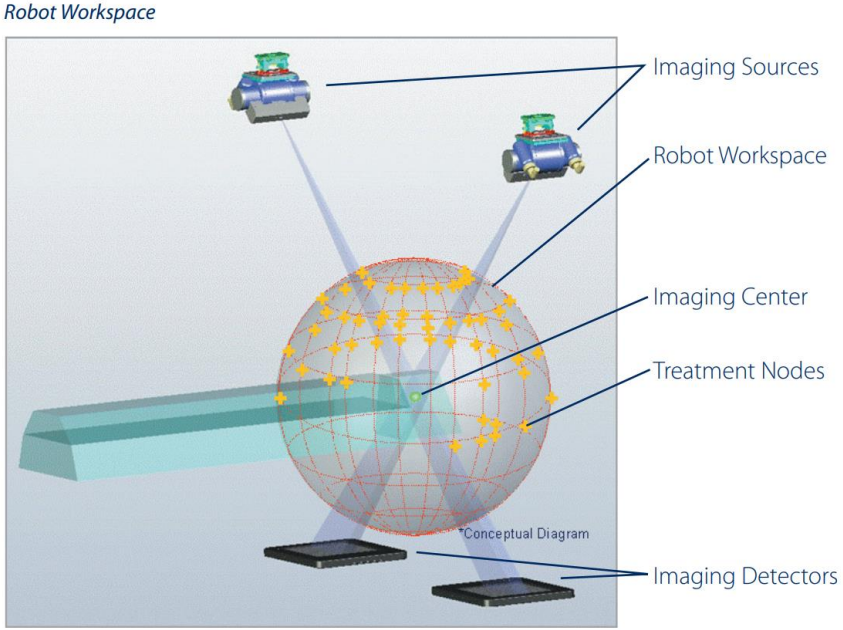


IRIS



Fixed

CyberKnife



Imaging center

→ intersection of imaging beams

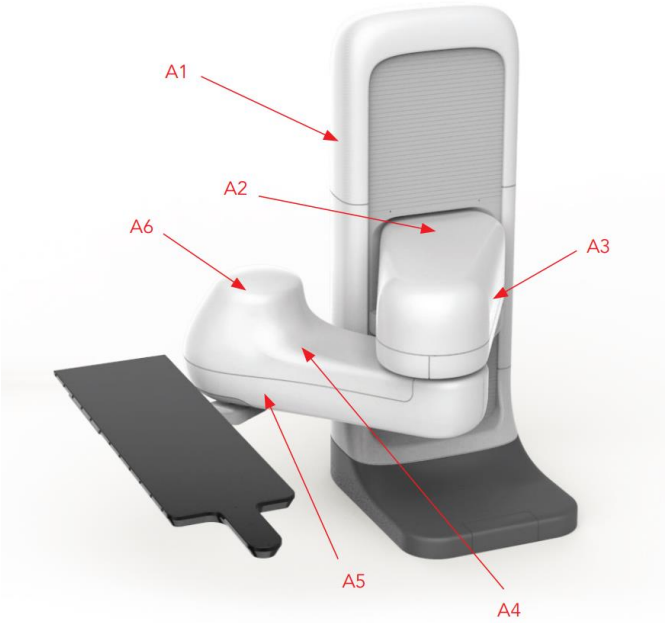
Nodes

→ possible robot positions defined on a sphere with imaging center as origin

CyberKnife

6D Robocouch

CyberKnife

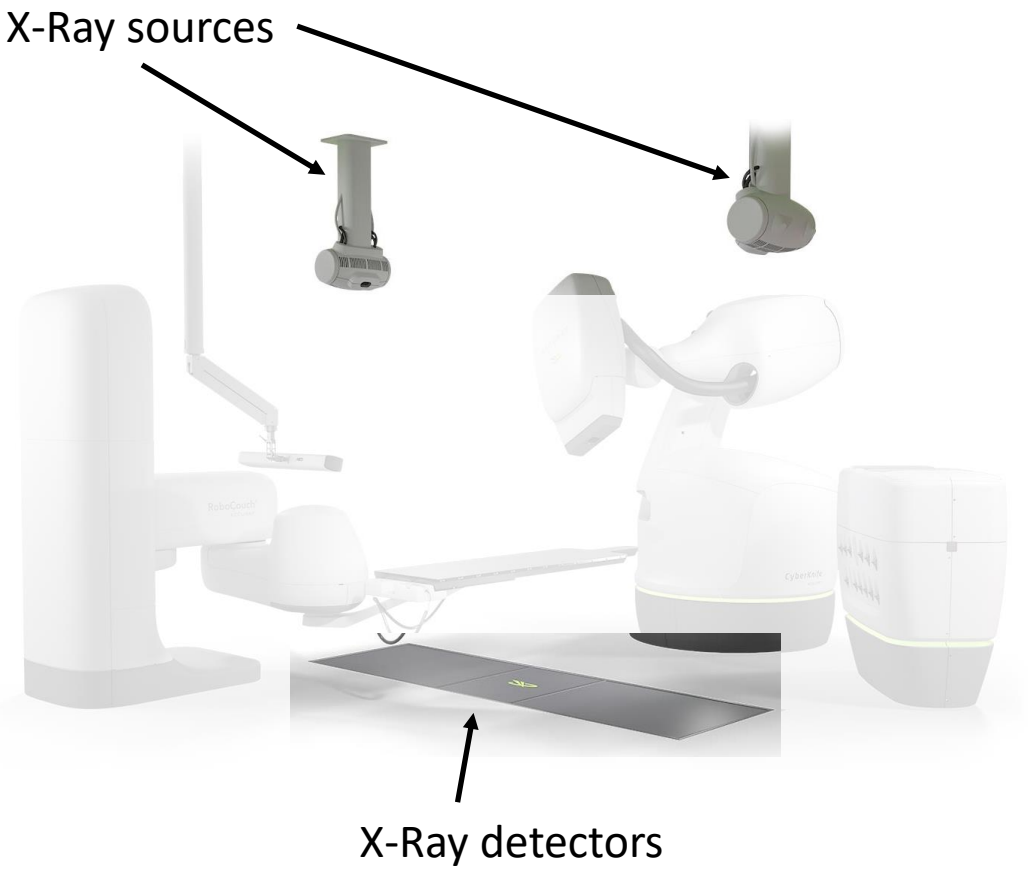


6 degrees of freedom Robocouch

6 DoF : Corrections of translations and rotations

Initial patient positioning

CyberKnife



Imaging system

2 kV sources + detectors

IGRT/Tracking : DRR comparison

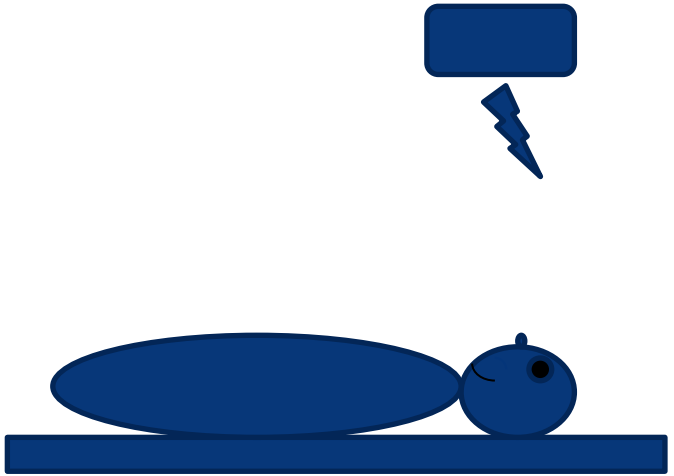
Patient positioning *before* treatment (robocouch correction)

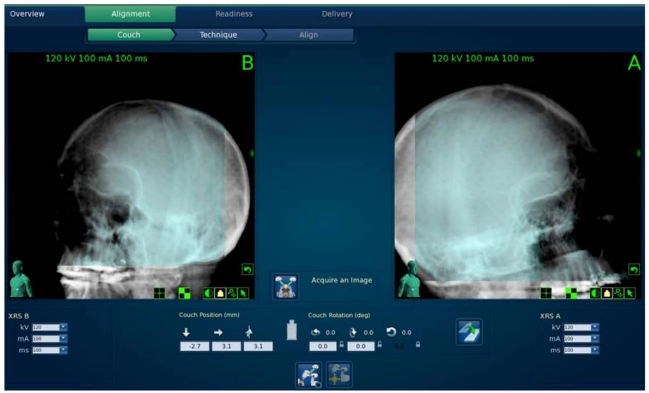
Tracking *during* treatment (robot correction)

IGRT: before treatment start

IGRT: before beam *on*

→ Patient on couch
→ kV imaging
→ DRR comparison
→ Couch correction

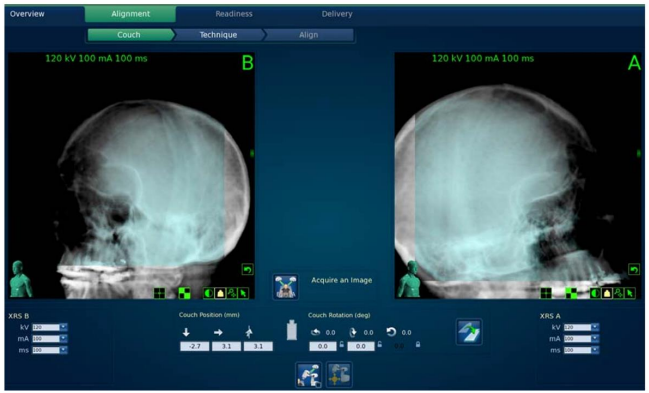


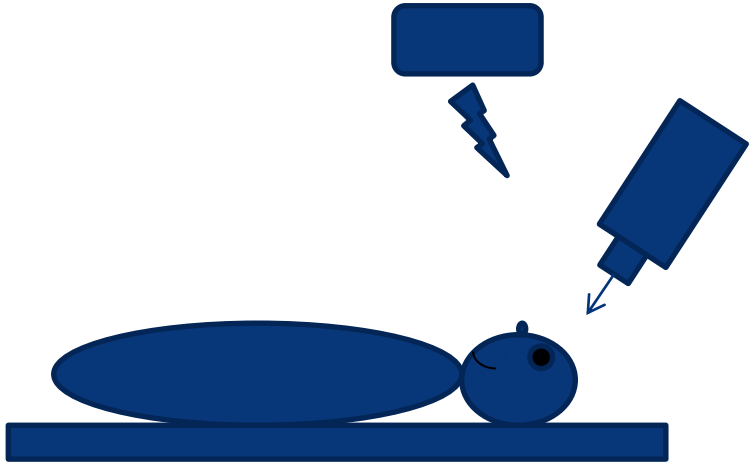


Tracking: during treatment

Tracking: during beam *on*

→ kV imaging
→ Automatic DRR registration
→ Beam incidence (robot) correction

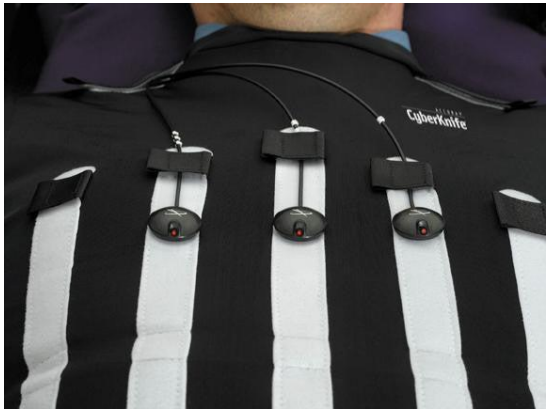




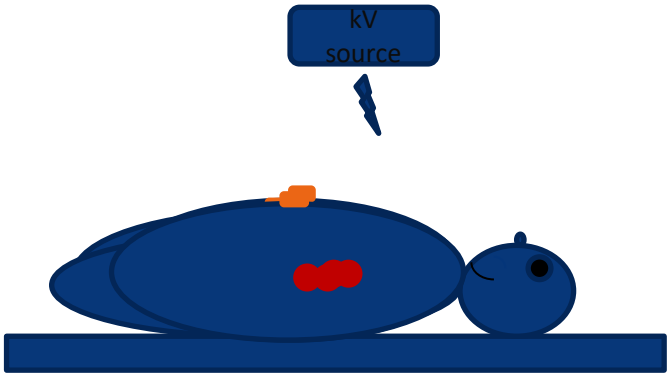
Synchrony

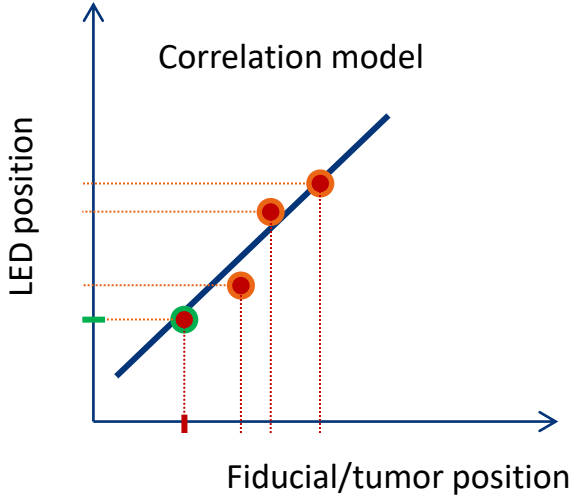
Continuous synchronization between beam and tumor movement during breathing

Correlation model between patient's breathing pattern (real-time, LED) and movement of the target (fiducials, kV imaging)



Synchrony: correlation model creation





1 image = 1 «external» respiratory position = 1 fiducial/tumor location
Model updated during treatment
Targeting accuracy < 1.5 mm