Joint ICTP-IAEA Workshop on Radiation Protection in Image-Guided Radiotherapy (IGRT)

Discussion on Radiological Protection for Adaptive Radiotherapy

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Note

Please feel free to photograph and share these slides on social media.

Conflict of Interest Disclosure

- No conflicts of interest to disclose

Outline

- Introduction: why do we talk of ART and Radiation Protection?
- Types of adaptive radiation therapy
  - Offline adaptive
  - Online adaptive
  - Real time tumour tracking
- Types of imaging that are used: balance between extra-dose from imaging and gain from treatment adaptation
- Is the gain superior to the loss in terms of extra dose to the patient?
- Dose measurements and evaluations from CBCT

EXTRA

ART and Radiological Protection

Adaptive Radiotherapy (ART): A treatment approach that modifies the radiation plan based on changes in the patient's anatomy or tumor characteristics over the course of treatment.

- Increased precision and effectiveness in targeting tumors.
- Potential to reduce radiation exposure to healthy tissues.

Radiological Protection: Measures and protocols to protect patients and healthcare workers from unnecessary radiation exposure.

- **Justification**: Ensuring the benefits outweigh the risks.
- **Optimization**: Keeping radiation doses as low as reasonably achievable (ALARA).

Why Radiological Protection in ART?

Patient Protection

- Frequent imaging increases exposure risk
- Balancing the need for imaging with minimizing dose

Techniques and Technologies

- Use of low-dose imaging protocols
- Optimize protocols (what to use) and timing (when to do it)
- Advanced imaging technologies to reduce exposure

- Increased complexity □ increase the risk of errors (incidental exposure)

Risk analysis to identify risks and mitigation strategies

Radiological Protection Principles in ART

The «dynamic» nature of ART requires constant monitoring and recalculations of dose distribution □ increasing imaging (?) □ increasing the complexity of radiological protection

ART main aim is the improvement of radiation treatment. To guarantee this improvement we need to balance:

From a dose optimization perspective, the most important thing is to adapt the plan as soon as the patient needs it.

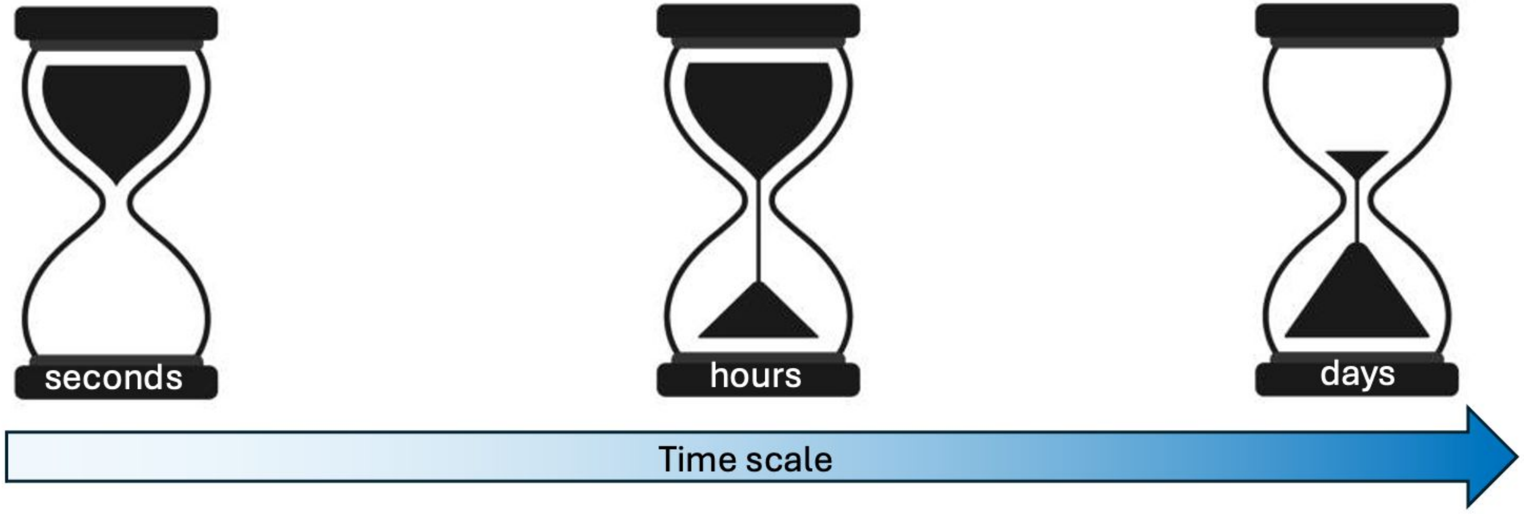
Adaptive radiotherapy time scale

Patient-specific treatment variations:

- systematic changes in weight, tumor, and organ geometric and biological response
- stochastic variations such as organ deformation, filling change, respiration and peristaltic motion

Glide-Hurst et al., IJROBP, 2021
(https://doi.org/10.1016/j.ijrobp.2020.10.021)

real-time	**online**	**offline**
during a treatment fraction	immediately before a treatment fraction	between treatment fractions



offline
between treatment fractions

Off-line adaptive

- Mostly addresses systematic and progressive changes that occur during the treatment course, such as patient weight loss and tumor morphologic changes

- Does not need dedicate equipment

- Yields **improved target coverage** and **OAR sparing** as shown in prospective clinical trials in the prostate, head and neck, and lung

Vargas et al., Int J Radiat Oncol Biol Phys 2005 (https://doi.org/10.1016/j.ijrobp.2004.12.017)
Vargas et al., Int J Radiat Oncol Biol Phys 2005 (https://doi.org/10.1016/j.ijrobp.2004.12.052)
Spoelstra et al., Int J Radiat Oncol Biol Phys 2009 (https://doi.org/10.1016/j.ijrobp.2008.12.027)
Schwartz et al., Int J Radiat Oncol Biol Phys 2012 https://doi.org/10.1016/j.ijrobp.2011.08.017)
Li et al., Int J Radiat Oncol Biol Phys 2013 (https://doi.org/10.1016/j.ijrobp.2013.04.014)

offline

between treatment fractions

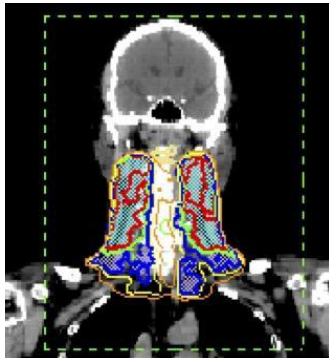
Which imaging?

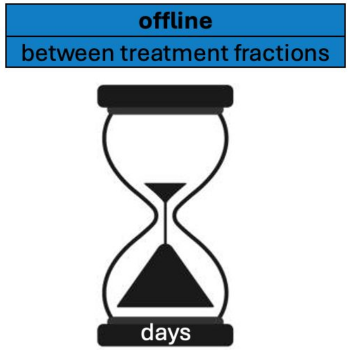
- Daily (or *frequent*) CBCT/MVCT/CT-on-rail for assessing variations
- New simulation CT if the acquired in-room image quality is not sufficient for treatment planning
- Direct calculation on the CBCT is also possible (no further simulation CT required) with different strategies

Giacometti et al., Phys Med, 2020
(https://doi.org/10.1016/j.ejmp.2020.06.017)

- Recently, there have been significant advancements in CBCT quality (e.g., Hypersight by Varian), enabling the direct use of CBCT for replanning. The primary benefit lies in improved workflow efficiency and faster replanning, rather than dose reduction.

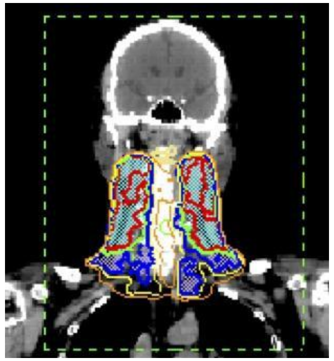
Dosimetric advantages

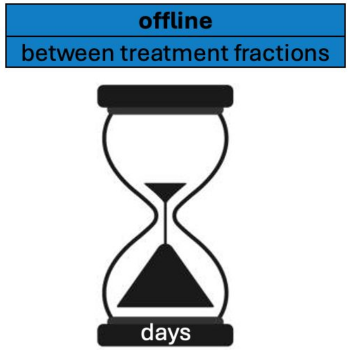




Paper	Target	OARs
Schwartz et al., Int J Radiat Oncol Biol Phys, 2012	Underdosing >5% avoided with ART	Reduced mean dose to contralateral and ipsilateral parotids: by 0.6 Gy (2.9%) and 1.3 Gy (3.8%) (ART1) and by 0.8 Gy (3.8%) and 4.1 Gy (9%) (ART2)
Chen et al., Head & neck, 2014	Improved locoregional control at 2 years: 88% (ART) vs 79% (non-ART). No difference in overall survival.	No difference in acute and late grade 3+ toxicity.
Dewan et al., Asian Pacific Journal of Cancer Prevention, 2016	Underdosage (V<93%) and overdosage (V>110%) of GTV, CTV and PTV significantly improved with ART	~30% reduction in Dmax to spinal cord and mean dose to ipsilateral and contralateral parotid glands
Maheshwari et al.,J Cancer Res Ther, 2020	Complete response was observed in 90% and 96.7% patients in the non-ART and ART groups, respectively, at 6 months.	Dose to spinal cord, ipsilateral, and contralateral parotid reduced by 4.3%, 6%, and 2.2%, respectively, with ART. Xerostomia was statistically significantly higher in the non-ART group at 6 months.

Dosimetric advantages: Exercise





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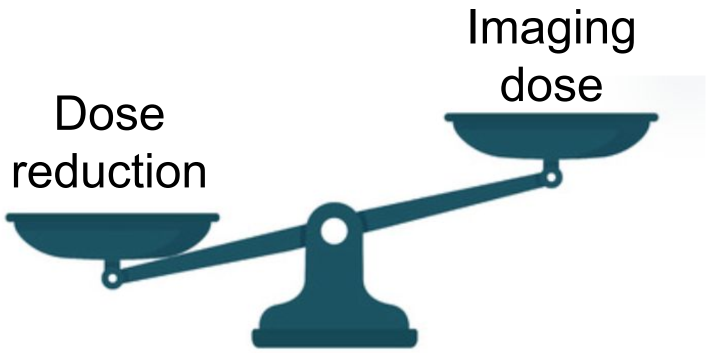
33 treatment fractions
<u>Daily CBCT</u>: H&N S20 Elekta XVI protocol 120kV 585.6 mAs Gantry rotation 205° (H&N enhanced)
H&N S20 Elekta XVI protocol 100kV 36.60 mAs Gantry rotation 205° (H&N S20)
<u>CBCT dose</u>: about 11.8 mGy daily to the parotids (H&N enhanced)
about 0.9 mGy daily to the parotids (H&N S20)
New CT scan dose: 1.2 mSv

Total parotid dose from imaging: 39.2 cGy □ 0.4Gy (H&N enhanced)
29.7 mGy □ 0.03 Gy (H&N S20)
Reduced mean dose to ipsilateral parotid: 4.1Gy



offline
between treatment fractions

Off-line adaptive: Helical Tomotherapy

- MVCT is performed daily in any case

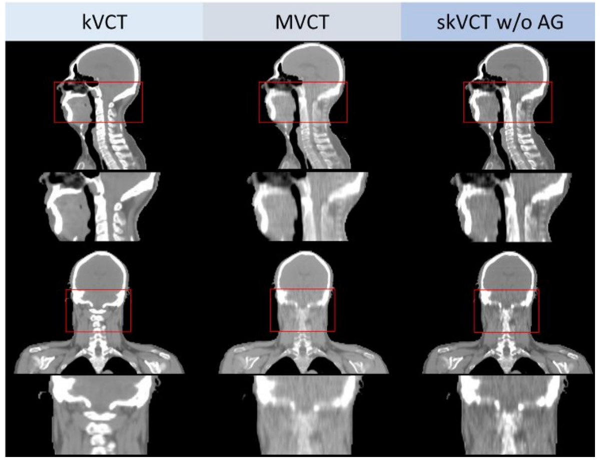
TABLE IE. Tomo MVCT dose at the center of a 30-cm water phantom and its dependency on acquisition protocols.

MVCT in Tomo	
Acquisition mode	Dose (cGy)
Fine pitch (4 mm couch travel/rotation)	2.5 cGy
Normal pitch (8 mm couch travel/rotation)	1.2 cGy
Coarse pitch (12 mm couch travel/rotation)	0.8 cGy

From Edward Chao, Accuray Incorporated and T. Rock Mackie, UW, Madison, WI.

Ding et al., Report of the AAPM Therapy Physics Committee Task Group 180, Med Phys, 2018 (https://doi.org/10.1002/mp.12824)

- The imaging dose differs significantly when different pitch parameters are selected
- Select MVCT scan pitch parameters that balance imaging dose with clinical need (i.e. patient positioning or adaptive planning)



Deep-learning-based approaches can be used to generate high-quality synthetic kilovoltage computed tomography from MVCT

Lv et al., Med Phys. 2024 (https://doi.org/10.1002/mp.16633)

offline
between treatment fractions

Off-line adaptive: who and when?

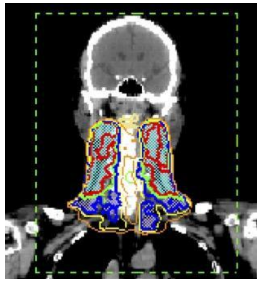
- ## Who? Patient selection

In many trials general trend towards decreased doses to OAR and enhanced target coverage with the use of ART

Still uncertain the precise method for identifying patients who would gain maximum benefit from replanning (large variability in the literature: baseline clinical and dosimetric factors, predictors occurring during treatment, …)

- ## When? Frequency and timing

Effective incorporation of ART in clinical setting requires an optimal timing of the intervention. Presently, there is a lack of consensus on the most suitable frequency and timing for replanning.



H&N: The ideal **timing** for replanning falls between the third and fourth week of the RT course.
Frequency: at least once, twice beneficial for some patients, more than twice (?)
Efforts have been initiated to develop automated methods using machine learning to anticipate the necessity for replanning interventions.

Nuyts et al., Cancer Med, 2024 (https://doi.org/10.1002/cam4.7192.)
Avgousti et al., Cancer/Radiothérapie, 2022 (https://doi.org/10.1016/J.CANRAD.2021.08.023)
Guidi et al., Phys Med, 2016 (https://doi.org/10.1016/J.EJMP.2016.10.005)

On-line adaptive

online
immediately before a treatment fraction

- Patient's treatment plan is adjusted before treatment delivery to account for temporal and stochastic changes detected in a single treatment fraction while the patient remains in the treatment position

- It is easier with dedicate equipment! There are approaches with standard equipment (i.e. plan of the day strategy)

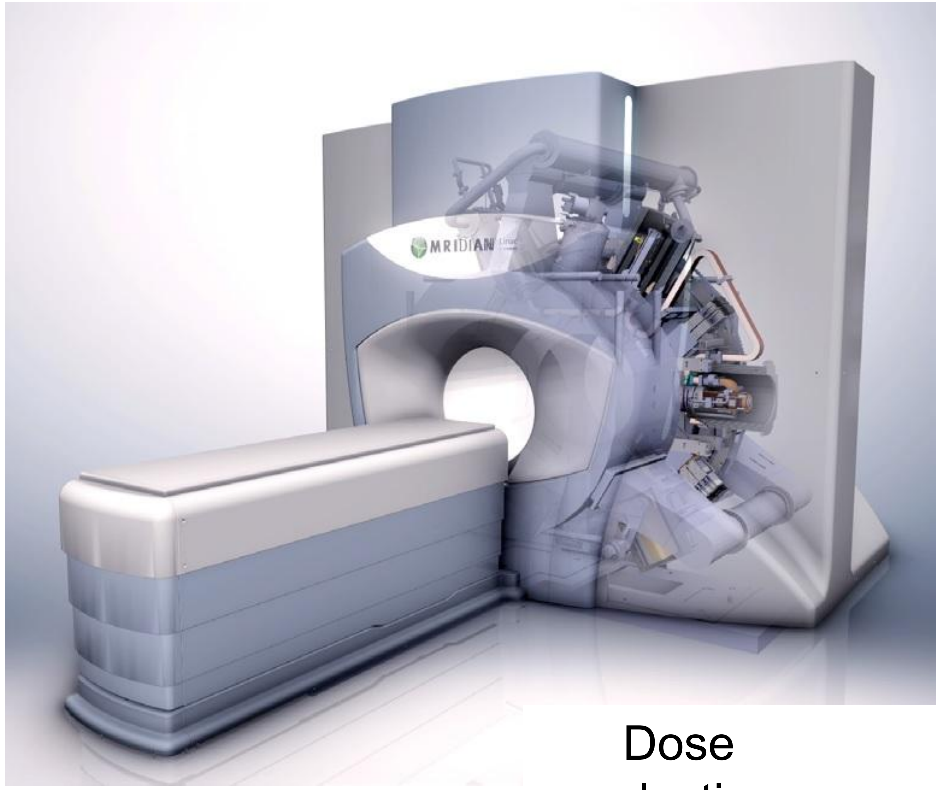
- Yields **improved target coverage** and **OAR sparing** in head and neck, abdomen, pelvis and lung

Henke et al., Radiother Oncol, 2018 (https://doi.org/10.1016/j.radonc.2017.11.032)
El-Bared et al., Pract Radiat Oncol, 2019 (https://doi.org/10.1016/j.prro.2018.08.010)
Li et al. Radiother Oncol, 2011 (https://doi.org/10.1016/j.radonc.2011.08.027)
Liu et al., Int J Radiat Oncol Biol Phys, 2012 (https://doi.org/10.1016/j.ijrobp.2011.12.073)
Court et al., Int J Radiat Oncol Biol Phys, 2005 (https://doi.org/10.1016/j.ijrobp.2004.09.045)
Ahunbay et al., Int J Radiat Oncol Biol Phys, 2010 (https://doi.org/10.1016/j.ijrobp.2009.10.013)
Mohan et al., Int J Radiat Oncol Biol Phys, 2005 (https://doi.org/10.1016/j.ijrobp.2004.11.033)
Heijkoop et al., Int J Radiat Oncol Biol Phys, 2014 (https://doi.org/10.1016/j.ijrobp.2014.06.046)
Henke et al., Adv Radiat Oncol, 2019 (https://doi.org/10.1016/j.adro.2018.10.003)

online
immediately before a treatment fraction

On-line adaptive: MR-linac

No extra dose in the MR workflow



Elekta Unity
1.5 T MRI and 7MV FFF linac

MRIdian (ViewRay)
0.35 T MRI and 6 MV linac

MR-linac: a consideration

Is **dose reduction** the main reason to choose MR-guidance over X-ray guidance?

I don't think so.

In my view, MR-guidance provides far superior imaging quality compared to X-rays, which is a valuable advantage for treating certain types of tumors.

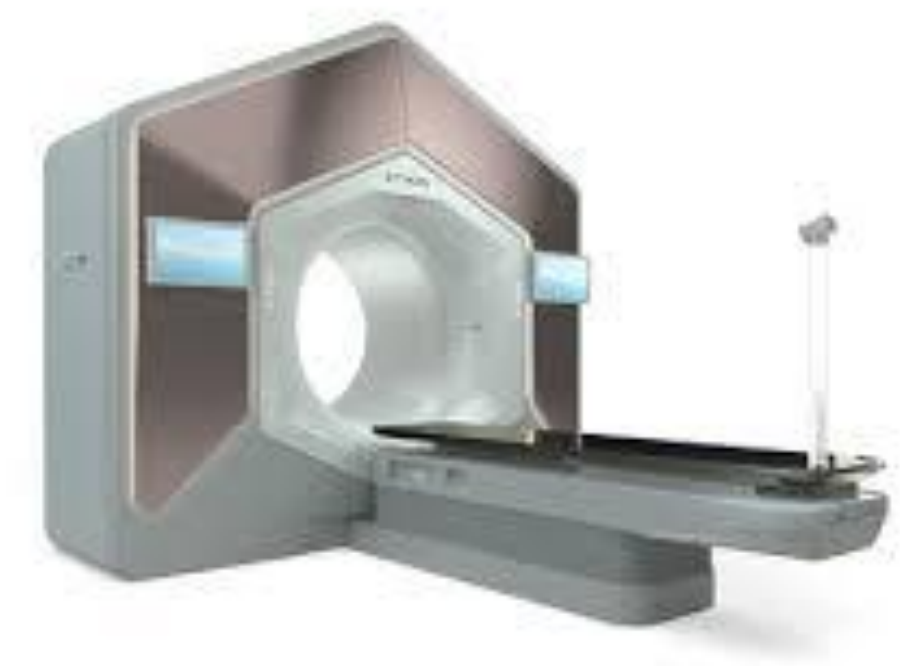
The absence of additional radiation dose is certainly an added benefit, but it's not the primary reason to opt for MR-guidance.

Dose reduction is a "nice to have," but not a "must have."

online
immediately before a treatment fraction

On-line adaptive: Ethos (Varian)

Online CBCT-guided adaptive radiation therapy



Dosimetric Features

6MV FFF Linac
Dose Rate: 800 MU/min
Double stacked MLC
0.5x0.5 cm^2 minimum field
28x28 cm^2 max field

Geometric Features

Bore: wide 100 cm, depth 75 cm

CBCT dose

$CTDI_{weighted}$ = (1.3±0.3) mGy

van de Schoot et al., J Appl Clin Med Phys. 2023
https://doi.org/10.1002/acm2.13905

Mechanical Features

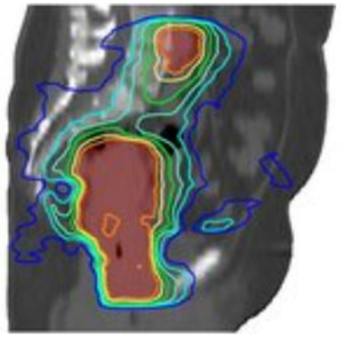
Leaf Speed: 5cm/sec (x2.5)
Gantry Speed: 4 rpm (x4)
2 min Beam-on time for IMRT or Rapid Arc

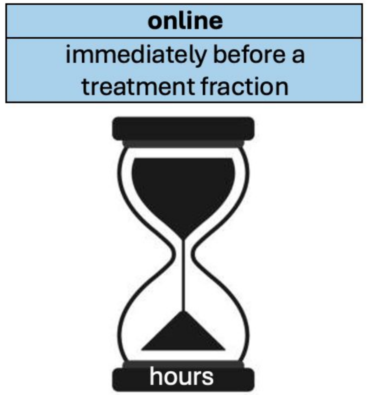
Imaging Features

iCBCT
Iterative reconstruction
15-sec full CBCT acquisition

Adapted from Davide Cusumano

On-line adaptive

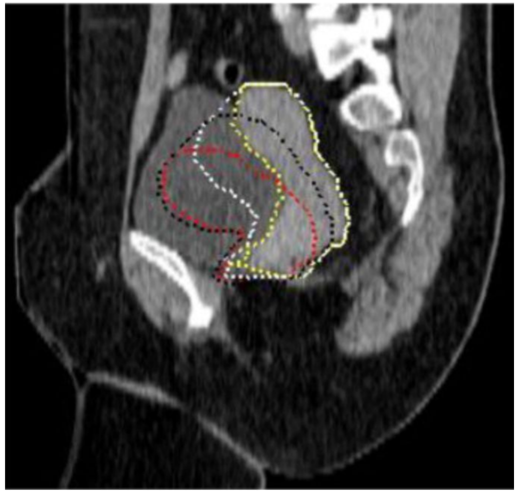




Plan of the day strategy: cervical cancer case

- Large and complex day-to-day variations in the pelvic area □ bladder-filling variations can have a large impact on shape and position of the cervix-uterus
- 15 mm margins are inadequate for many patients □ increase margins to 24-40 mm □ jeopardize tissue-sparing properties of IMRT

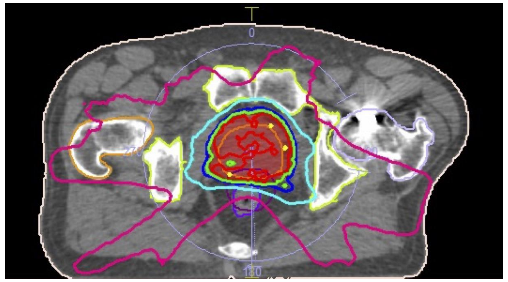
Lim et al., Int J Radiat Oncol Biol Phys, 2009 (https://doi.org/10.1016/j.ijrobp.2008.12.043)
Ahmad et al., Radiotherapy and Oncology, 2011 (https://doi.org/ 10.1016/j.radonc.2010.11.010)
Heijkoop et al., Int J Radiat Oncol Biol Phys. 2014 (https://doi.org/10.1016/j.ijrobp.2014.06.046)



- Full and an empty bladder CT scan
- Model for predicting any intermediate position of bladder/cervix
- <u>Plan of the day strategy dramatically reduces the percentage of bladder and rectum inside the PTV and the CTV-to-PTV volume</u>

---- empty-to-half-full model-predicted ITV
---- half-full-to-full model-predicted ITV

Dosimetric advantages



online
immediately before a treatment fraction

Paper	Target	OARs
Liu et al., Medical Physics. 2014	CTV V100 were 88.0%, 98.4%, 99.2%, and 99.3% for the IGRT, ART, reoptimization, and original plans, respectively. ART and reoptimization provided better target coverage.	Rectal V45Gy (V60Gy) were 58.7% (27.3%), 48.1% (20.7%), 43.8% (16.1%), and 44.9% (16.8%). The results for bladder were comparable among three schemes. ART and reoptimization provide better OAR sparing.
Keall et a., International Journal of Radiation Oncology, Biology, Physics. 2020	With real-time IGRT, no patient had CTV D98% 5% less than planned. Without real-time IGRT, 5.5% would have this level of underdosing. CTVD98% was 1.0% closer to planned with real-time correction.	

Online ART based on prostate motion can allow safe **margin reduction.**
(Deutschmann et al., 2012; Ost et al., 2011)


Innovations in image-guided radiotherapy

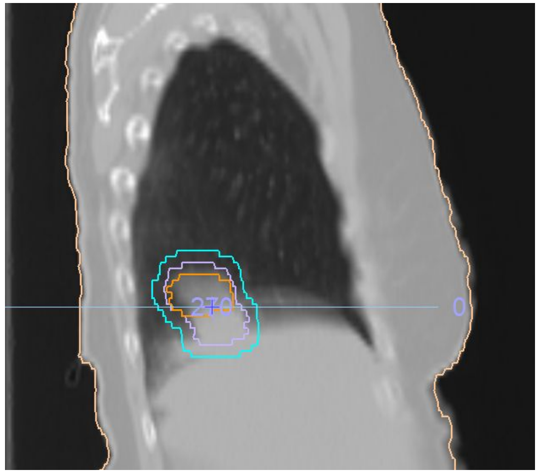
Dirk Verellen, Mark De Ridder, Nadine Linthout, Koen Tournel, Guy Soete and Guy Storme

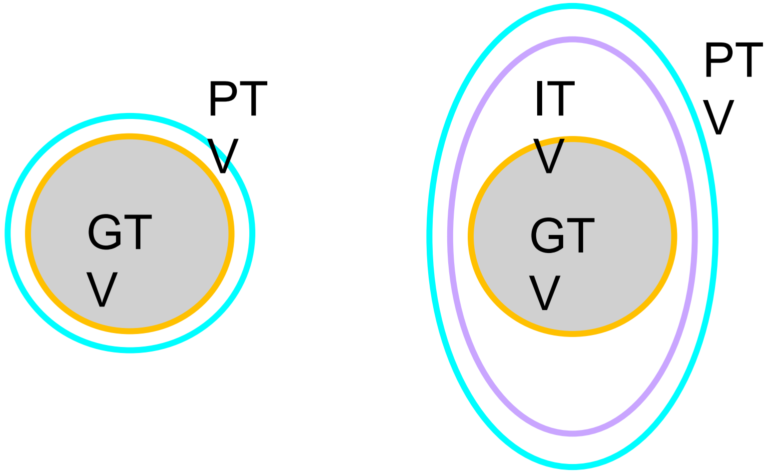
NATURE REVIEWS | CANCER VOLUME 7 | DECEMBER 2007 | 949

real-time
during a treatment fraction

Real-time adaptive

- It accounts for variations that occur within a treatment fraction, such as respiration, internal status changes, and peristalsis motion □ treatment plan is automatically adapted during treatment delivery without operator intervention
- It does need dedicate equipment!
- Yields **smaller PTV volumes □ improved doses to OARs**



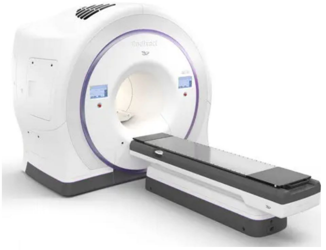


Real-time adaptive

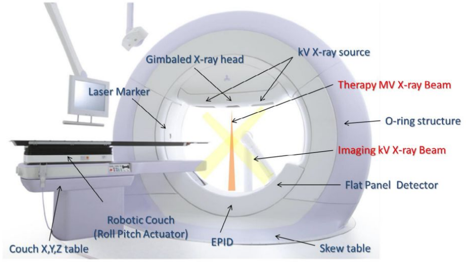
real-time
during a treatment fraction

- Cyber Knife (Accuray)

- Radixact Synchrony (Accuray)



- VERO (Brainlab)

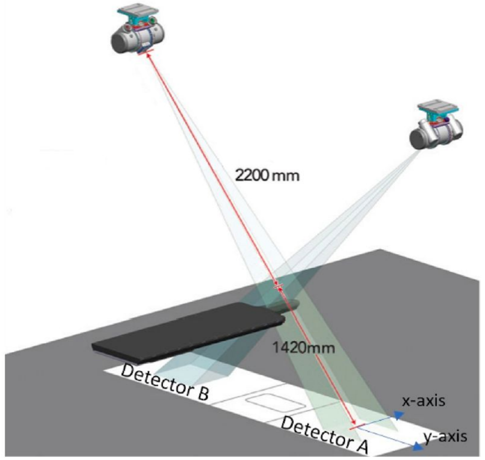


- MLC linac tracking

real-time
during a treatment fraction

Real-time adaptive: Cyber Knife

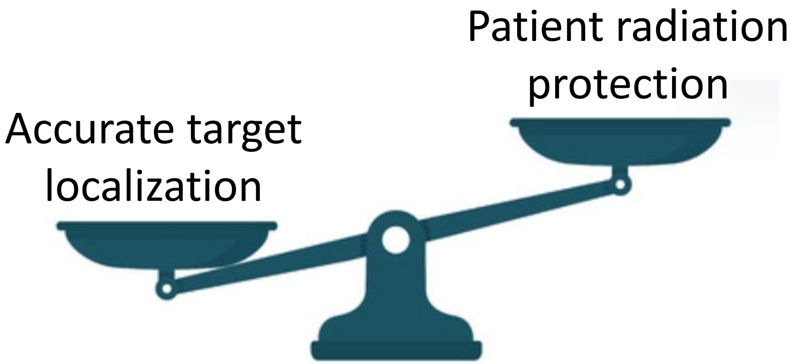
Physica Medica 103 (2022) 11–17

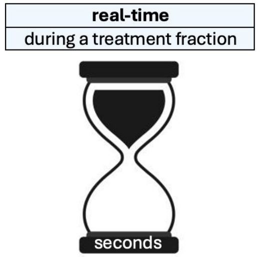


CyberKnife' s image guidance system

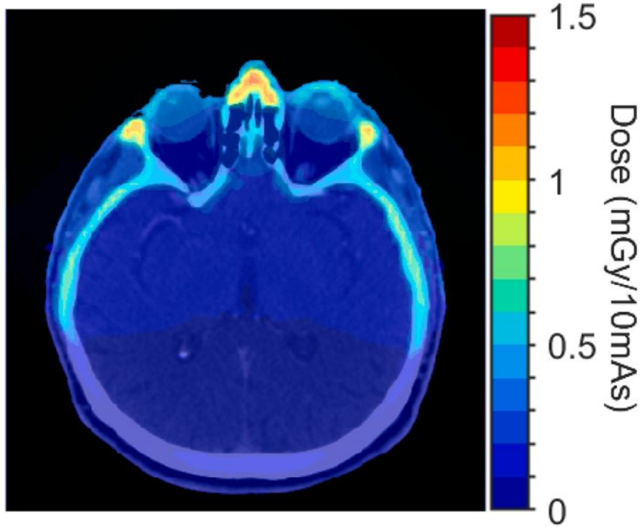
<u>Frequent acquisition</u> of radiographs during treatment delivery comes at the expense of patient imaging dose, the amount of which also depends on imaging protocol and imaged anatomy.

The <u>registration uncertainty</u> depends on the <u>image</u> <u>quality</u> of the acquired radiographs from the image guidance system.
It can be improved (e.g., mAs increase) □ increased patient dose

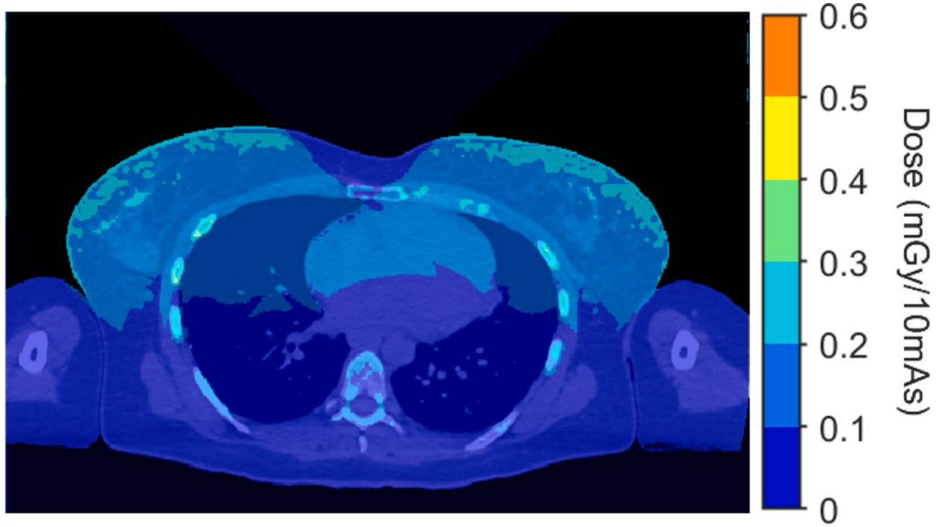




Cyber Knife: imaging dose estimation



Head case



Thoracic spine case

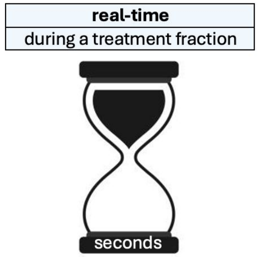
Spatial distribution of the imaging dose (MC calculation) overlayed on the corresponding axial CT slices (synchronous acquisition of a pair of radiographs, 120 kV - 10 mAs). [80-140 kV, 5-30 mAs]

Maximum imaging dose = 1.5 mGy (close to the surface of the patient's head and in the nasal and orbital bones)
Average (±1σ) imaging dose to the eye lenses per acquisition = 0.37 (±0.05) mGy
Healthy brain tissue dose per acquisition < 0.2 mGy

Maximum imaging dose = 0.6 mGy (rib bones)
Entrance dose = 0.4 mGy
Maximum dose per image pair acquisition to the thoracic pleura = 0.6 mGy
Dose delivered to the heart < 0.2 mGy

Archontakis et al., Physica Medica, 2022
https://doi.org/10.1016/j.ejmp.2022.09.011

Assuming a total number of 100 image pair acquisitions for treatment completion □ imaging dose to the eye lenses of 3.7 cGy can be calculated.



Cyber Knife: imaging dose estimation

AAPM Task Group 75

TABLE I. Measured planar radiographic entrance dose levels per image for the CyberKnife image-guided radiosurgery system.

Site	kV	mA	ms	mAs	mGy
Cranium and C-spine	105–125	100	100	10	0.25
T-spine	120–125	100–150	100–125	10–20	0.25–0.50
L-spine	120–125	100–200	100–150	10–30	0.25–0.75
Sacrum	120–125	100–300	100–300	10–90	0.25–2.00
Synchrony	120–125	100–300	50–75	5–22.5	0.10–0.50

Murphy et al., Med Phys, 2007
https://doi.org/10.1118/1.2775667

Modality		*CyberKnife*
Surface Dose [cGy]		
Head	Ant	4.33 ± 0.07
	Post	0.50 ± 0.01
	Left	2.27 ± 0.04
	Right	2.09 ± 0.04
Thorax	Ant	3.86 ± 0.06
	Post	0.45 ± 0.01
	Left	1.75 ± 0.03
	Right	1.74 ± 0.03
Pelvis	Ant	6.50 ± 0.10
	Post	0.30 ± 0.01
	Left	3.30 ± 0.05
	Right	3.25 ± 0.05

Surface dose using the RANDO phantom and radiochromic films for a total number of 100 pairs of radiographs .

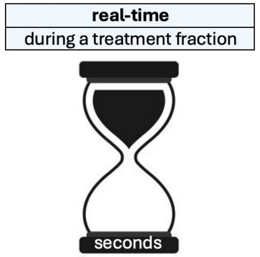
Nobah et al., JACMP, 2014
https://doi.org/10.1120/jacmp.v15i6.5006

	Peak Acquisition Technique	*Beam Energy*	*Total Quality*	*mAs / MUs*
Head	6D Skull / 100 image pairs	100 kV	5.4 mm Al	1250
Thorax	C-spine / 100 image pairs	110 kV	5.7 mm Al	1500
Pelvis	L-Spine / 100 image pairs	125 kV	6.4 mm Al	4000

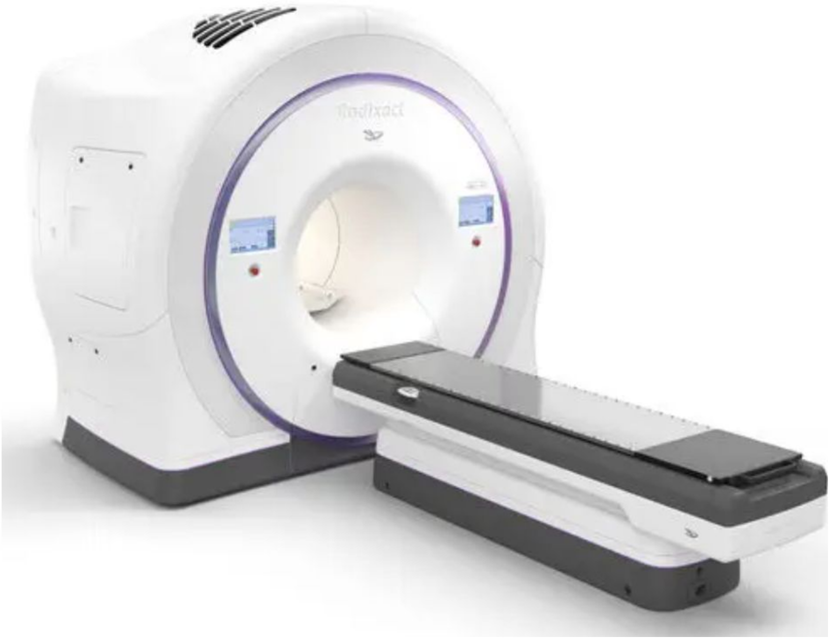
MC imaging dose calculations using the PCXMC code and phantom geometries simulating adult patients of different sizes.

Typical organ doses (single exposure): 0.23 mGy to the brain, 0.29 mGy to the heart, 0.08 mGy to the kidneys, depending on the imaging protocol and site.

Sullivan and Ding, Med Phys, 2015
https://doi.org/10.1118/1.4924094



Real-time adaptive: Radixact Synchrony



Equipped with a pair of kV (X-ray tube voltage) radiography and a flat detector panel mounted on the gantry.

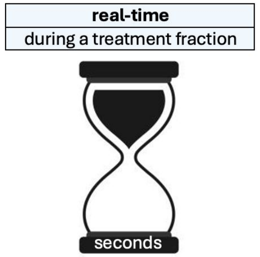
Target position is calculated based on the fiducial marker position detected by successive 2D kV radiographs, and the target motion is compensated by the jaw sweeping in the longitudinal direction and MLC shifting in the lateral and vertical directions.

Monte Carlo simulation.

Ferris et al, Med Phys. 2020 https://doi.org/ 10.1002/mp.14461.

TABLE III. Simulated patient dose in mGy from 100 radiographs.

Patient	$u_{med,10\%T}$ (%)	D_{iso}	Volume	D_{ave}	$D_{50\%}$	$D_{10\%}$	$D_{1\%}$
Large lung *L thorax*	10	6.8	Heart	6.8	6.9	8.5	10.1
			Lungs	7.4	7.3	11.4	15.1
			Ribs	12.7	8.9	33.4	47.7
			Skin	3.8	1.5	11.4	16.3
			Soft tissue	4.6	3.5	10.1	15.0
			Spinal cord	6.6	6.4	10.0	32.2
Small lung *XS Thorax*	8	4.1	Heart	3.2	3.2	4.4	5.3
			Lungs	3.2	3.1	4.8	6.2
			Ribs	6.4	4.7	15.0	20.2
			Skin	1.7	1.1	4.2	6.6
			Soft tissue	2.2	2.0	4.4	6.2
			Spinal cord	1.8	1.6	3.3	6.0
Prostate *M Pelvis*	9	6.8	Bladder	7.2	6.9	9.2	10.7
			Pubic bone	11.9	12.6	19.1	26.0
			Prostate	5.4	5.4	6.1	6.8
			Rectum	6.0	6.1	7.3	8.2
			Skin	2.9	1.8	6.9	10.2
			Soft tissue	3.1	2.6	6.6	9.7
Endothelium *XL Pelvis*	9	10.9	Bladder	11.4	11.4	13.5	15.3
			Femurs	11.1	6.8	29.9	46.5
			Pubic bone	29.8	25.4	52.0	71.7
			Rectum	12.8	12.6	16.5	20.5
			Skin	6.1	1.8	21.6	35.9
			Soft tissue	7.3	4.6	18.4	31.0
Pancreas *L Pelvis*	10	6.9	Liver	8.3	8.3	10.6	13.3
			Lungs	4.4	3.7	8.4	11.9
			Pancreas	10.4	10.5	12.2	13.6
			Skin	3.9	1.5	11.7	18.2
			Soft tissue	4.5	3.0	10.6	15.5
			Spinal cord	5.9	5.9	9.7	16.7



Real-time adaptive: VERO

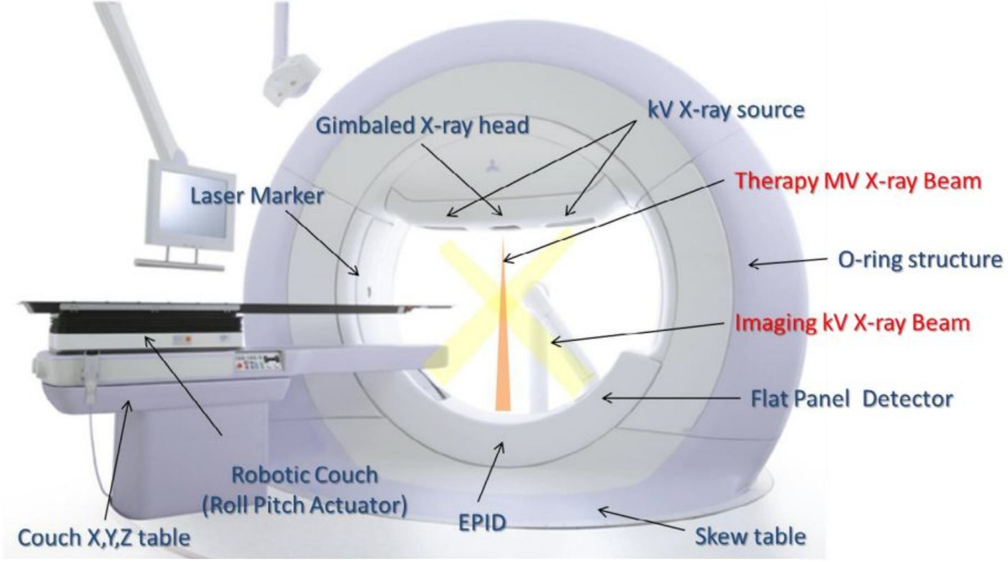


TABLE III. Entrance air kerma at the patient from the Hokkaido fluoroscopic tracking system for an exposure period of 60 s at 30 image frames per second.

			Air kerma @ Patient (mGy)		
kV	mA	ms	@Isocenter	5 cm from Isocenter	30 cm from Isocenter
60	80	2	1.11	1.14	1.38
		4	2.07	2.15	2.60
80	80	2	2.45	2.54	3.07
		4	4.28	4.44	5.37
100	80	2	4.35	4.51	5.46
		4	7.41	7.68	9.30
120	80	2	6.69	6.94	8.39
		4	10.90	11.30	13.67

Gimbaled linac

Stereoscopic dual-source kV X-ray imaging system and flat panel detectors

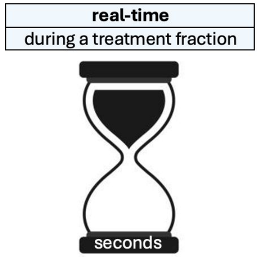
60 kVp - 120 kVp
FPD size 40 cm × 30 cm.
Distance kV X-ray source /isocenter = 100 cm
Distance source /FPD = 188 cm
Isocenter FOV = 21 cm (in the O-ring plane) × 16 cm (perpendicular to the O-ring plane).

Kamino et al., IJROBP, 2006
https://doi.org/10.1016/j.ijrobp.2006.04.044.

Hiraoka et al., Radiotherapy and Oncology, 2020
https://doi.org/10.1016/j.radonc.2020.07.002.

AAPM Task Group 75

Murphy et al., Med Phys, 2007
https://doi.org/10.1118/1.2775667



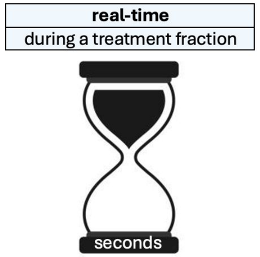
Real-time adaptive: MLC linac tracking

MLC tracking is a form of real-time adaptive radiotherapy enabled on a conventional linear accelerator utilizing the MLC to adapt to location and position changes during treatment, representing a potentially highly accessible motion management solution.

Booth et al., Radiotherapy and Oncology, 2021
https://doi.org/10.1016/j.radonc.2020.10.036.

KV or MV imaging/fluoroscopy

MLC tracking is often coupled with electromagnetic transponders implanted in or near the tumor. These transponders emit signals that are detected, allowing for precise tracking of the tumor's position, even as the patient moves or breathes no extra dose to the patient



Real time tumor tracking: dosimetric advantages

Table 1
A summary of feasibility studies for dynamic tumor tracking in Japan.

Site of cancer	Number of patients	Patient characteristics			Treatment delivery				Difference from non-tracking irradiation			Treatment outcomes	
		Age [y]	Gender [M:F]	Motion amplitude [mm]	Prescription	Technique	Treatment time [min]	Tracking error [mm]*	GTV D95	PTV volume	OAR doses	Local control	Severe AE
Lung [7]	16	83 (58–87)	11:5	17 (10–46)	48–56 Gy/4 fr	SBRT	36.2 (19–70)	2.4	−0.4%	−30.2%	Lung V20, −19.5%	94%	None
Liver [25]	10	71 (44–88)	7:5	7 (2–17)	48–60 Gy/4-8 fr	SBRT	28 (17–48)	2.3	−0.4%	−35.1%	Liver mean, −16.2%	90%	G3 liver enzyme, 1
Pancreas [9]	10	71 (64–79)	8:2	13 (SD, 3.3)	45–51 Gy/15 fr	IMRT	24.5	2.9	–	−18.0%	–	74%	G3 gastritis, 1

Abbreviations: SBRT, stereotactic body radiotherapy; IMRT, intensity-modulated radiotherapy; GTV, gross tumor volume; PTV, planning target volume; AE, adverse event.
* Tracking errors were defined as the 95th-percentiles of the absolute errors in the cranio-caudal direction.

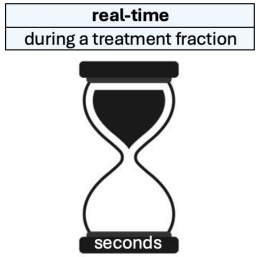
Hiraoka et al., Radiotherapy and Oncology, 2020
https://doi.org/10.1016/j.radonc.2020.07.002.

Lung and liver lesions:

Average PTV volume reduction using Real Time Tumor Tracking (RTTT) was 35% (range 16–53%) relative to the PTV_{ITV} volume

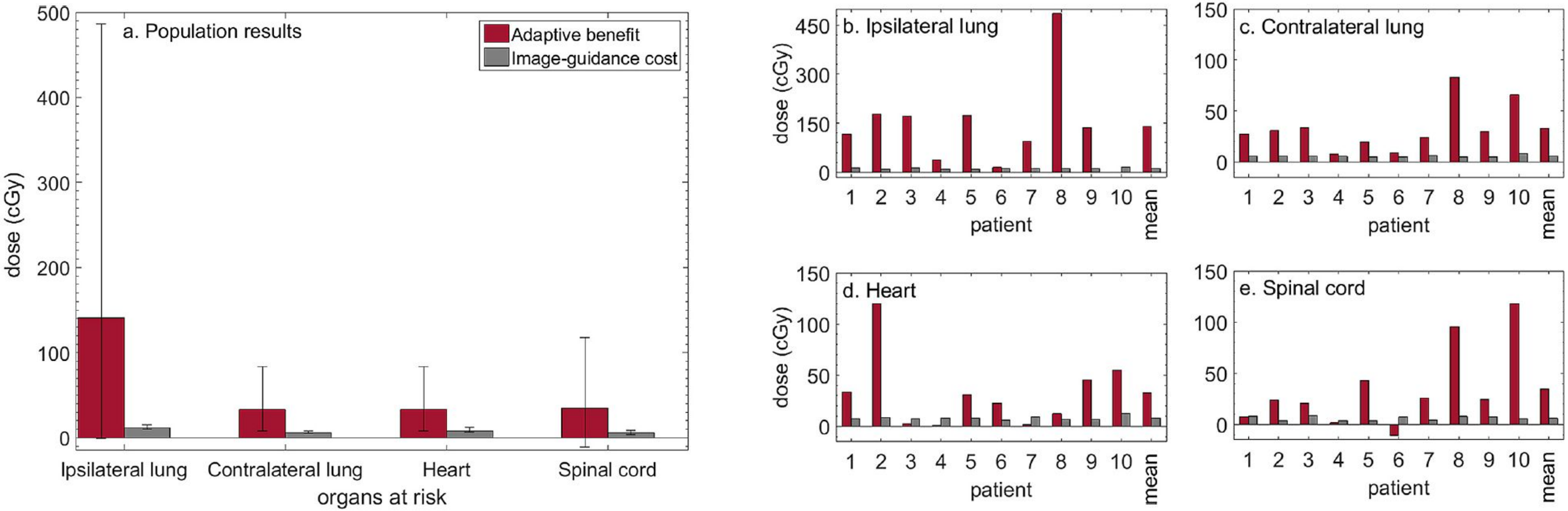
Average values (over 10 patients) of lung, liver, heart, oesophagus and spinal cord doses were reduced in the RTTT plan compared to the ITV plan, but with a large inter-patient variability

Depuydt et al., Radiotherapy and Oncology, 2014
https://doi.org/10.1016/j.radonc.2014.05.017.



Real time tumor tracking: dosimetric advantages

kV image guidance for application of real-time adaptation with MLC tracking for lung SBRT delivers lower integral dose to OAR than an ITV-based approach, particularly if respiratory motion is large.



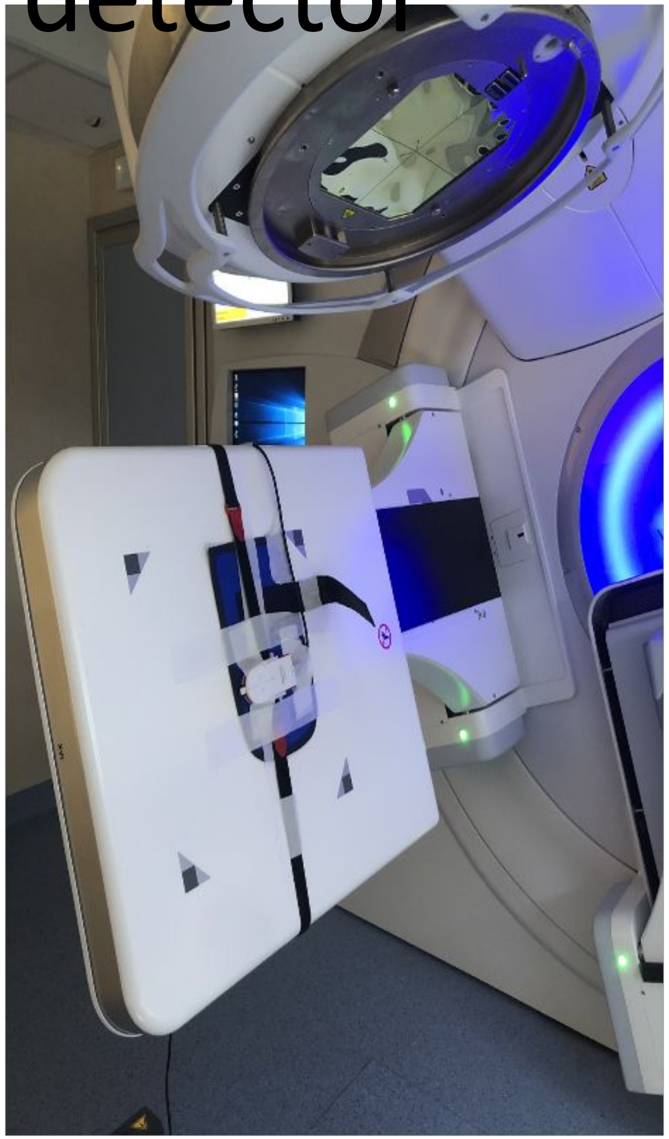
Prabhjot et al., Radiotherapy and Oncology, 2016
https://doi.org/10.1016/j.radonc.2016.08.030.

Outline

- Introduction: why do we talk of ART and Radiation Protection?
- Types of adaptive radiation therapy
  - Offline adaptive
  - Online adaptive
  - Real time tumour tracking
- Types of imaging that is used: balance between extra-dose from imaging and gain from treatment adaptation
- Is the gain superior to the loss in terms of extra dose to the patient?
- Dose measurements and evaluations from CBCT

Adriana Taddeucci

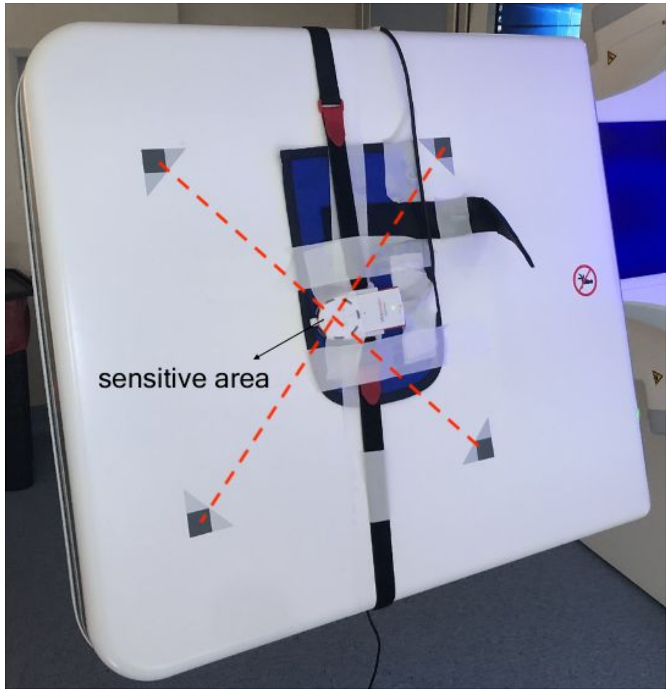
Measurement of incident air kerma at the detector



Ka,i (FDD): incident air kerma at the detector

FDD= focal spot-to-detector distance

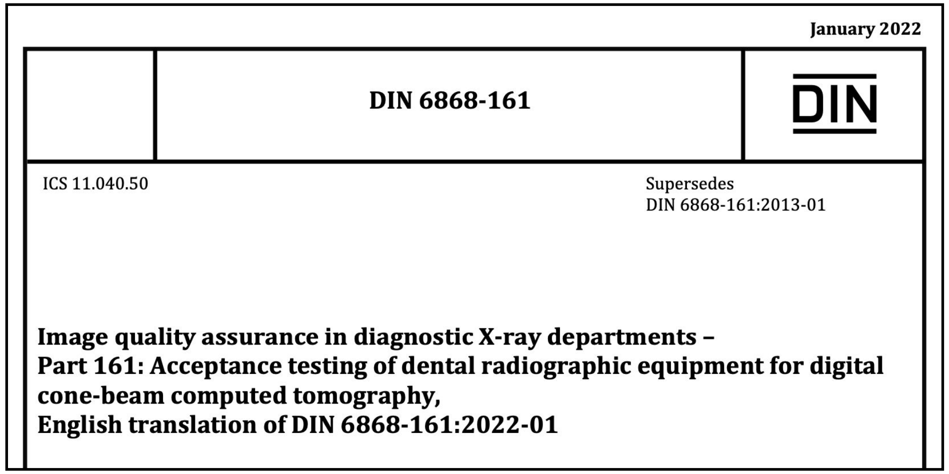
CBCT protocols dose measurement with dosimeter attached to EPID



- Elekta XVI
- PTW Nomex dosimeter
- 0.50 mm Pb lead shielding to prevent EPID damage

We tested measurement repeatability: dose deviation <1%

Estimating D_{FOV} in CBCT


January 2022

DIN 6868-161

DIN

ICS 11.040.50

Supersedes
DIN 6868-161:2013-01

Image quality assurance in diagnostic X-ray departments –
Part 161: Acceptance testing of dental radiographic equipment for digital cone-beam computed tomography,
English translation of DIN 6868-161:2022-01


Quality control in cone-beam computed tomography (CBCT)

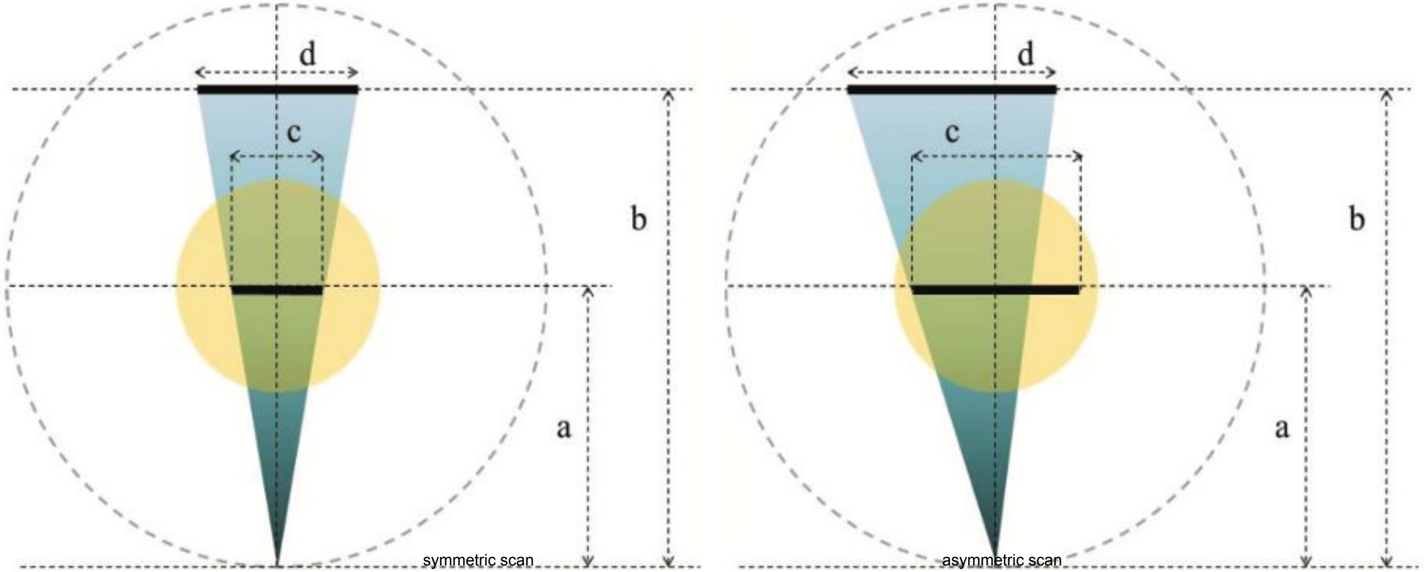
EFOMP-ESTRO-IAEA protocol

EFOMP
European Federation of Organisations for Medical Physics

ESTRO

IAEA
International Atomic Energy Agency

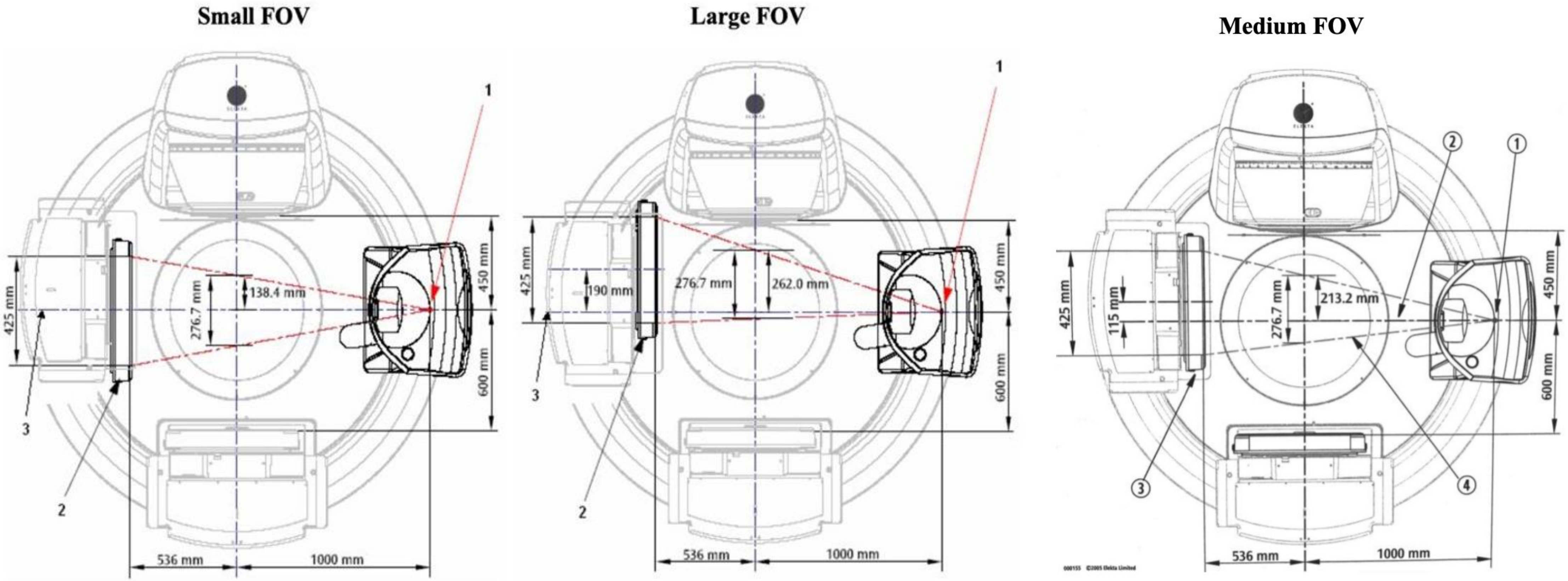
EFOMP
2nd edition, May 2019



$$D_{FOV} = K_{a,i}\,(FDD) \cdot \frac{b}{a} \cdot \frac{d}{c},$$

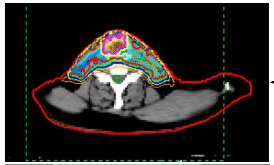
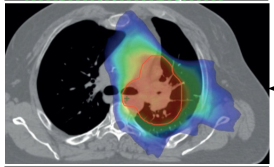
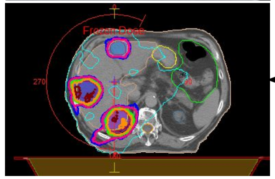
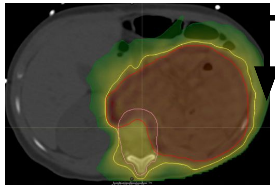
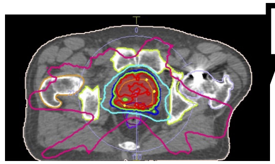
Estimation of the average dose calculated over the diameter of the FOV.

Elekta XVI geometry



Different collimators (and panel positions) are used for different FOV (small, medium, large): only imaging protocols with “small FOV” use a symmetric cone beam

Results

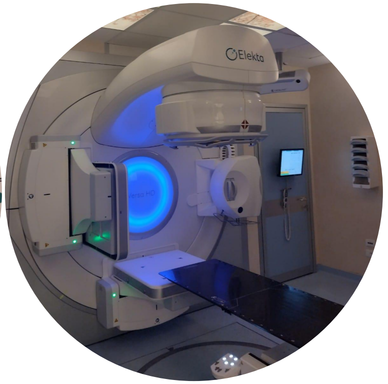






Preset XVI	Collimator	Filter	kV	Gantry rotation [°]	NSD [mGy]	mAs	$K_{a,i}$ [mGy]	D_{FOV} [mGy]
[Head and Neck Enhanced CW]	S20	F1	120	205	0,6	585,6	7,79	18,4
[Head and Neck S20 CW]	S20	F0	100	205	0,6	36,6	0,68	1,6
[Head and Neck S10 CW]	S10	F0	100	205	1,1	36,6	0,71	3,4
[Head and Neck Fast S20 CW]	S20	F0	100	205	0,6	18,3	0,38	0,9
[Chest M20 CW]	M20	F1	120	360	4,6	264,0	4,28	10,1
[Chest Fast M20 Enhanced CW]	M20	F1	120	360	11,8	330,0	5,84	13,8
[Symmetry Lung CW]	S20	F0	120	200	11,4	312,0	9,57	22,6
[Breast LT CW]	S20	F1	120	215	9,5	234,2	6,81	16,1
[Liver Half Scan CW]	S20	F1	120	200	12,0	1040,0	14,39	33,9
[Liver CW]	M20	F1	120	360	24,0	1040,0	17,68	41,7
[Symmetry Liver CW]	S20	F1	120	200	26,0	520,0	24,62	58,1
[Peds Right]	S10	F0	100	205	1,1	33,0	0,72	3,5
[Prostate Fast M20 Enhanced CW]	M20	F1	120	360	29,5	844,8	15,04	35,5
[Prostate Fast M20 Low Dose CW]	M20	F1	120	360	18,4	422,4	7,45	17,6
[Prostate Seed S10 CW]	S10	F0	120	205	5	117,1	3,89	9,2
[Prostate Seed Fast S10 CW]	S10	F0	120	205	2,5	46,8	1,64	3,9
[Prostate M10 CW]	M10	F1	120	360	26,9	1689,6	24,60	58,0
[Prostate M15 CW]	M15	F1	120	360	29,5	1689,6	24,45	57,7
[Pelvis Fast L20 CW]	L20	F1	120	360	18,8	844,8	9,36	22,1
[Pelvis M20 CW]	M20	F1	120	360	18,4	1056,0	17,64	41,6
[Pelvis Fast M20 Enhanced CW]	M20	F1	120	360	18,4	422,4	7,46	17,6
[Pelvis M15 CW]	M15	F1	120	360	17,9	1056,0	15,50	36,6

Results

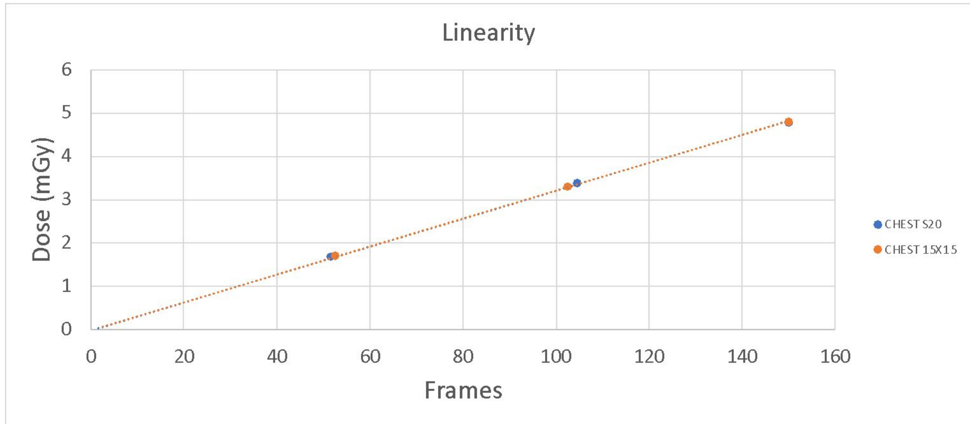
We tested measurement variation at different linacs (7 protocols @4 linacs)

Maximum deviation: 2.2 mGy
Average deviation: (0.0±1.0) mGy
Average abs deviation: (0.8±0.6)mGy

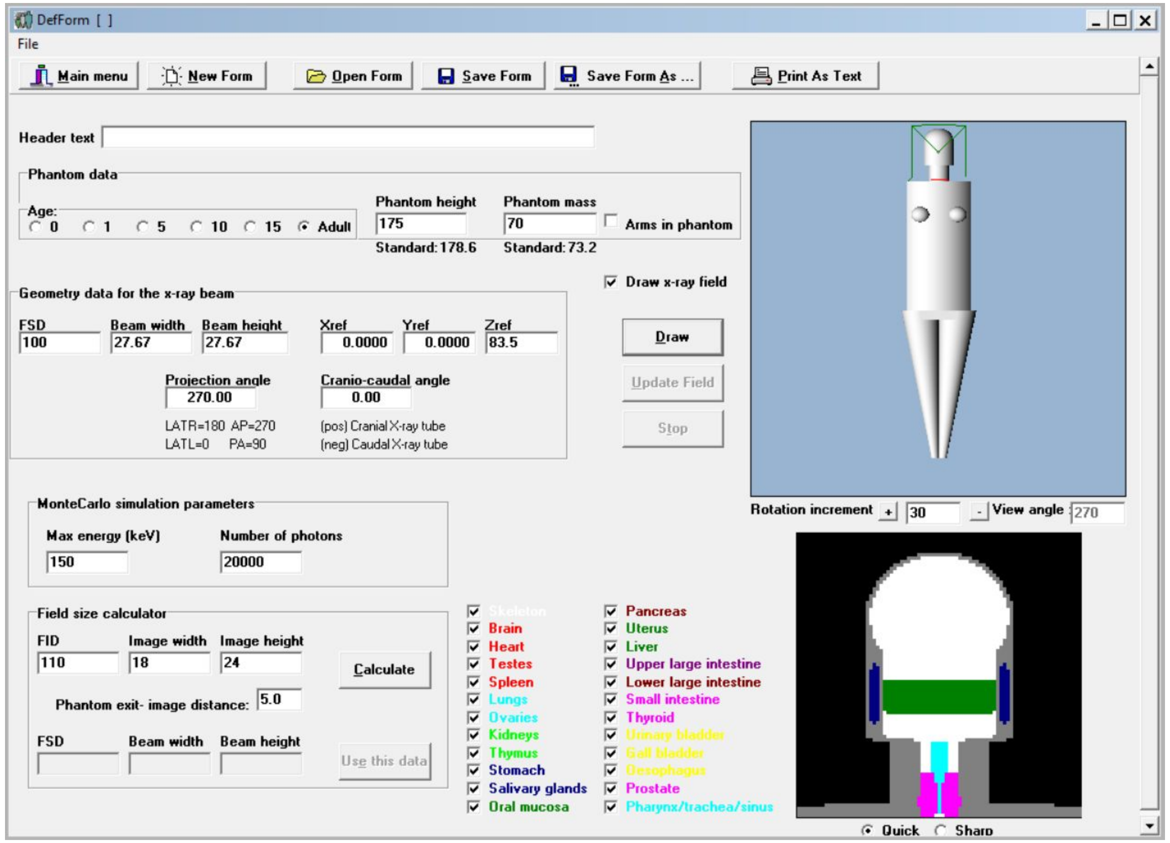
In the context of performing adaptive radiotherapy (real-time tumor tracking), the kV motion view (fluoroscopy) protocols are particularly interesting.

kV Motion View Protocol	Collimator	Filter	kV	Time (s)	Frames	Dose [mGy]
Chest	S20	F0	120	27	150	4,8
Chest 15x15	15x15	F0	120	27	150	4,8



Simulations:PCXMC software

PCXMC (2.0,STUK,Helsinki, Finland) is a computer program for calculating patients' organ doses and effective doses in medical X-ray examinations (radiography and fluoroscopy).



The program calculates the **effective dose** with both the present tissue weighting factors of ICRP Publication 103 (2007) and the old tissue weighting factors of ICRP Publication 60 (1991).
The anatomical data are based on the mathematical hermaphrodite phantom models of Cristy and Eckerman (1987), and the sizes are adjustable to mimic patients of arbitrary weight and height.

Protocol	Organ	PCXMC	TLD	% diff
Head & neck	Oral mucosa	0.89	0.82	8
	Salivary glands	0.93	0.95	−3
	Respiratory airways	0.84	1.01	−16
Chest 4D (symmetry)	Lungs	8.9	7.9	12
	Heart	10.1	10.2	−1
	Breasts	15.6	16.0	−2
Chest F0	Lungs	21.7	19.9	9
	Heart	20.4	20.2	1
	Breasts	21.3	19.2	11
Chest F1	Lungs	20.9	21.5	−3
	Heart	23.1	23.3	−1
	Breasts	18.6	17.3	8
Pelvis	Ovaries	19.7	22.3	−12
	Colon	16.4	18.2	−10
	Prostate	16.0	13.5	18
	Bladder	22.5	21.5	5

Rampado et al., Med Phys. 2016 (https://doi.org/10.1118/1.4947129.)

Some criticalities

Rampado et al., Med Phys. 2016
(https://doi.org/10.1118/1.4947129.)

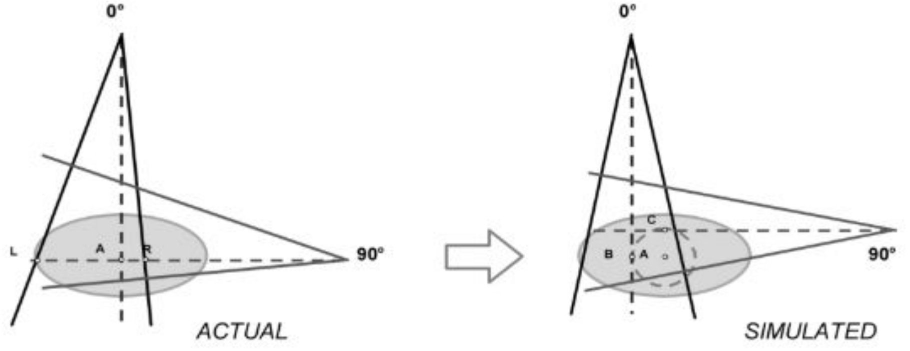


FIG. 2. Adaptation of beam geometry for asymmetric beam simulation by the program PCXMC. With the collimator M20, the beam width at isocenter LR was 276 mm, with a left side LA of 213 mm and a right side AR of 63 mm. In the simulated geometry, the same beam width was considered, but with a symmetric beam centered 75 mm off axis, like the *B* and *C* centers as examples for 0° and 90° projections.

Asymmetric beams cannot be simulated in the program.

As an alternative, a symmetric beam with a displaced isocenter can be used.

F1 (bow-tie) filter cannot be simulated in the program.

In the presence of F1 filter, two simulations were performed for each projection, considering a beam over the total irradiated area with a contribution of 2/3 of total KAP and a second beam component with half width and 1/3 of total KAP.

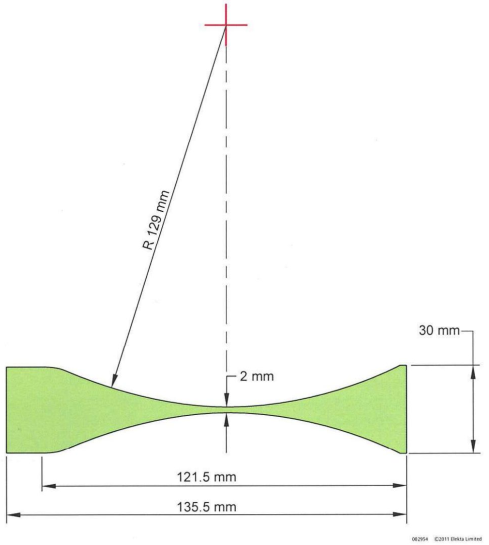
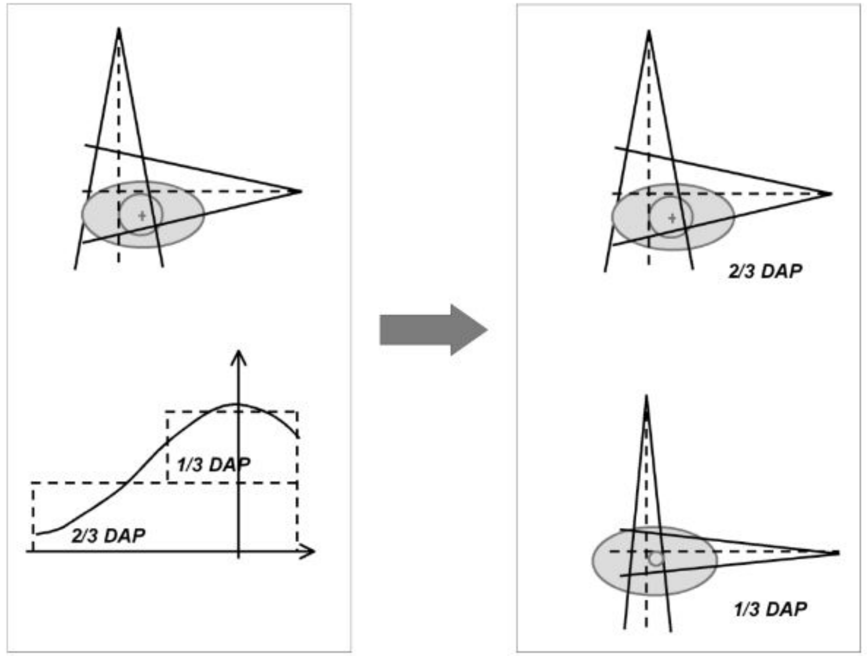


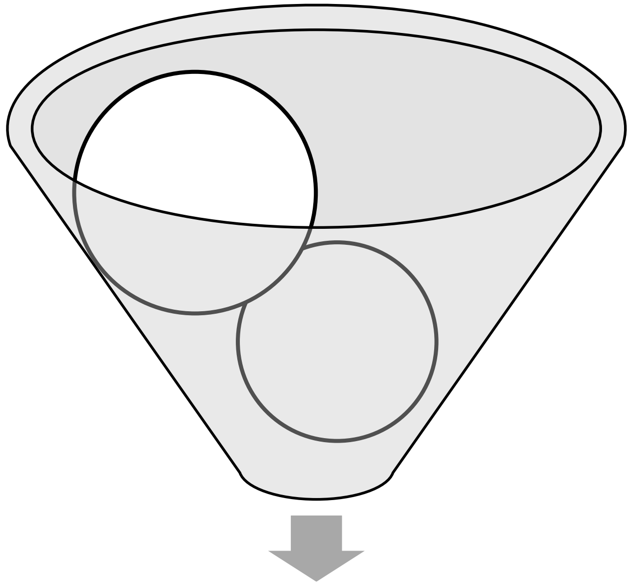
Figure 1.11 Cross-section of the F1 Bowtie filter



Simulations

- Comparison between two simulations: the first with sampling every 5°, the second every 10°
- Comparison between two simulations: F1 filter as described in the article, homogeneous F1 filter
- Simulations for each protocol, for different patients' sizes:

Adult		**Paediatric**		
Height (cm)	**Weight (kg)**	**Height (cm)**	**Weight (kg)**	**Age**
152	41	102	14	3
163	60	110	18	3
165	65	119	24	5
173	91	126	14	5
176	73	138	31.5	10
188	111	150	44	10



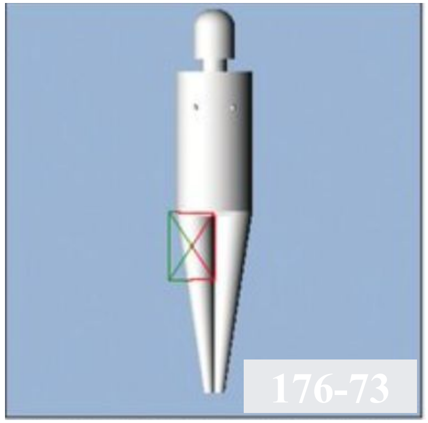
Average effective dose (mSv)

Average effective dose per organ (mSv)

Results

- No difference between the two sampling strategies (<0.3%) ✅
- Differences up to 20% between F1 filter as described in the article vs. homogeneous F1 filter 🆘

	[Liver Half Scan CW] Dose (mGy)
Adrenals	15,5
Gall bladder	12,6
Heart	9,0
Kidneys	18,4
Liver	11,7
Pancreas	14,3
Spleen	17,1
Stomach	17,1
Average dose in total body	3,8



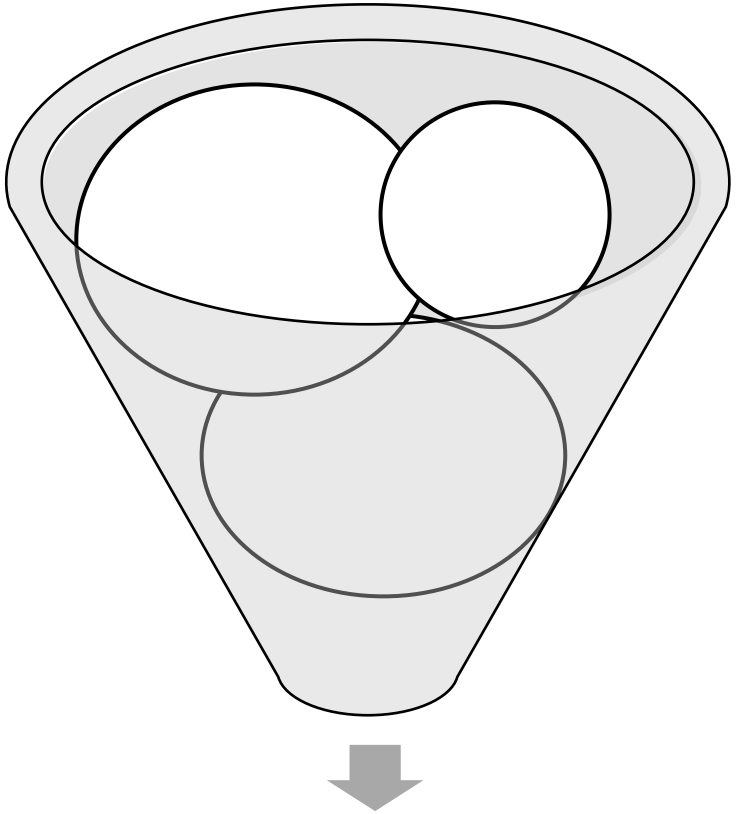
	[Head and Neck Enhanced CW] Dose (mGy)	[Head and Neck S20 CW] Dose (mGy)
Brain	8,6	0,6
Extrathoracic airways	8,4	0,6
Oral mucosa	9,2	0,6
Salivary glands	11,8	0,9
Thyroid	8,8	0,9
Average dose in total body	1,1	0,1

	[Pelvis Fast L20 CW] Dose (mGy)	[Prostate Fast M20 Enhanced CW] Dose (mGy)
Ovaries	6,1	7,0
Colon	4,9	5,4
Kidneys	3,8	0,4
Prostate	7,6	13,2
Small intestine	4,4	3,5
Testicle	10,1	18,6
Uterus	8,0	7,2
Urinary bladder	5,8	11,6
Average dose in total body	2,8	4,2

	[Breast LT CW] Dose (mGy)	[Chest Fast M20 Enhanced CW] Dose (mGy)	[Symmetry Lung CW] Dose (mGy)
Breasts	6,6	6,2	11,6
Heart	7,1	5,8	9,6
Liver	3,6	2,4	2,2
Lungs	7,8	6,0	11,5
Oesophagus	4,9	3,7	6,2
Thymus	7,7	6,3	10,4
Average dose in total body	1,8	1,5	2,9

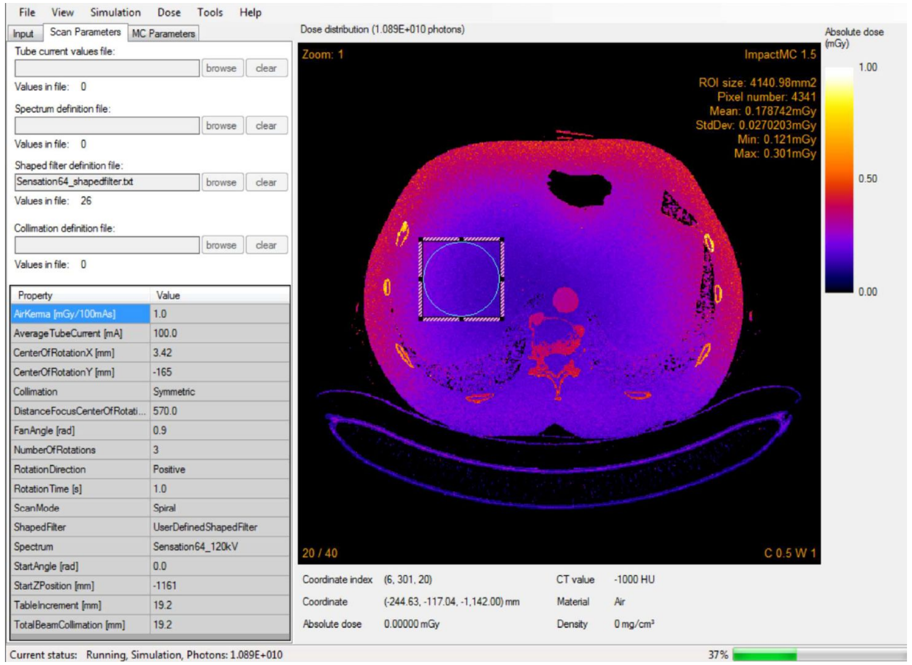
What’s next?

ImpactMC software (CT Imaging, Erlangen, Germany)



Dose distribution

- The software handles asymmetric beams and bow-tie filters.
- Allows to generate a full 3D dose distribution.
- Allows to extract average doses in ROI.



Final considerations

Is the gain superior to the loss in terms of extra dose to the patient?

Challenges

- Managing cumulative radiation dose from frequent imaging (IGRT more than ART)
- Managing increased complexity
- Balancing image quality with radiation dose
- Study timing, frequency, patient selection…

With the recent trend toward hypofractionated treatment regimens, imaging doses are expected to be less of a concern.

Future advances

- Technological Advances

  Integration of AI and machine learning to optimize imaging and ART strategies
- Research and Development

  Refinement of radiological protection strategies (optimization)
- Best Practices

  Protocols and guidelines from leading institutions

  Training and Expertise: Importance of having well-trained users who understand both ART and radiological protection standards

Vendors should prioritize the development of tools that more easily account for the dose contribution from image-guided radiotherapy (IGRT), ensuring that it is accurately considered in treatment planning.

Thank you for your attention

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