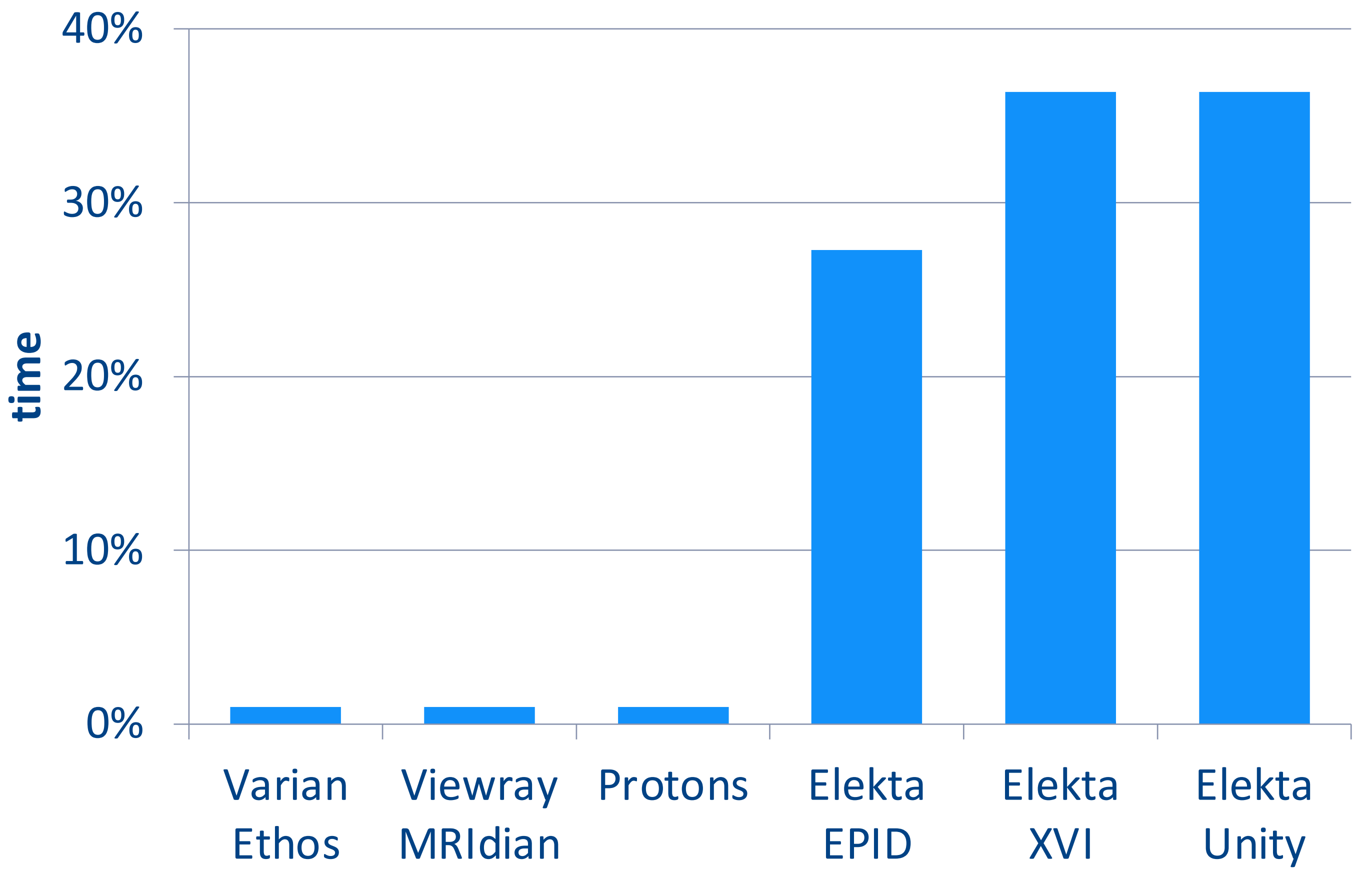
Unity MR-linac physics

Simon Woodings

UMC Utrecht

Konference Radiologické Fyziky, Ostrava 20. 4. 2023

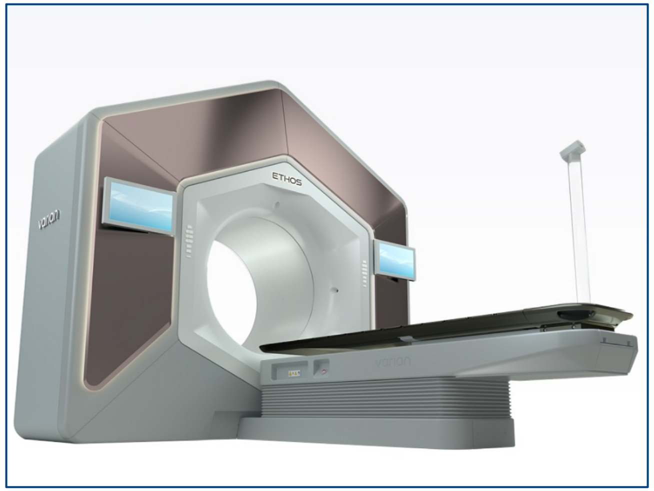
Disclosure



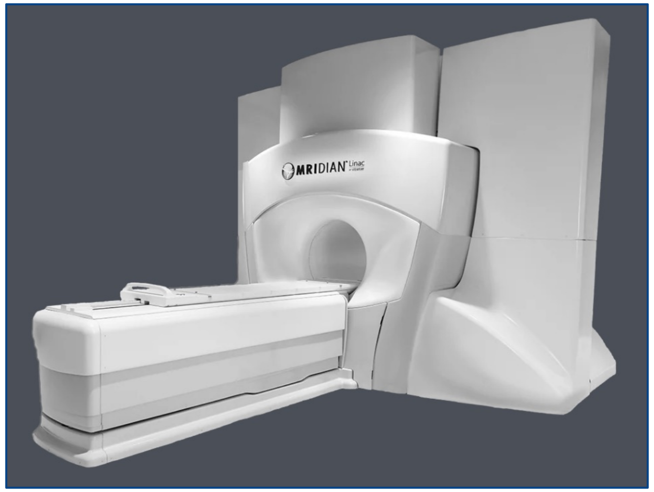
- UMCU has strong R&D connections with Elekta & Philips
- Elekta have supported my attendance today
- I have 22y experience – but only with Elekta equipment!

New era of adaptive radiotherapy

Three commercial systems in world-wide use



Varian Ethos



Viewray MRIdian

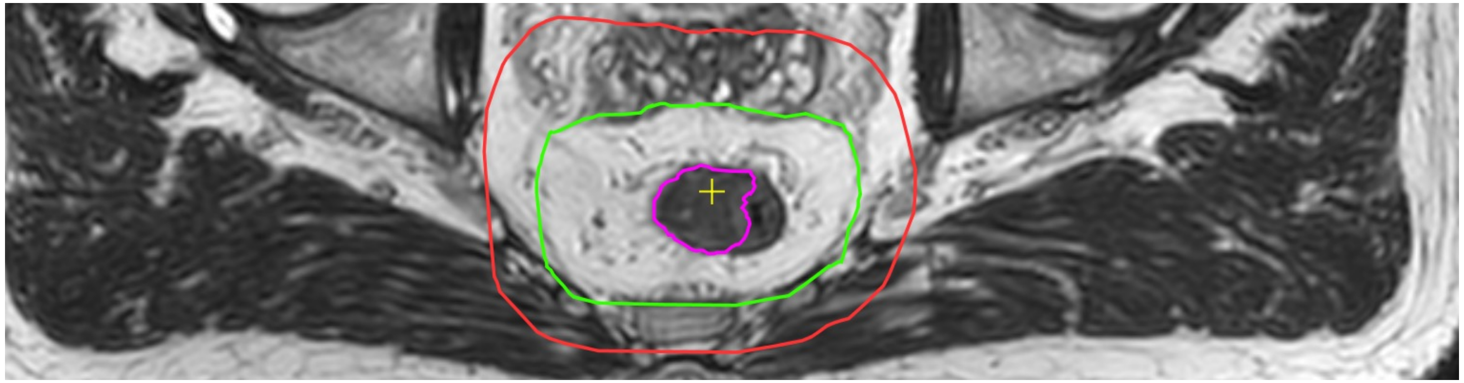
Elekta Unity

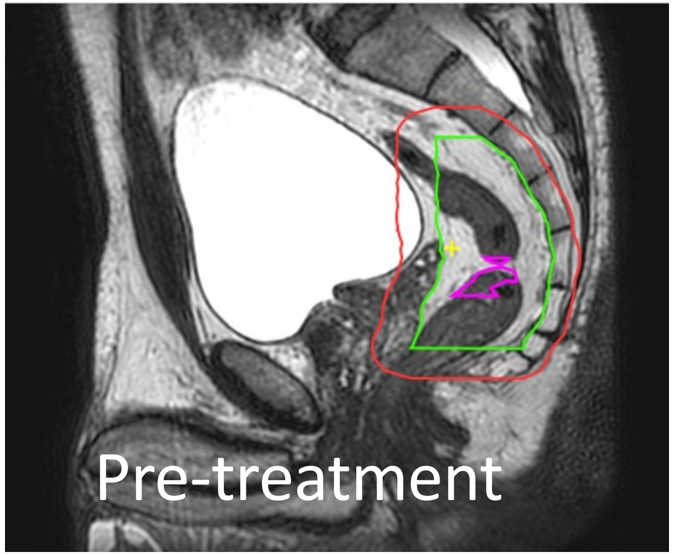
Vision at time of treatment enables ART

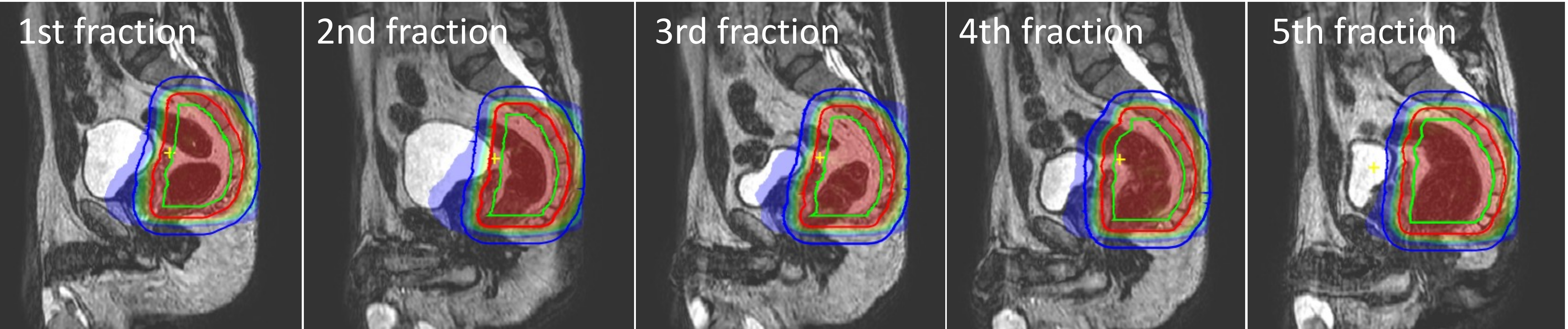
Rationale for MR-guided radiotherapy

Martijn Intven, Rob Tijssen and UMCU clinical team, 2018

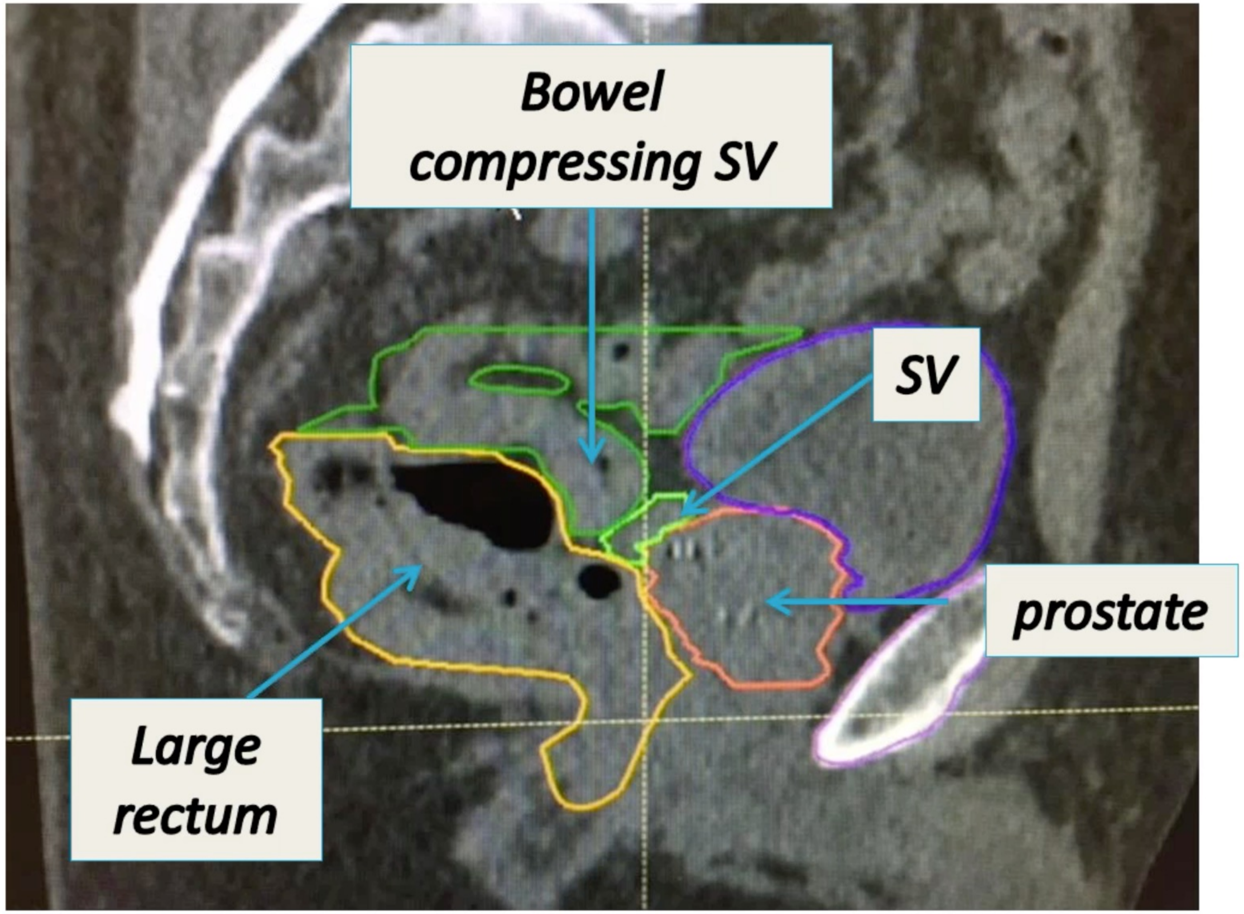
Interfraction variation
rectal cancer treatment CTV 5x5Gy



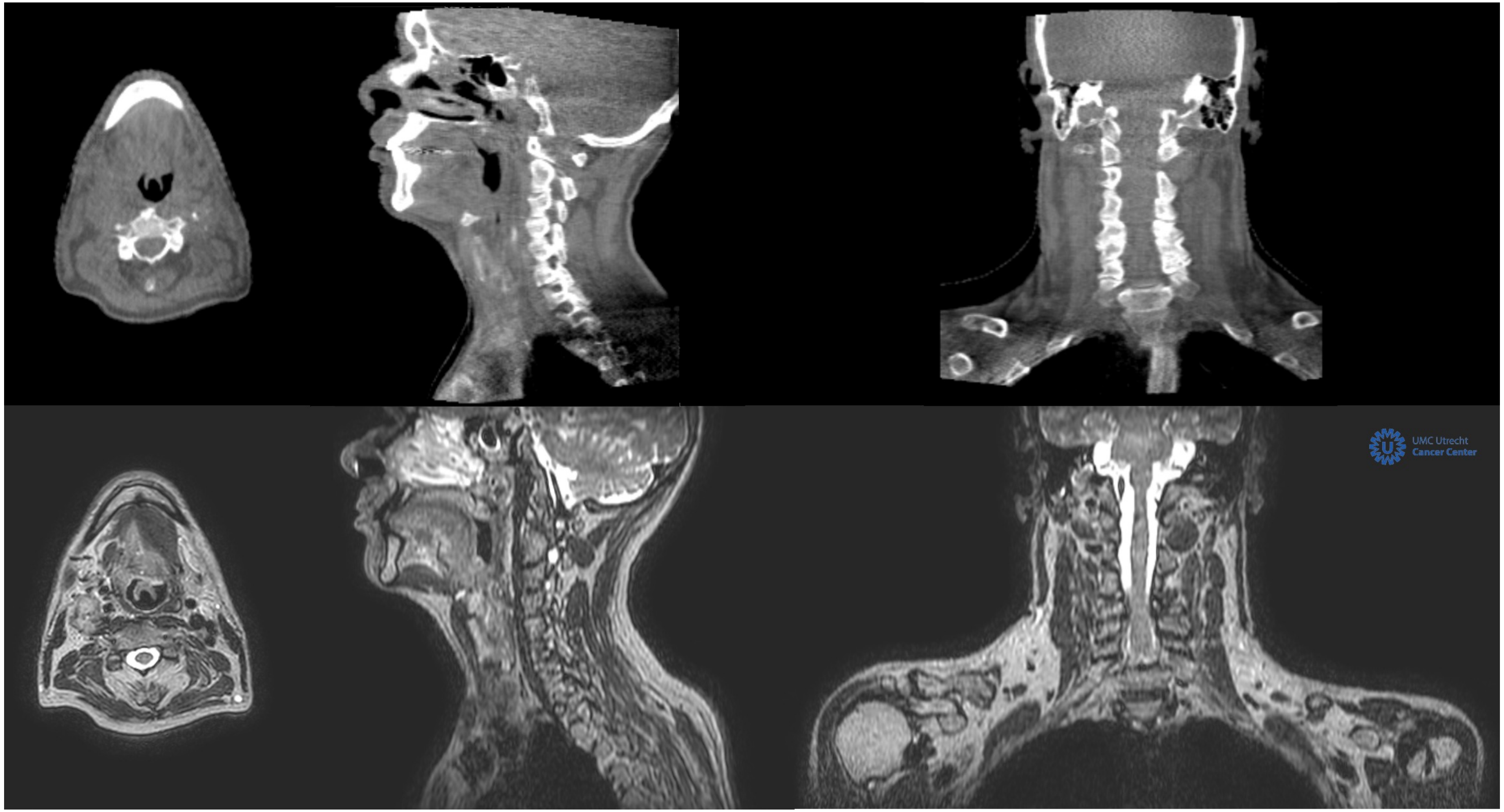




Adaptive MR-guided RT
Patient 3- the perfect/worst candidate?



CBCT v MR-linac image quality



Imagine the perfect radiotherapy system for curing cancer

- Start radiotherapy immediately – no waiting
- See cancer clearly before and during treatment
- Change radiotherapy as often as the internal anatomy moves
- Alter dose day by day depending on anatomy/biology
- Few fractions

Dr Alison Tree, Radiation Oncologist
Royal Marsden UK

Unity MR-linac

BASE
1.5 T wide bore scanner

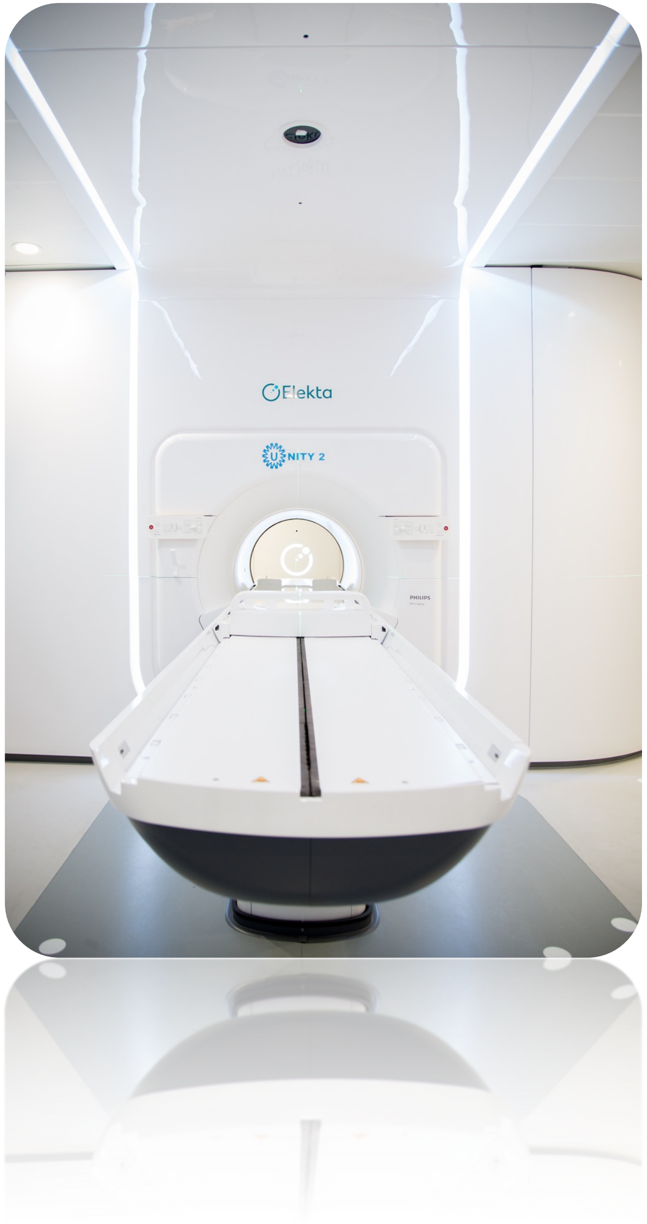
GANTRY
7 MV FFF linear accelerator
57 x 22 cm^2
Co-planar IMRT

GRADIENTS
Split gradient design
15 mTm^{-1}, 65 $mTm^{-1}ms^{-1}$

RECEIVER COILS
Radio lucent coil array (2 x 4 ch)

Content

- The new era
- Unity and the patient workflow
- Impact of the magnetic field
- Machine performance and physics tests
- Motion management
- Current status and future developments



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Unity and the patient workflow

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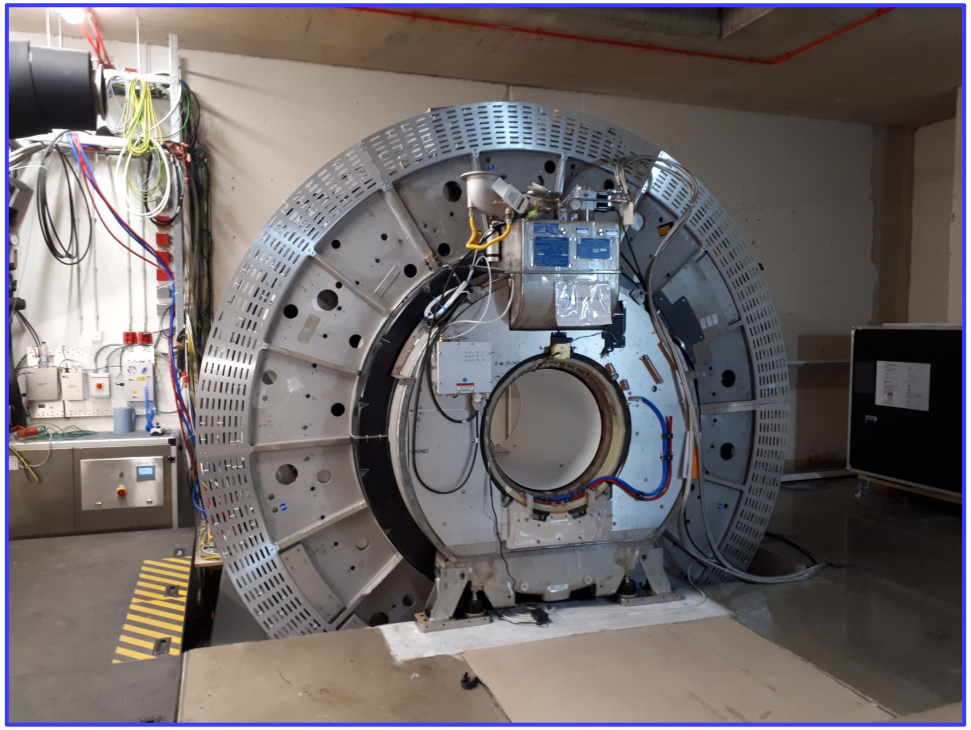
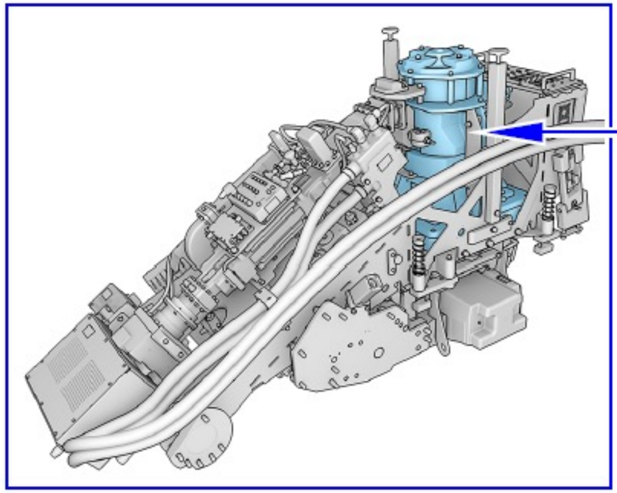
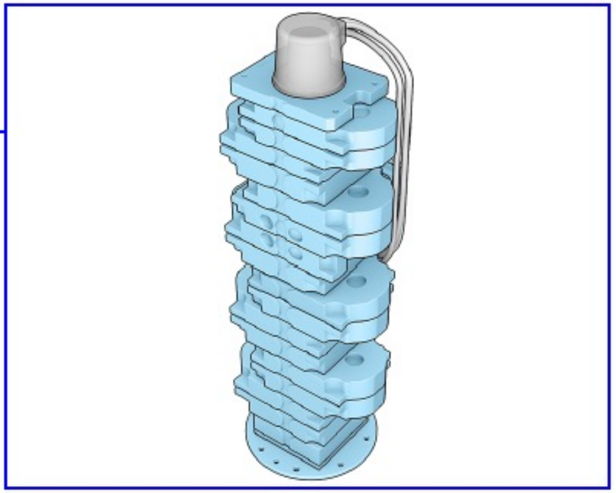
Design of the Unity

- Fixed mounting on ring gantry
- Standing waveguide
- No bending magnets, steering
- No flattening filter
- No gantry-dependent look-up-tables
- x1 energy: 7 MV FFF
- Simple, no options,
  no adjustments
- Magnetic field 1.5 T







Elekta handleiding

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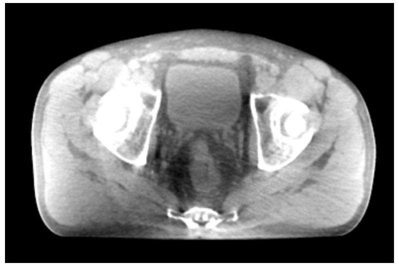
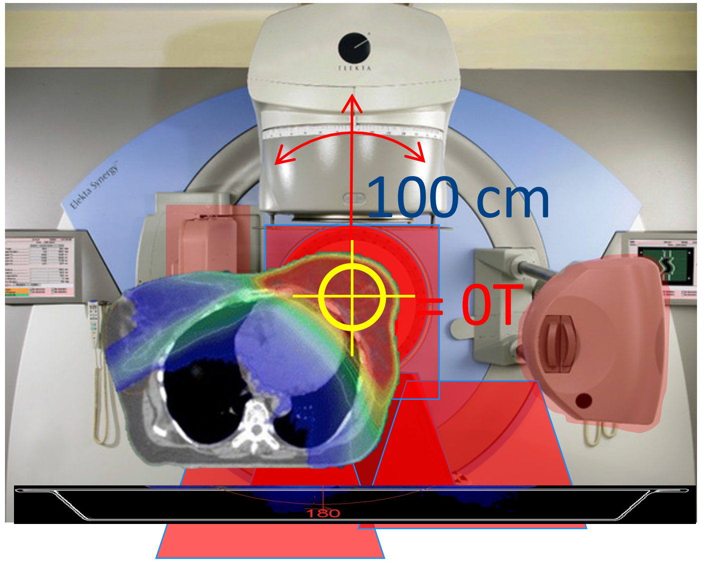
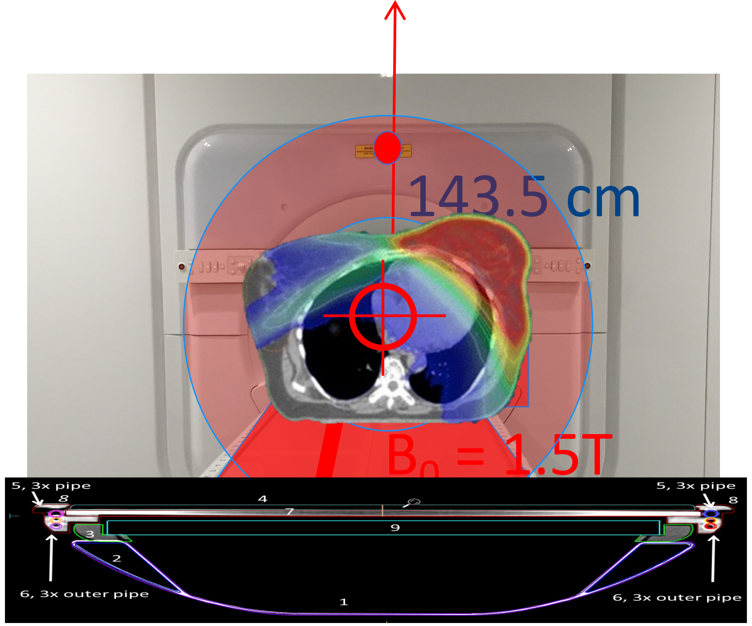
Conv. Linac

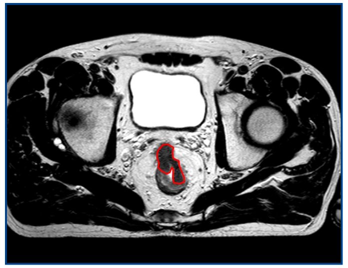




vs.

MR-Linac





- Open (much space)
- Isocenter in the target
- Table movements possible all directions
  - Correct positioning errors using table
- Field size: 40 x 40 cm^2
- Isoc at 100 cm
- Collimator rotations possible
- Cone-beam CT
- Magnetic field: 0.0005 Tesla (Earth magn. field)
- Couch attenuation (< 2%)

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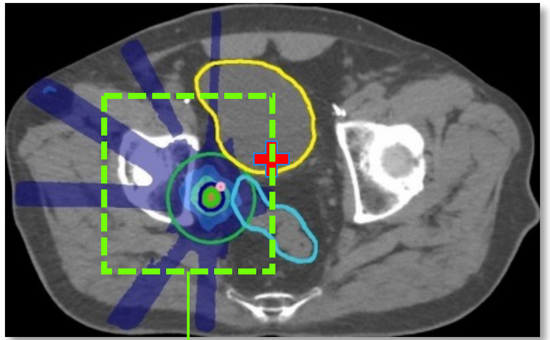
- Closed (small bore → less clearance)
- Fixed isocenter at the body center
- No LR and AP table movements
- Correct positioning errors using TPS/software solutions
- Field size: 57 x 22 cm^2
- Isoc at 143.5 cm
- No collimator rotations
- MR imaging
- Magnetic field: 1.5 Tesla
  (= 30000 x Earth magn. Field)
- Couch attenuation (< 26%)

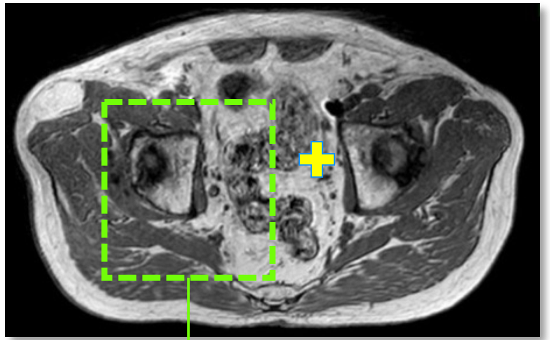
Plan adaptation

Adapt-to-position

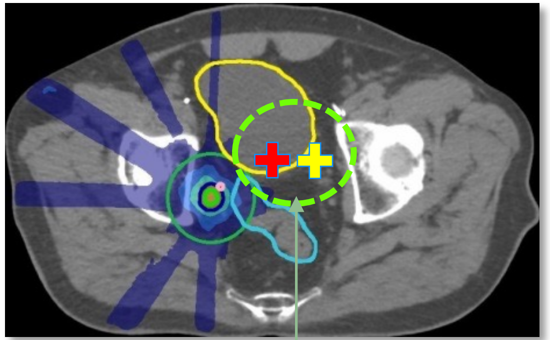
Pretreatment CT or MRI



Online MRI



Pretreatment CT or MRI



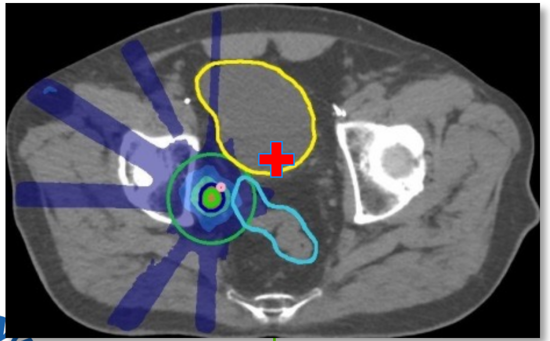
Rigid registration

Translation

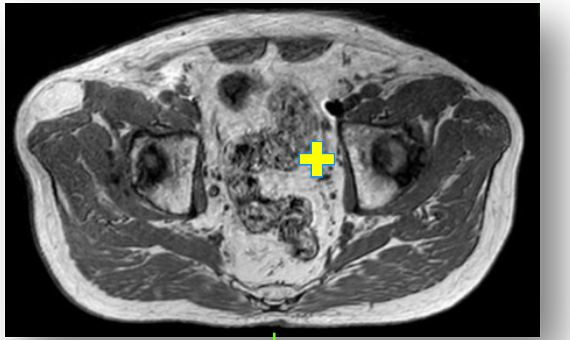
Plan adaptation on pretreatment CT or MR

Adapt-to-shape

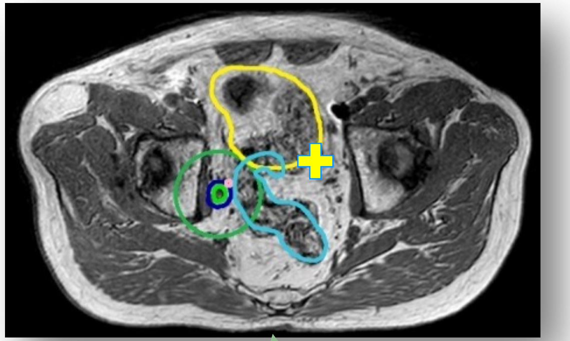
Pretreatment CT



Online MRI



Online MRI



Deformable registration

Deformed structures

- Adapt structures
- Plan adaptation on MRI

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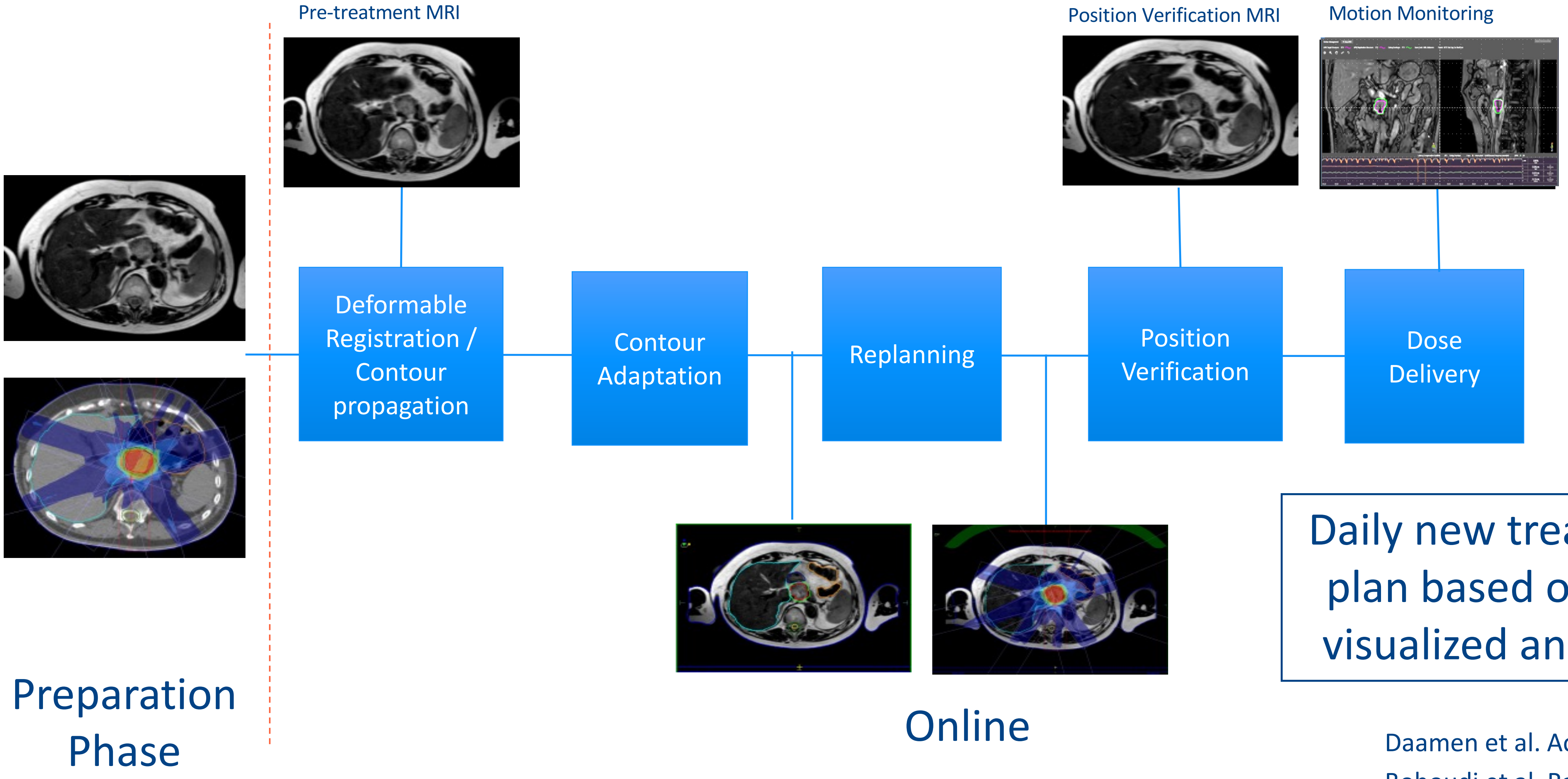
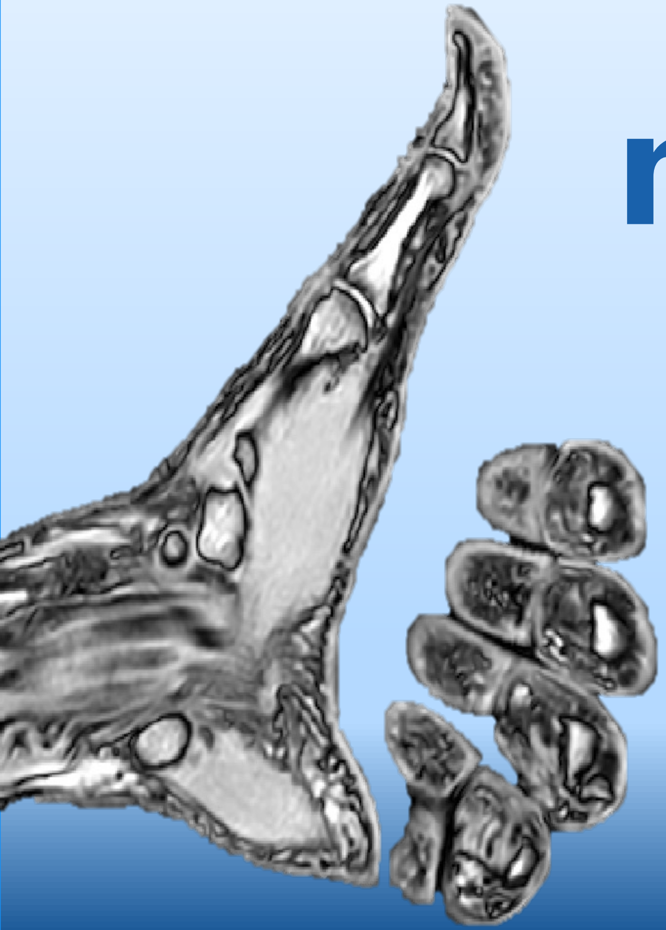
Unity MR-linac workflow

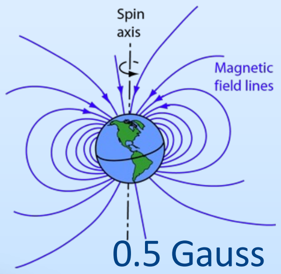


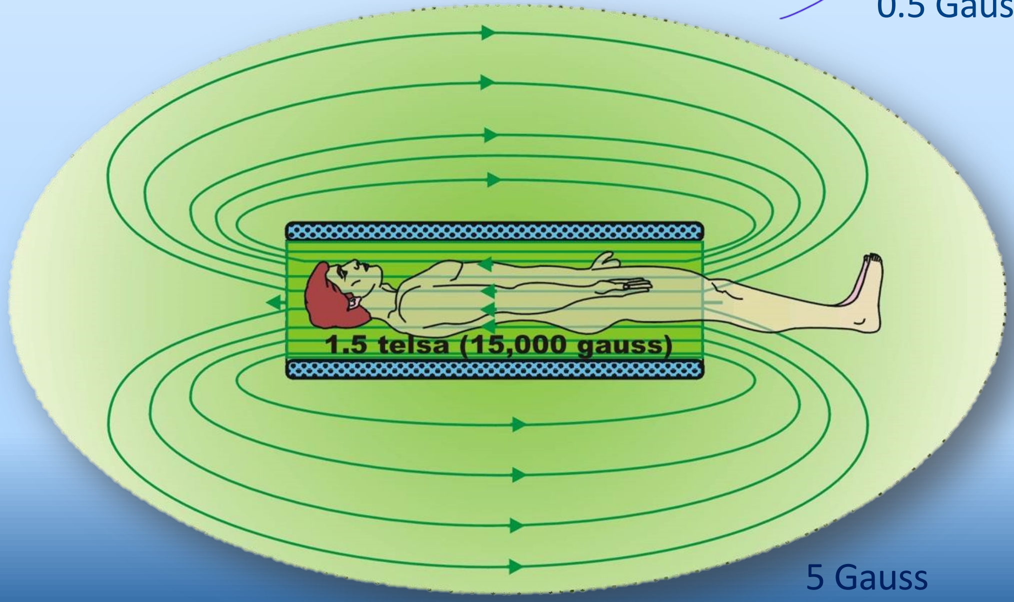
Daily new treatment plan based on MRI visualized anatomy

Daamen et al. Acta Oncologica 2021
Bohoudi et al. Radiother Oncol 2017

Impact
of the
magnetic field
on the
dose

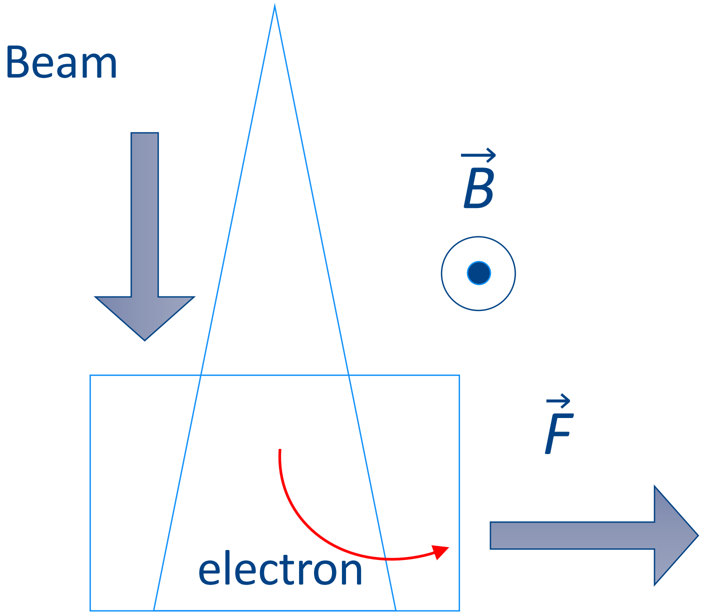




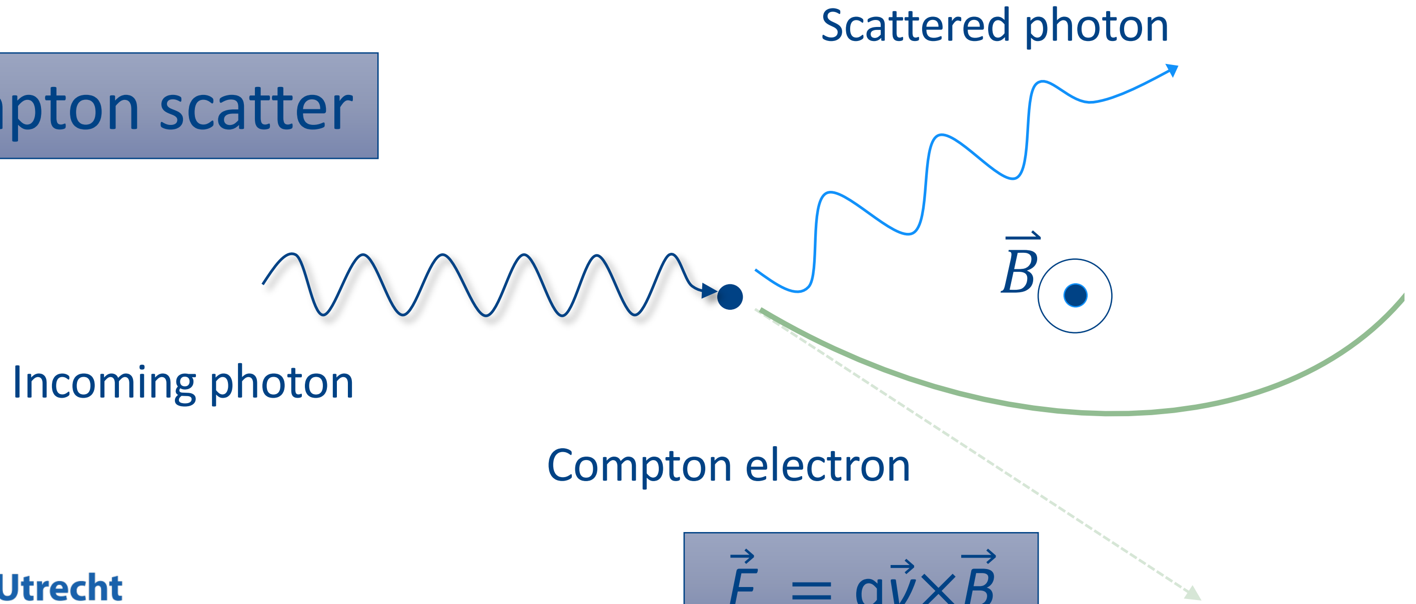


Dose delivery in a magnetic field

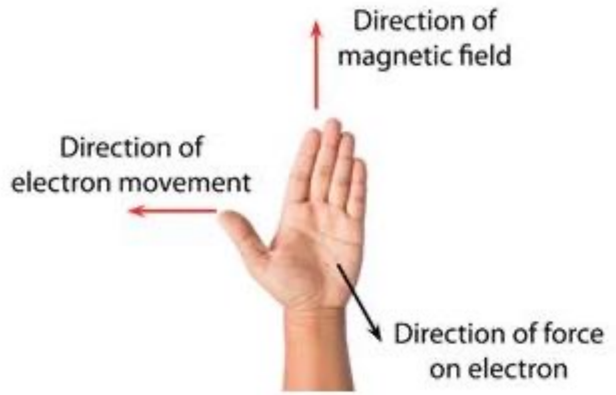
- Photons are *not* affected by the magnetic field
- Electron trajectory is changed by the Lorentz force
- Therefore the local dose deposition will change



Compton scatter



$\vec{F} = q\vec{v}\times\vec{B}$



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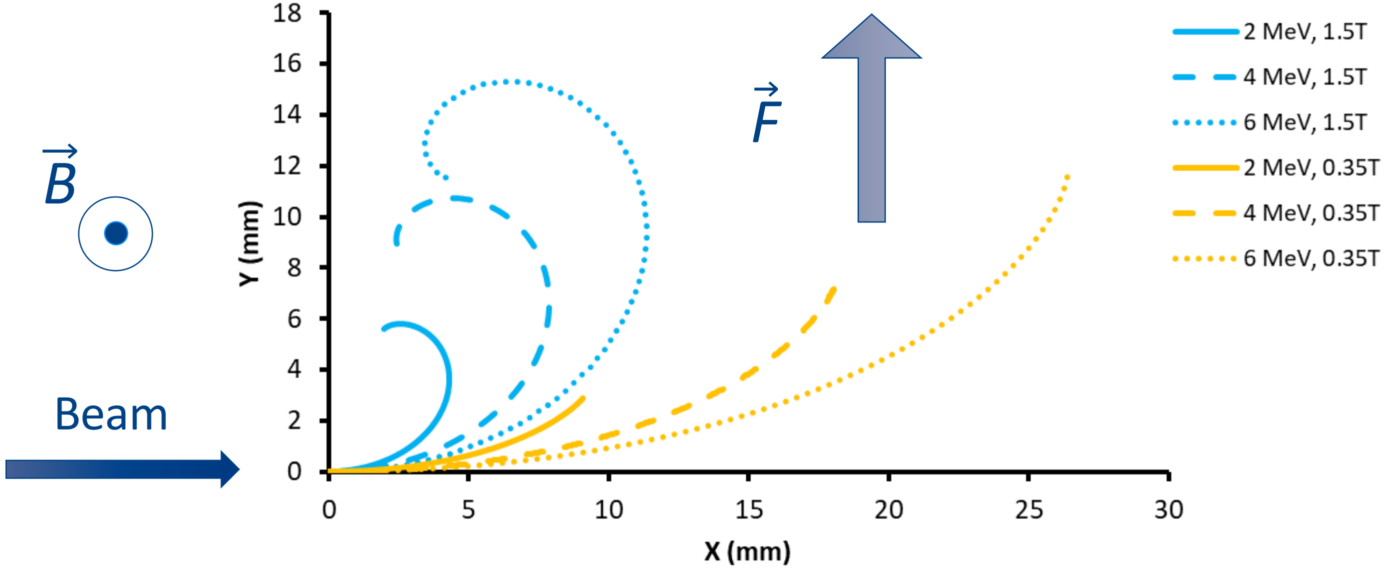
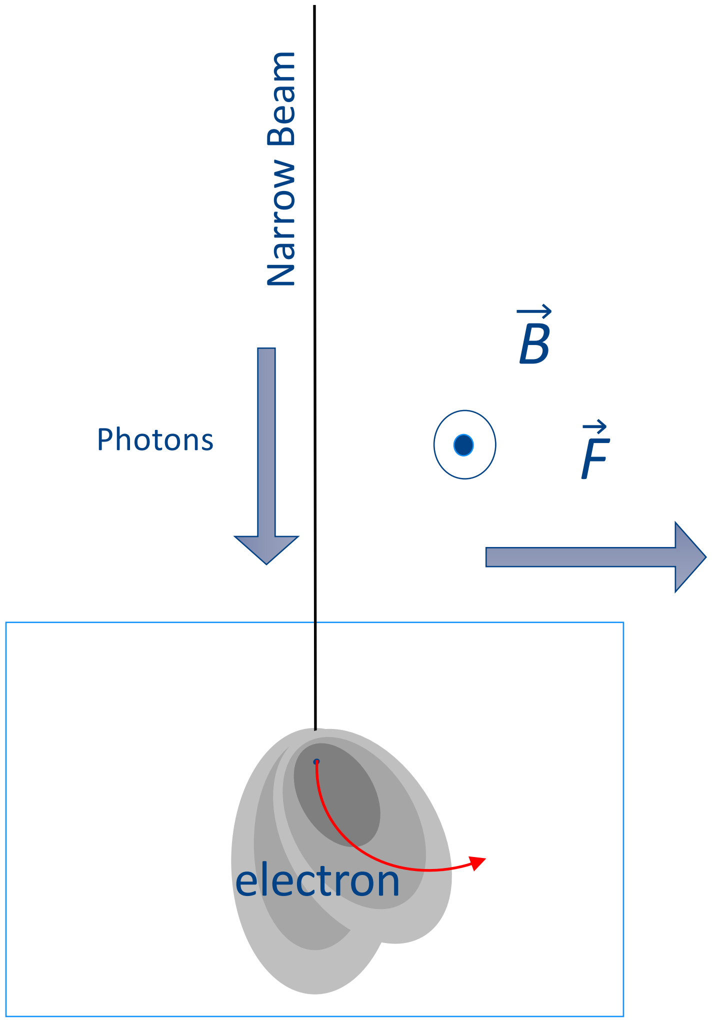
Trajectory of an electron in water

Force on the electron:

- Lorenz force
  - Will change the trajectory
- Stopping power
  - Interactions in matter will slow down the electron





Point spread dose distribution

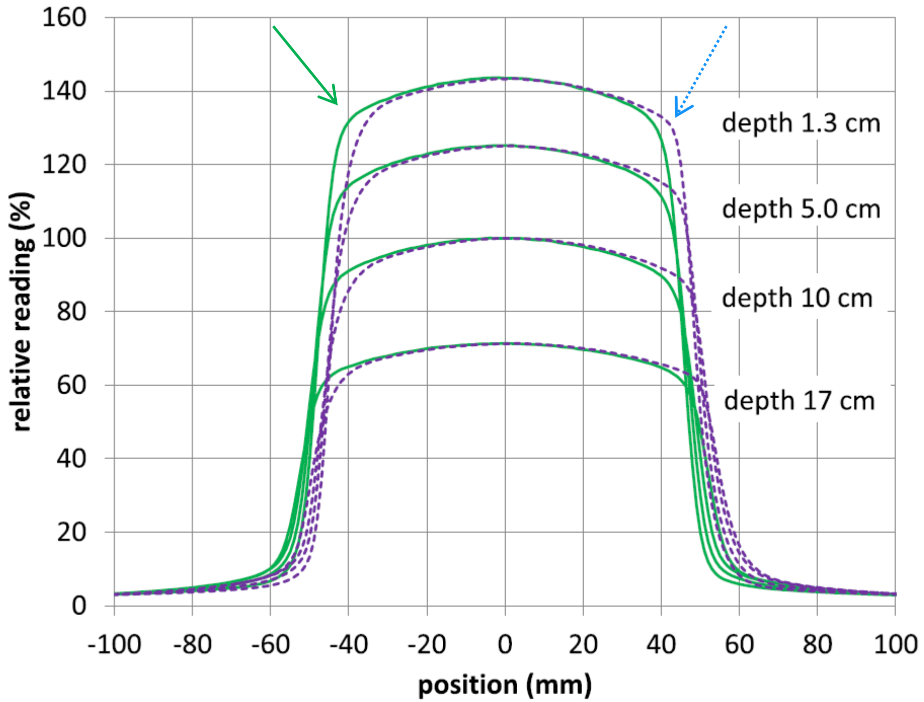
De Pooter J *et al*, PMB (2020)

Beam aspects

Lateral dose shift

Inline

Crossline



Woodings et al. PMB 2018 ***63****(8)*

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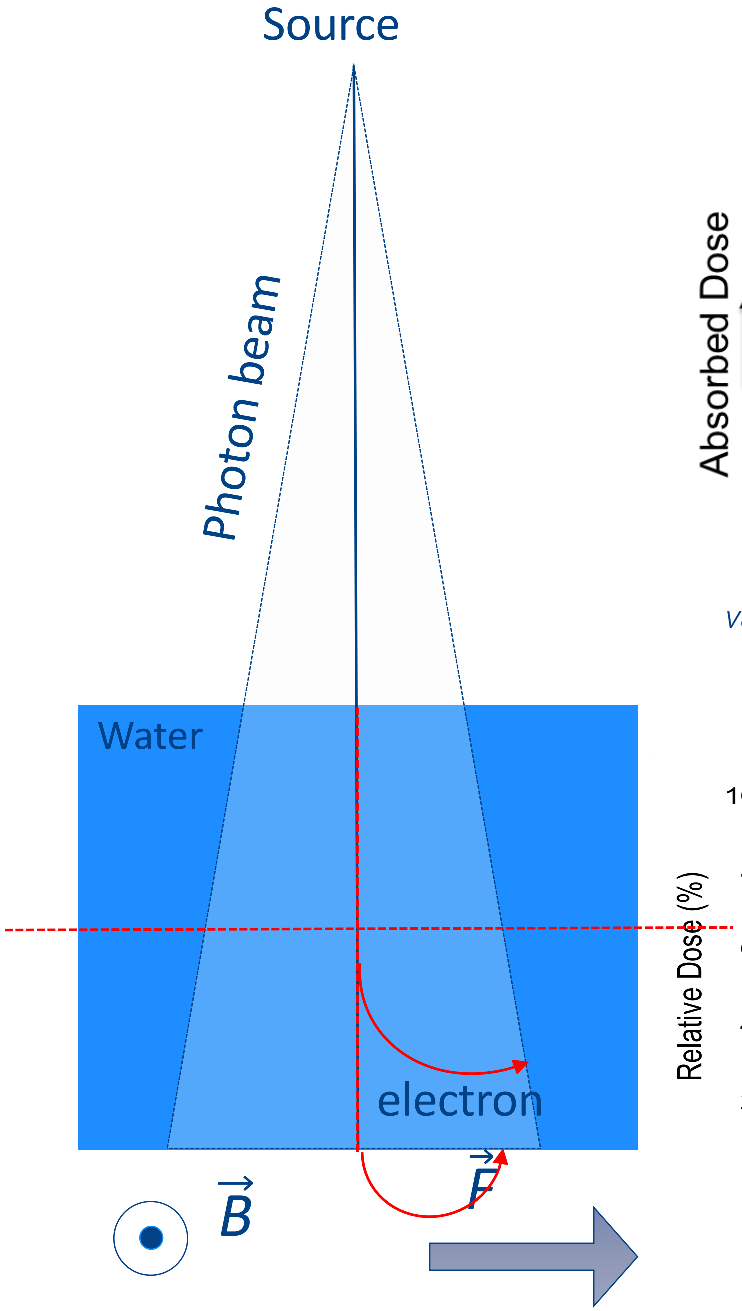
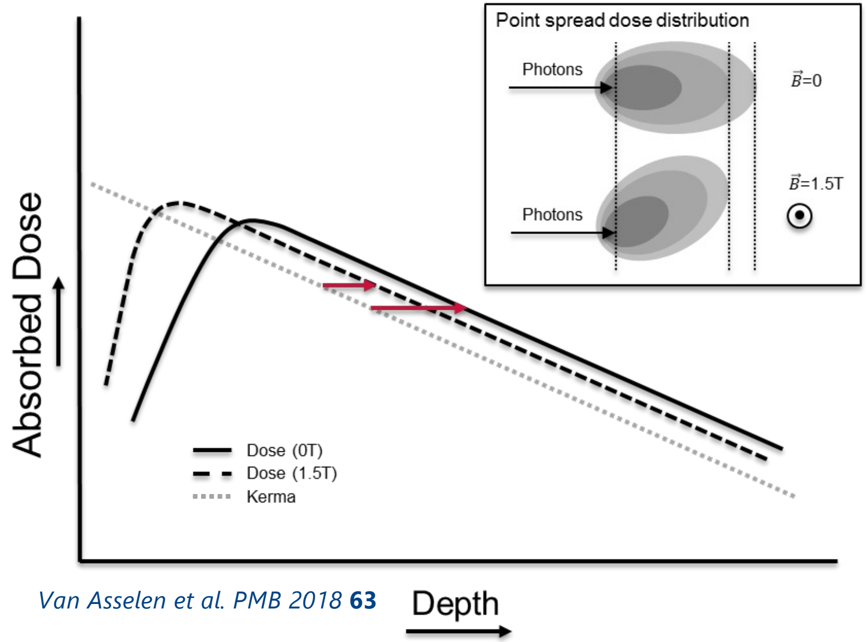
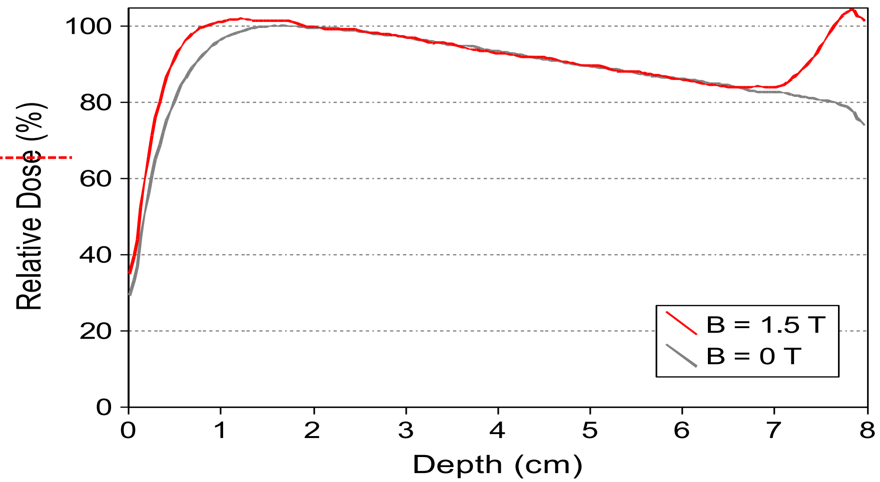


Dose difference CAX



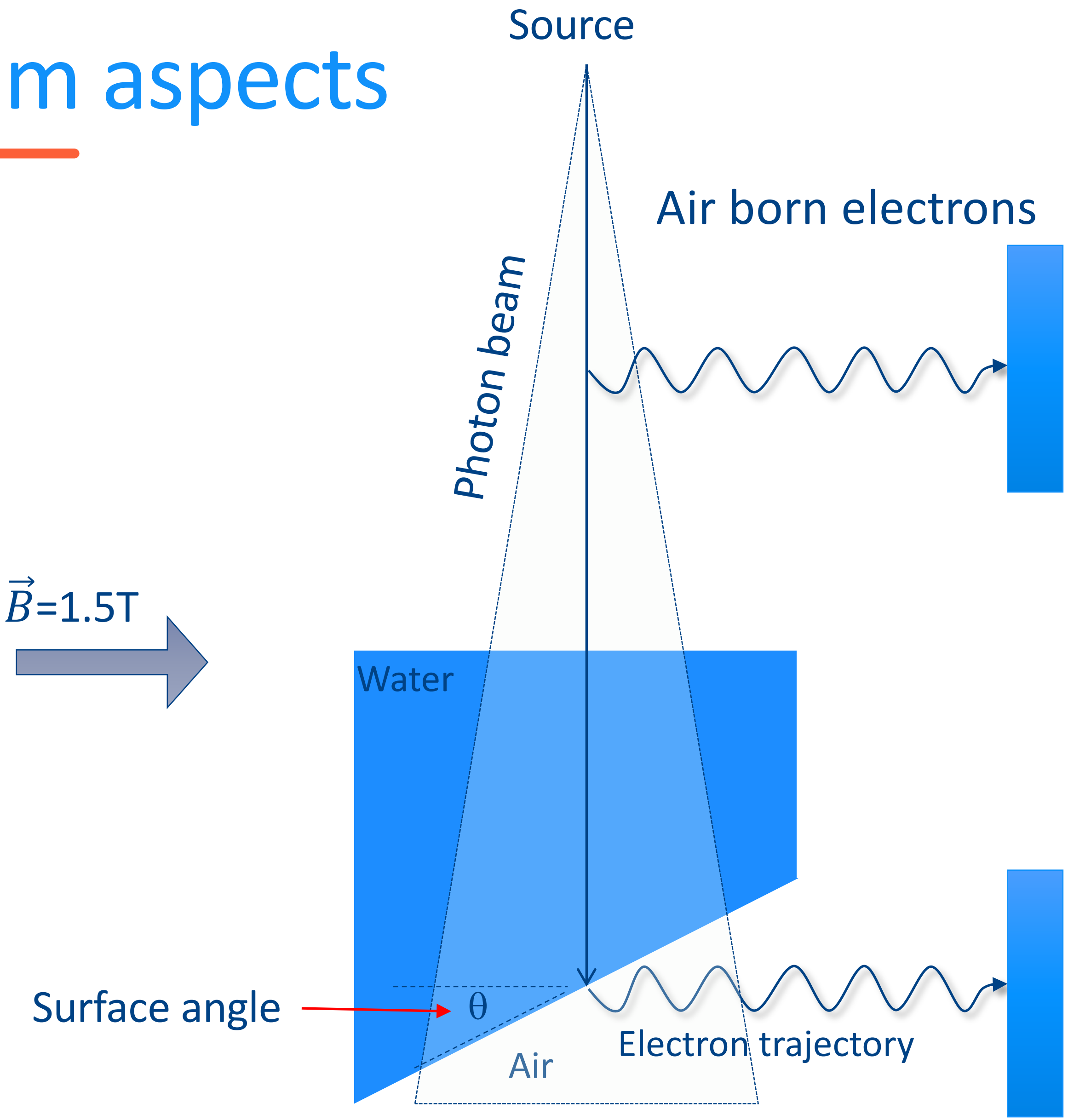
Van Asselen et al. PMB 2018 ***63***

Electron return effect



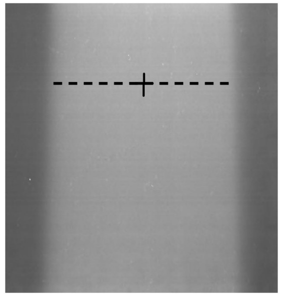
A J E Raaijmakers et al. PMB 50(7) (2005)

Beam aspects

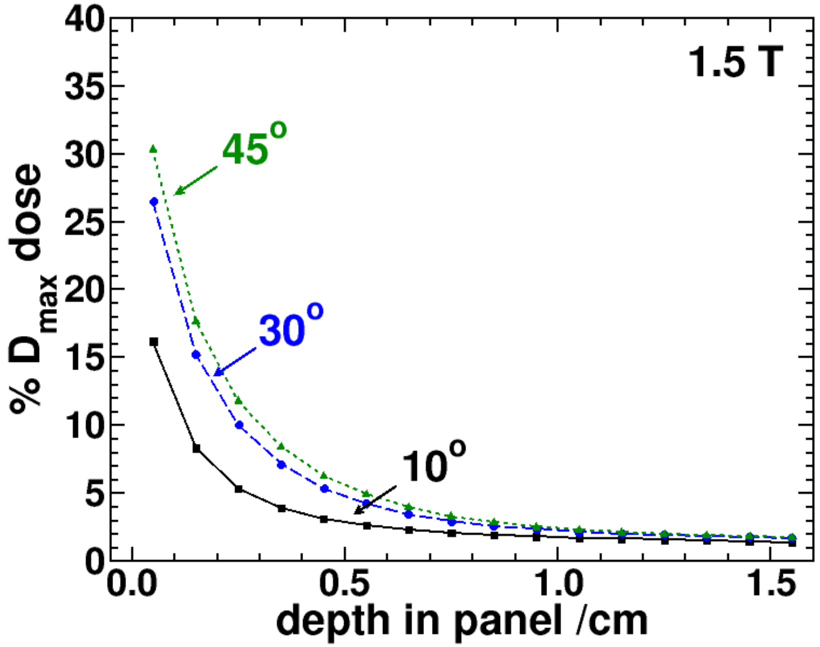


Electron streaming

Film measurement



Hackett, S. L. et al. PMB **63**(9)



Malkov, V. N., et al PMB 64 (2019)

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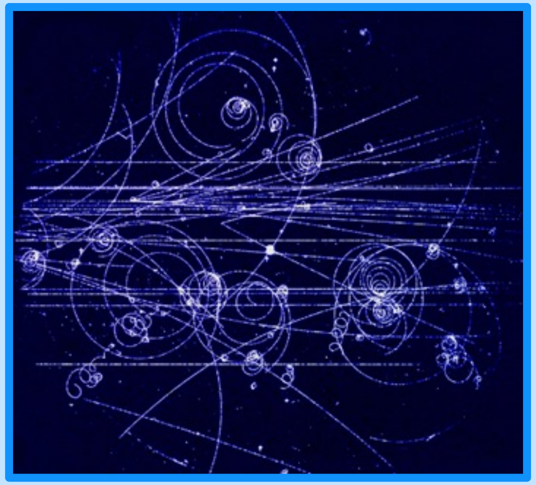
Machine performance and physics tests



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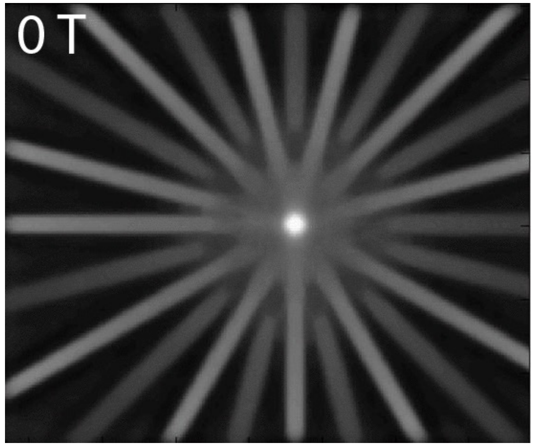
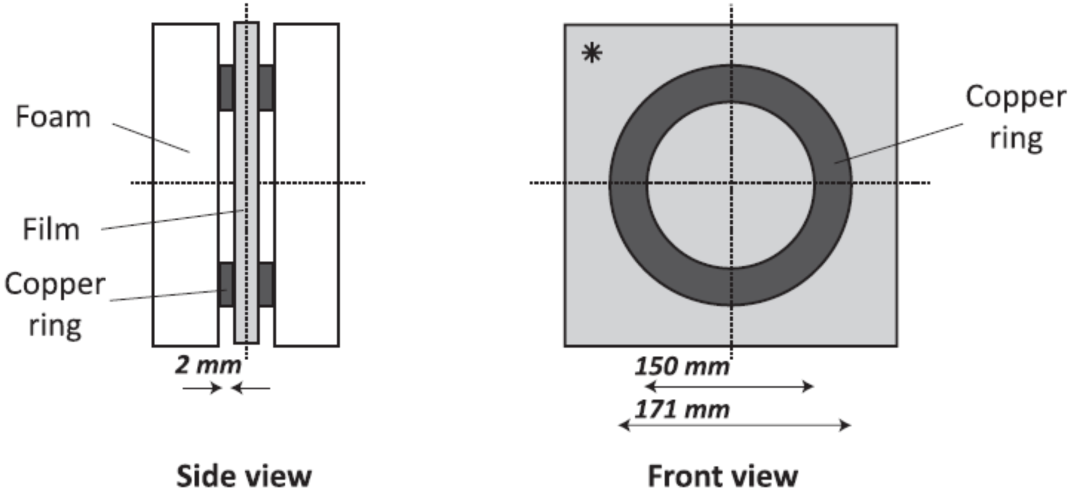
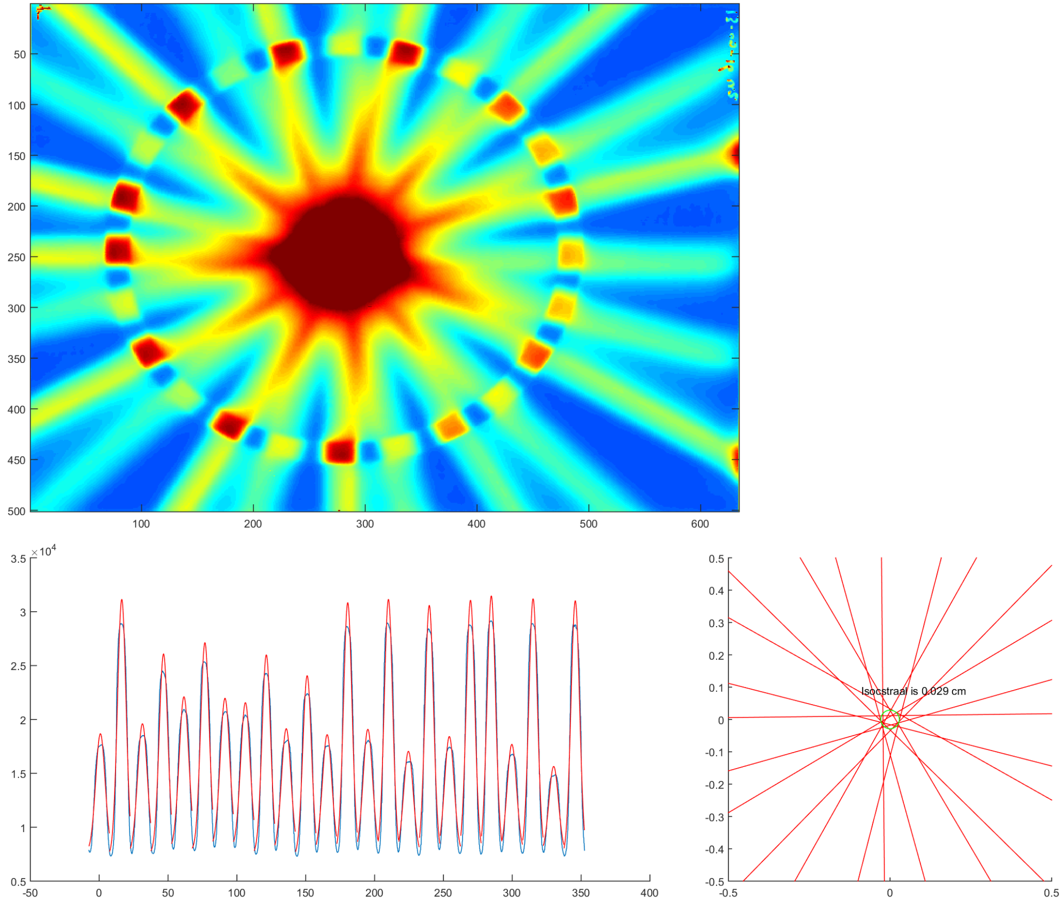
Accurate beam alignment - isocenter







Isocenter radius = 0.3 mm
(conventional linac = 0.5 – 1.0 mm)

Van Zijp et al. PMB ***61*** *(3)*

Reference dosimetry


IOP Publishing   Phys. Med. Biol. 63 (2018) 125008 (9pp)   https://doi.org/10.1088/1361-6560/aac70e

IPEM Institute of Physics and Engineering in Medicine

Physics in Medicine & Biology

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PAPER

A formalism for reference dosimetry in photon beams in the presence of a magnetic field

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Keywords: reference dosimetry, MRI-Linac, MRI-guided radiotherapy

Abstract

A generic formalism is proposed for reference dosimetry in the presence of a magnetic field. Besides the regular correction factors from the conventional reference dosimetry formalisms, two factors are used to take into account magnetic field effects: (1) a dose conversion factor to correct for the change in local dose distribution and (2) a correction of the reading of the dosimeter used for the reference dosimetry measurements. The formalism was applied to the Elekta MRI-Linac, for which the 1.5 T magnetic field is orthogonal to the 7 MV photon beam. For this setup at reference conditions it was shown that the dose decreases with increasing magnetic field strength. The reduction in local dose for a 1.5 T transverse field, compared to no field is 0.51% ± 0.03% at the reference point of 10 cm depth.

$$\underbrace{D_{w,Q,B}}_{\text{Dose to water, beam quality Q, field strength B}} = \underbrace{M_{Q,B}}_{\text{Measured charge}} \cdot \underbrace{N_{D,w,Q_0}}_{\text{Absorbed dose calibration coefficient, traceable to standards laboratory}} \cdot \underbrace{k_{Q,Q_0}}_{\text{Beam quality}} \cdot \underbrace{k_B}_{\text{Magnetic field}}$$

Absorbed dose calibration coefficient, traceable to standards laboratory

Dose to water, beam quality Q, field strength B

Measured charge

Beam quality

Magnetic field

Review paper: De Pooter J *et al*, PMB (2020)
AAPM TG351 - Clinical reference dosimetry in MR-guided radiotherapy (not yet published)

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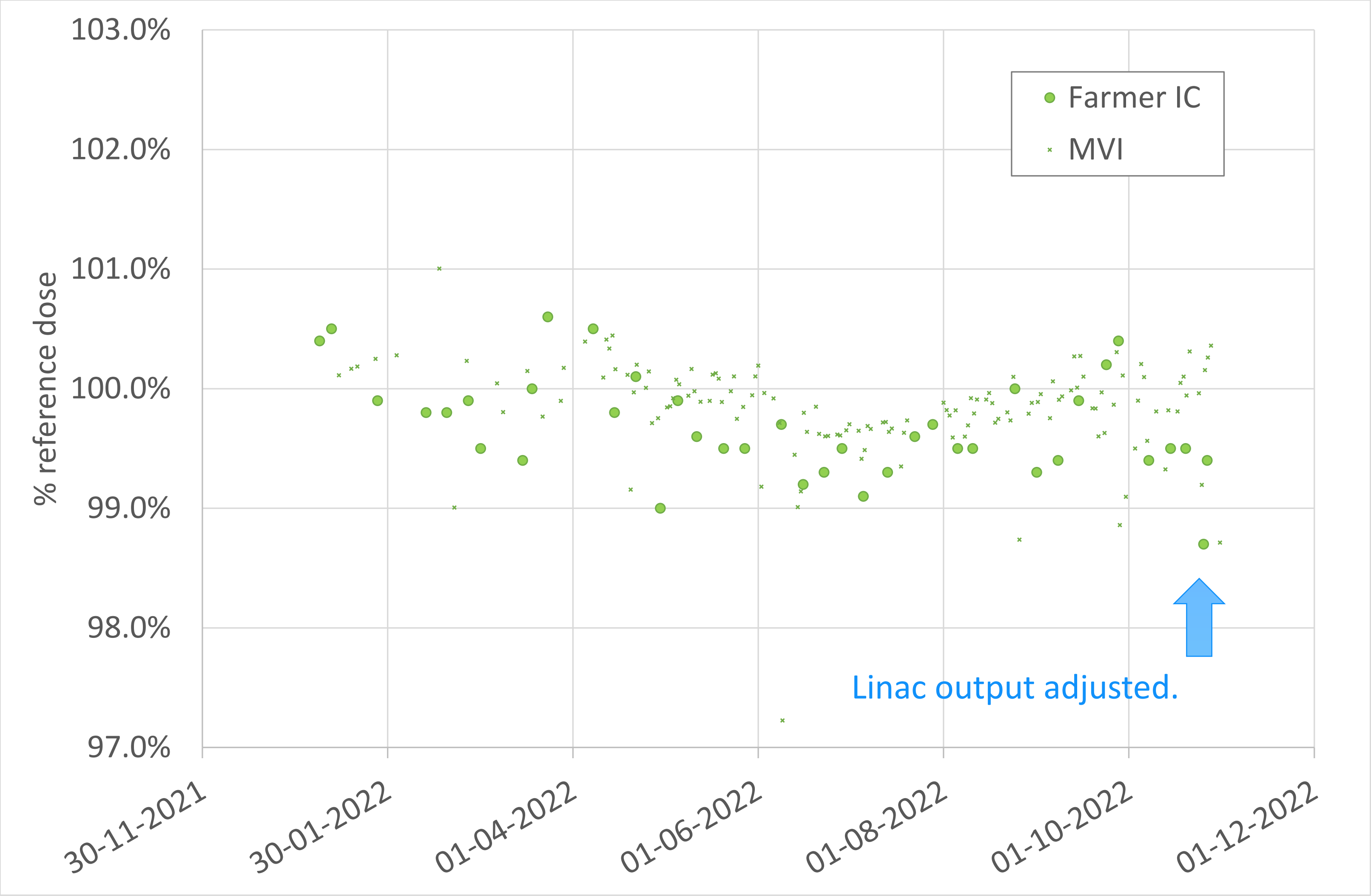
Dosimetry – U03 MRL



Standard deviation:
U02 0.60% (x4 adjustments)
U03 0.48% (x1 adjustments)
(due to linac variation and measurement uncertainty)

UMCU Unity Linac QA schedule

Test	Frequency
Daily constancy	
EPID-imaging (output and field edges)	Daily
Safety and functionality checks	
Inhibits and warning systems	Weekly
Dosimetry	
Absolute Dosimetry	Weekly
Dose Linearity	Weekly
Energy Measurement	Weekly
Starcheck Profile Measurement	Monthly
Film measurements	
Opposing Fields	Monthly
Focal Spot Alignment	Monthly
MLC Stripe Test	Monthly
Spokefilm	3-Monthly
X-jaw Accuracy	3-Monthly
Watertank Measurements	
Profiles and PDD's	3-Monthly
Outputfactors	3-Monthly
Diagonals	3-Monthly
Other Measurements	
Radiation Leakage	Annual
Cryostat and Couch transmission	Annual
End-to-end test	Annual
Workflow test	As required

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MRI acceptance testing and commissioning

System configuration and Connectivity (SCC)

System & connectivity	test#		
general inventory	1.1		
DICOM functionality	1.2		
patient couch	1.3		
patient communication	1.4		
cameras	1.5		

Quality Control (QC)

B0 field	test#	Field gradients	test#	RF fields	test#
absolute field strength	2.1	image orientation	3.1	flip angle accuracy	4.1
f0 stability	2.2	ghosting	3.2	RF cage seal	4.2
cryogen level	2.3	*gradient delays*	*N/A*	receiver coil performance	4.2
B0 homogeneity	2.4	*eddy currents*	*N/A*		
HYBRID TESTS		***HYBRID TESTS***		***HYBRID TESTS***	
B0 direction	5.1	gradient non-linearities	5.3	linac induced RF interference	5.4
gantry dependent B0	5.2			radiation influence	5.5

Quality Assurance (QA)

General image quality	test#	Sequence specific evaluation	test#	
PIQT	6.1	signal-to-noise	6.2	
ACR	6.2	low contrast detectability	6.2	
FBIRN	6.3	geometric fidelity	3.2	

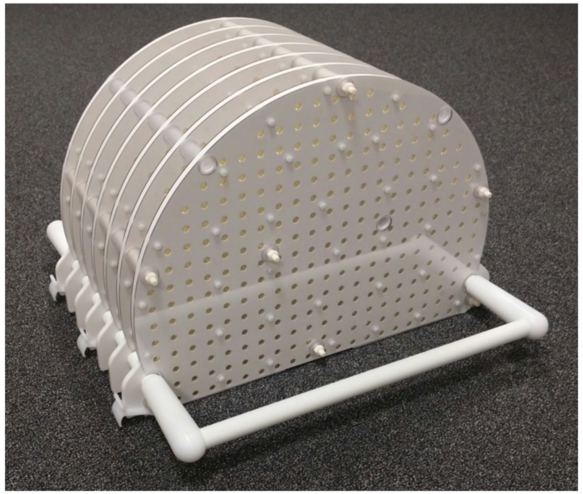
Protocol is Unity consortium effort

- Rationale presented in manuscript
- Benchmark results of four systems

- Detailed instructions in appendices
- MRI Protocols ('Examcards') free to download as supplementary material

Tijssen et al., Radiother Oncol 2019, 132:114-20

Gradient fidelity on the MRL



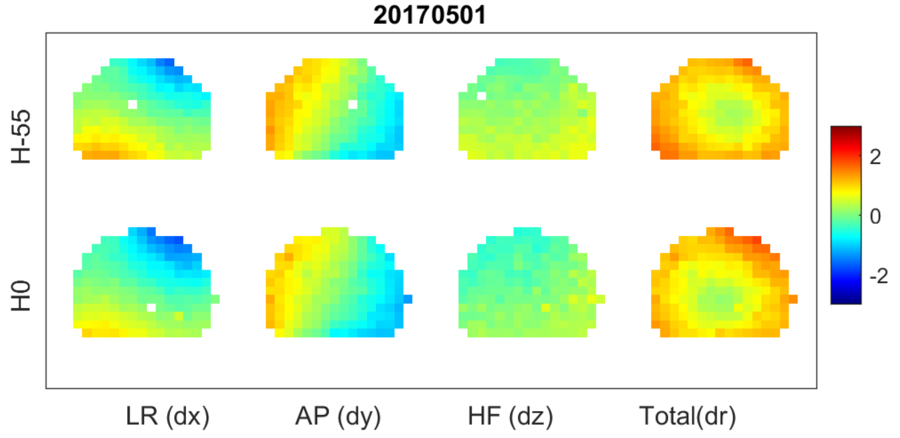
3D FFE sequence
Geometric correction turned ON

Right column shows total distortion
vector sum of x y and z distortions

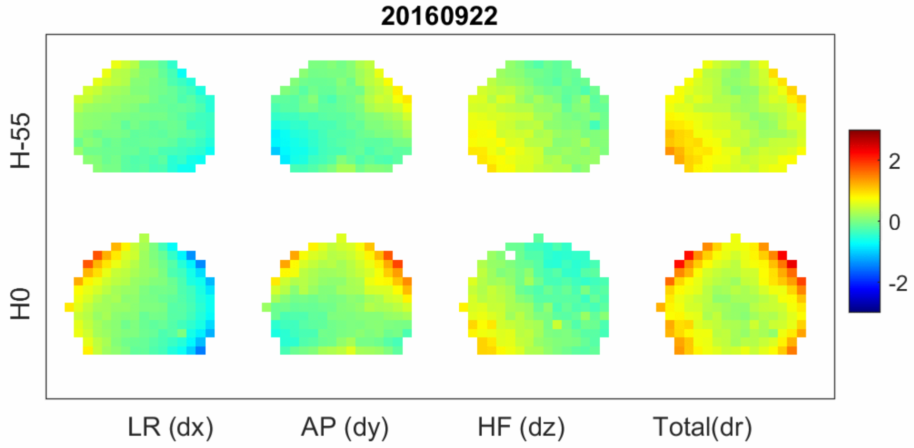
3D Geometric QA
for research use

DSV (mm)	Maximum total displacement Ingenia	Maximum total displacement vector MR-Linac
150	0.73 mm	0.84 mm
250	1.22 mm	1.11 mm
350	**1.87 mm**	**1.25 mm**
400	2.23 mm	1.55 mm

1.5T Ingenia (MRI-sim)



1.5T Marlin (MRL)



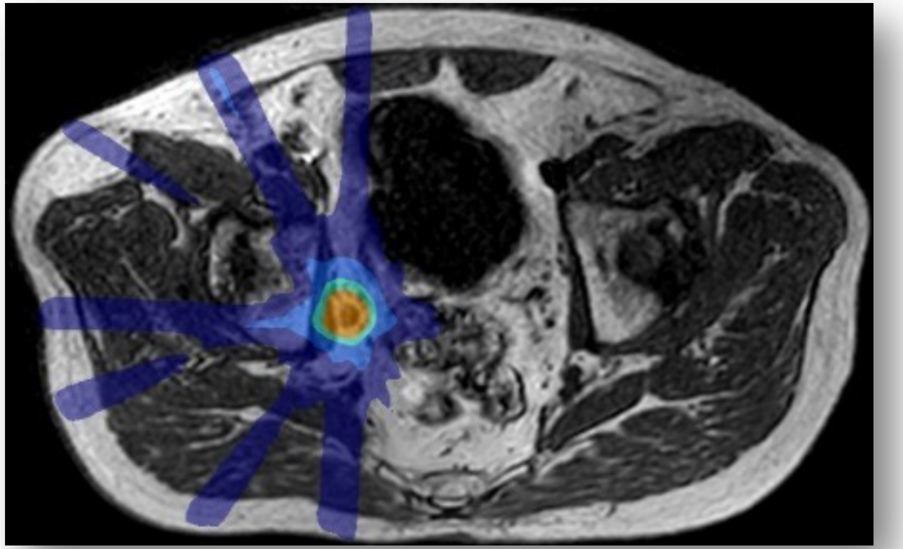
Tijssen, Phillipens et al., Radiother Oncol, 132:114-20 (2019)

Treatment planning

Magnetic field is incorporated in the dose calculation

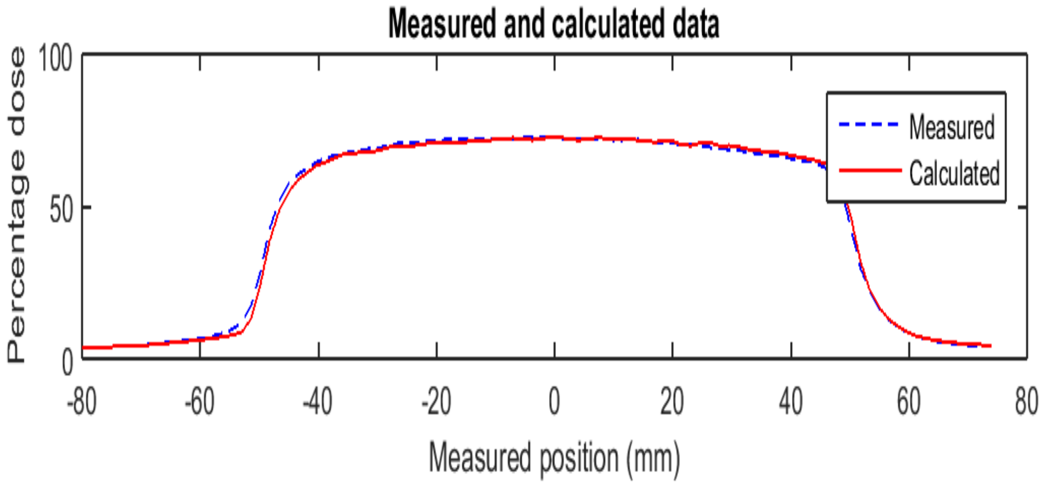
- Thus also the effects on the dose distribution
- GPUMCD Monte Carlo algorithm

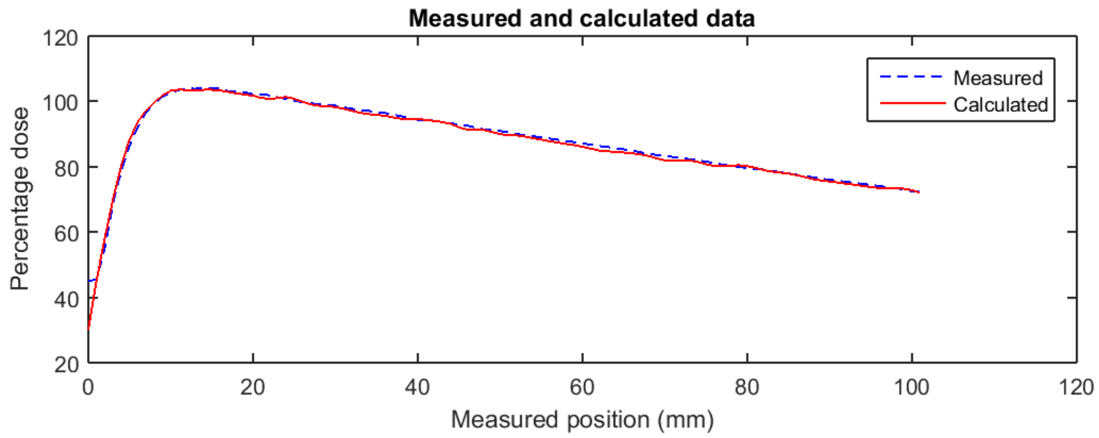
Effects of the magnetic field are most times not visible due to IMRT optimization



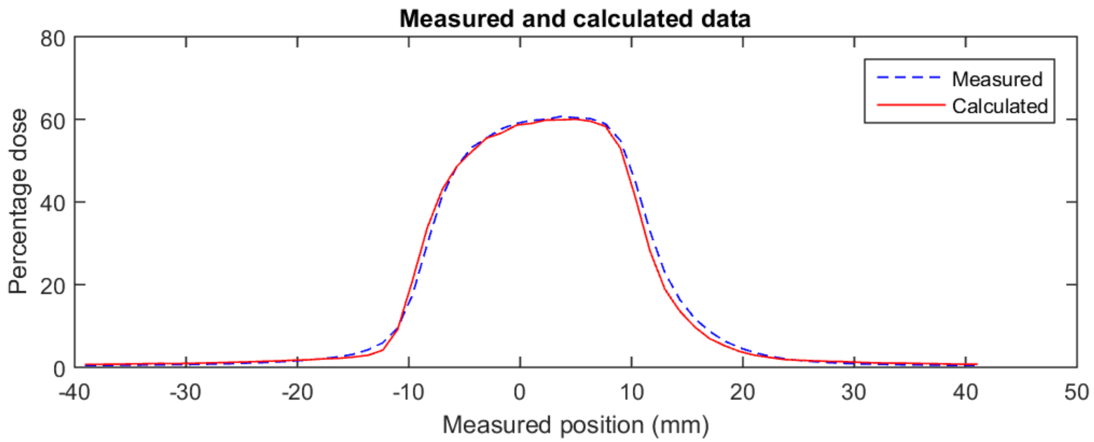
Beam model verification – TPS v measurements

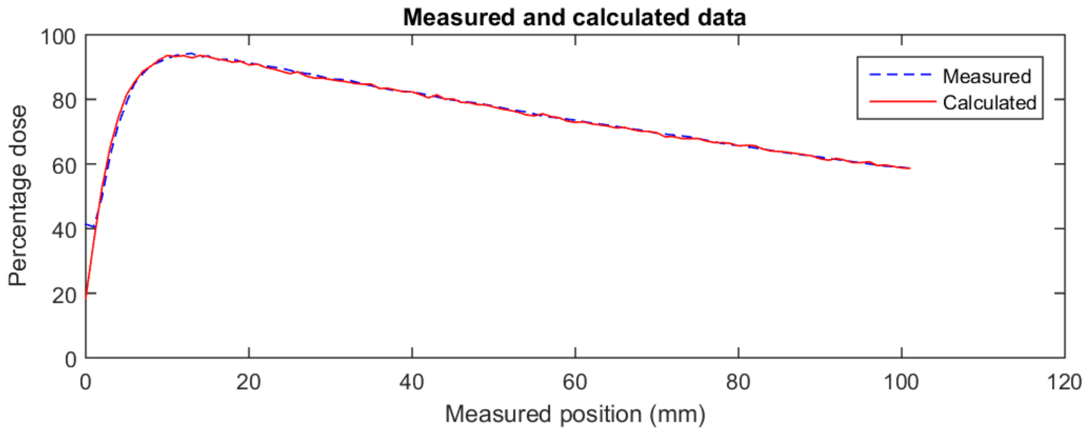
10 x 10 cm^2 field



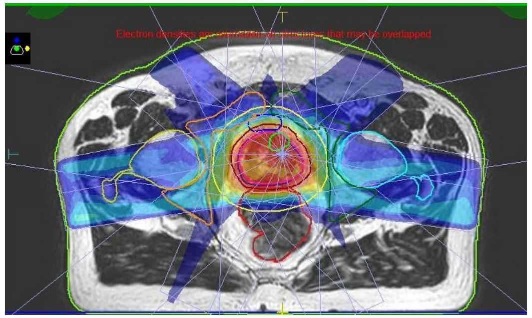


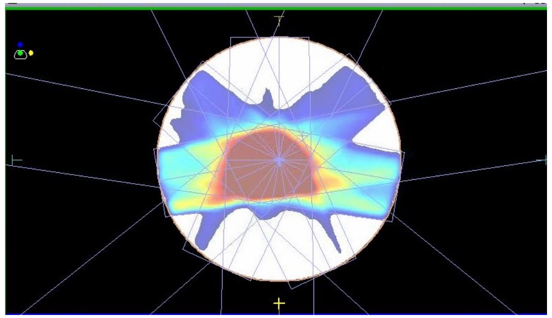
2 x 2 cm^2 field



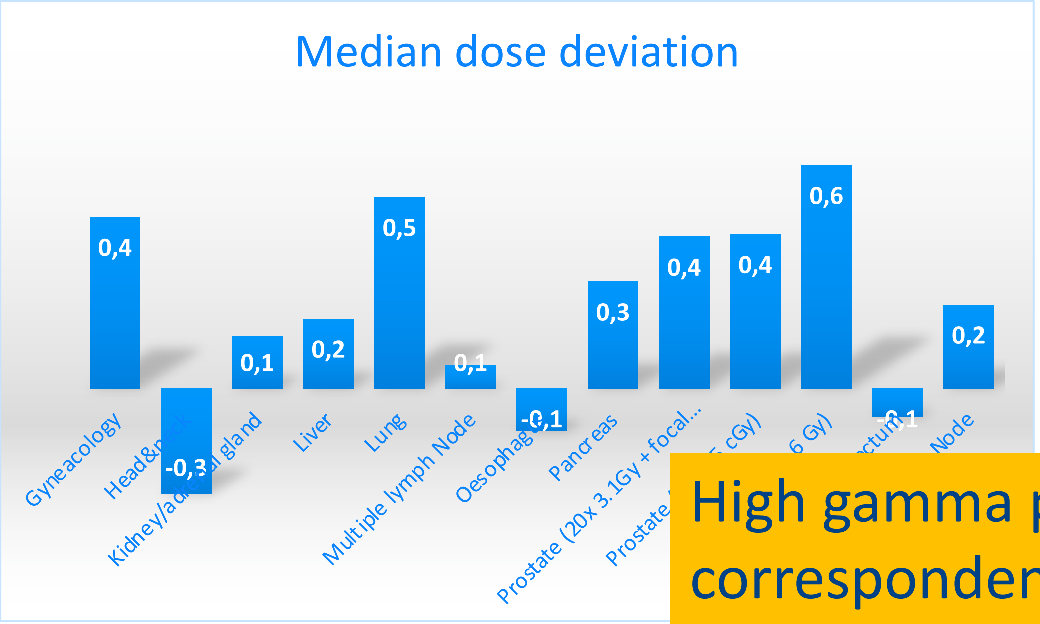


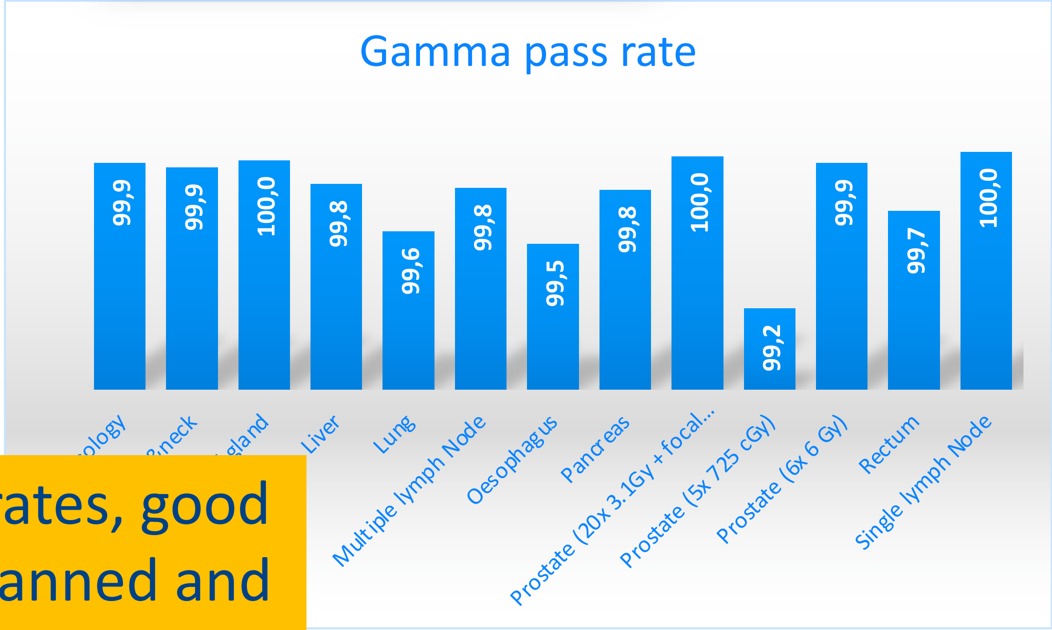
Patient QA: Delta4 MR phantom





	#
Gyneacology	20
Head&neck	9
Kidney/adrenal gland	12
Liver	13
Lung	33
Multiple lymph Node	20
Oesophagus	13
Pancreas	42
Prostate (20x 3.1Gy + focal boost)	28
Prostate (5x 725 cGy)	55
Prostate (6x 6 Gy)	18
Rectum	35
Single lymph Node	16





High gamma pass rates, good correspondence planned and delivery

UMC Utrecht

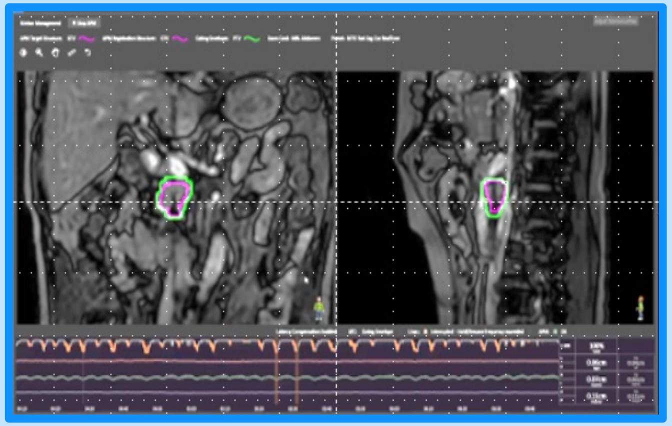
AC Houweling *et al.* PMB 61 (2016)
de Vries et al. PMB 63 (2018)

Summary of physics measurements

- Impact of the magnetic field well studied
- Absolute dose can be determined using new formalism
- Equipment should be MR proof
- Patient QA results using various devices are good
- Online QA is needed for plan adaptation

UMC Utrecht

Motion management



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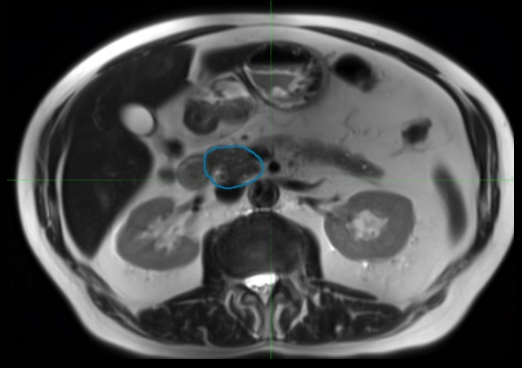
Comprehensive Motion Management: 4 Strategies / 11 Contrasts + DWI

Stationary

T1, T2 & Flair

Accelerated by C-SENSE

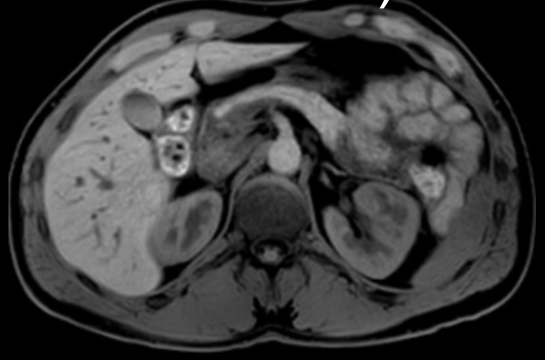
Full Exhalation



T2 Navigated

Accelerated by C-SENSE

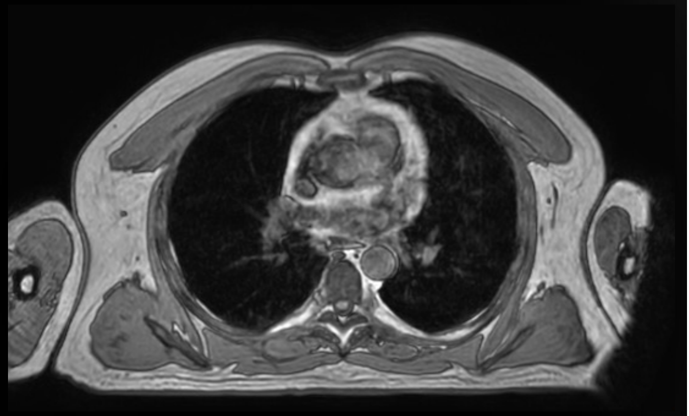
Free Breathing (Time Average Position)



T1 (FatSat / no FatSat), Balanced (FatSat / no FatSat)

Motion Artifact Suppression by 3D Vane

Breath-Hold



T1, T2 & Balanced

Accelerated by C-SENSE

Elekta

Elekta Unity with Comprehensive Motion Management (CMM) has CE mark and U.S. FDA 510(k) clearance. Not available in all markets.

Unity comprehensive motion management (CMM)

Key features

True Tracking

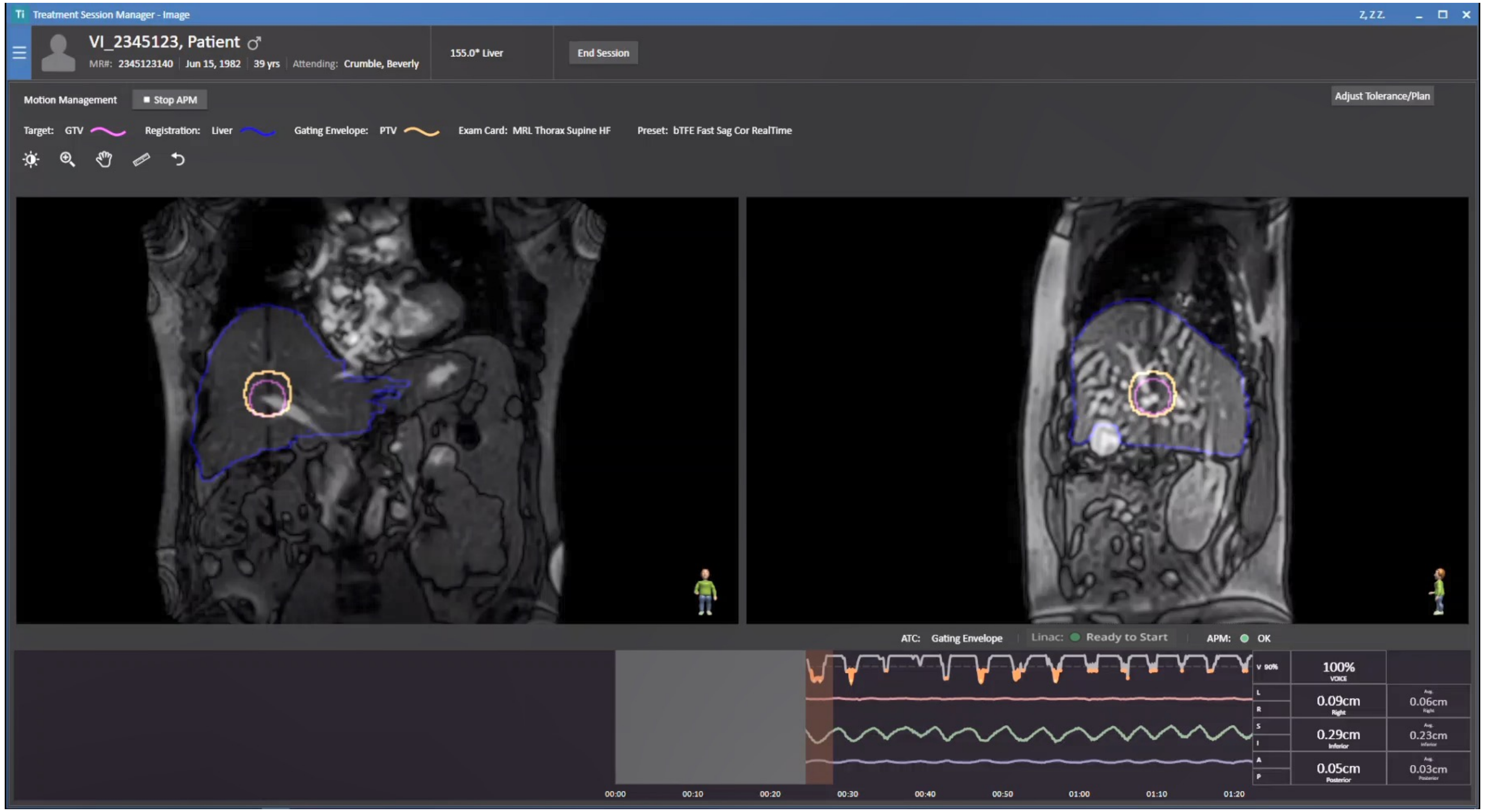
- Measures the displacement of the registration structure (usually the target)

Automatic gating

- Gates the beam on / off depending on True Tracking

Intrafraction drift correction

- Corrects for drifts based on True Tracking – without performing a new 3D MR

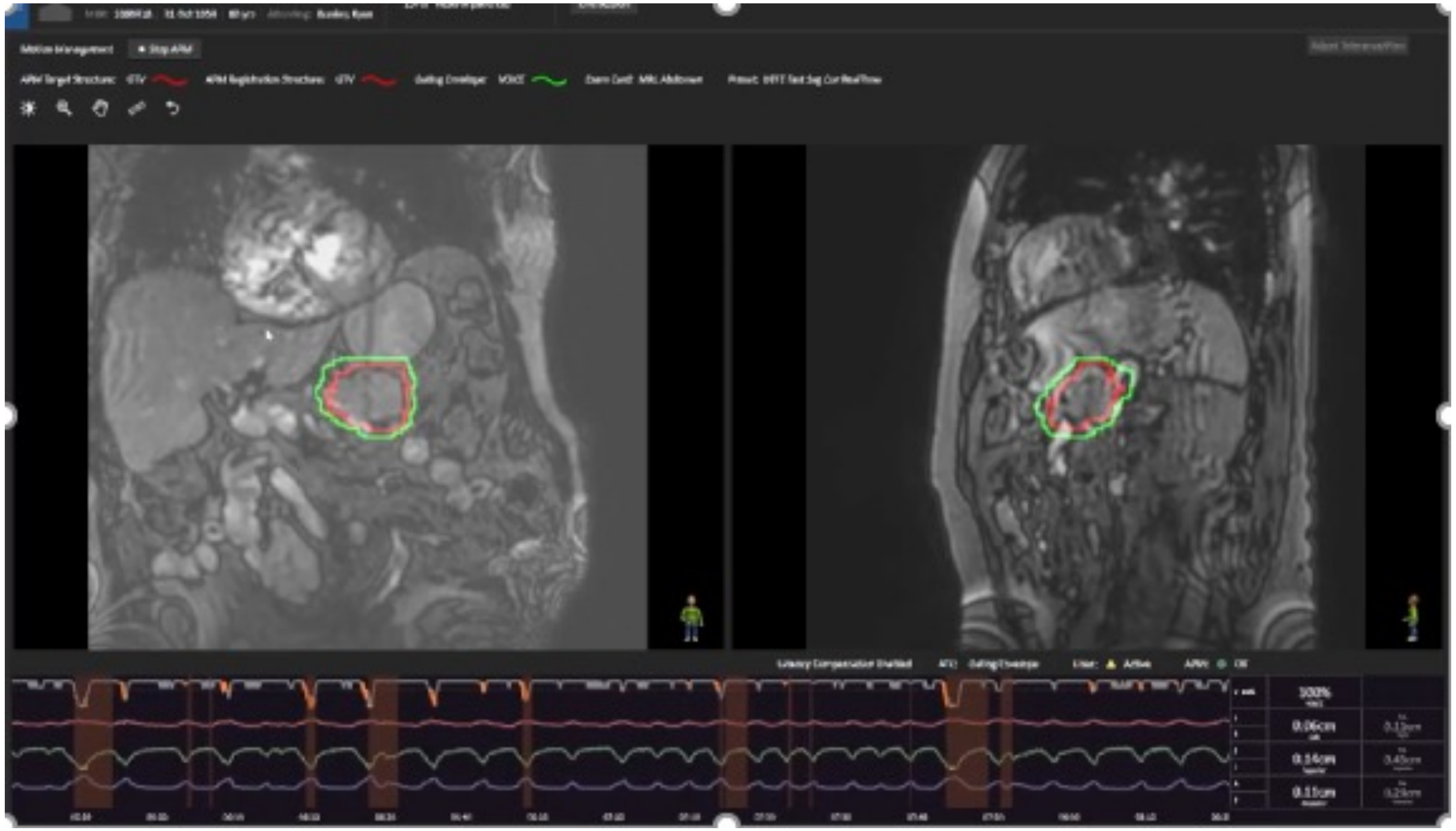


UMC Utrecht

Elekta Unity with Comprehensive Motion Management (CMM) has CE mark and U.S. FDA 510(k) clearance. Not available in all markets.

Intra-fraction motion

Gating

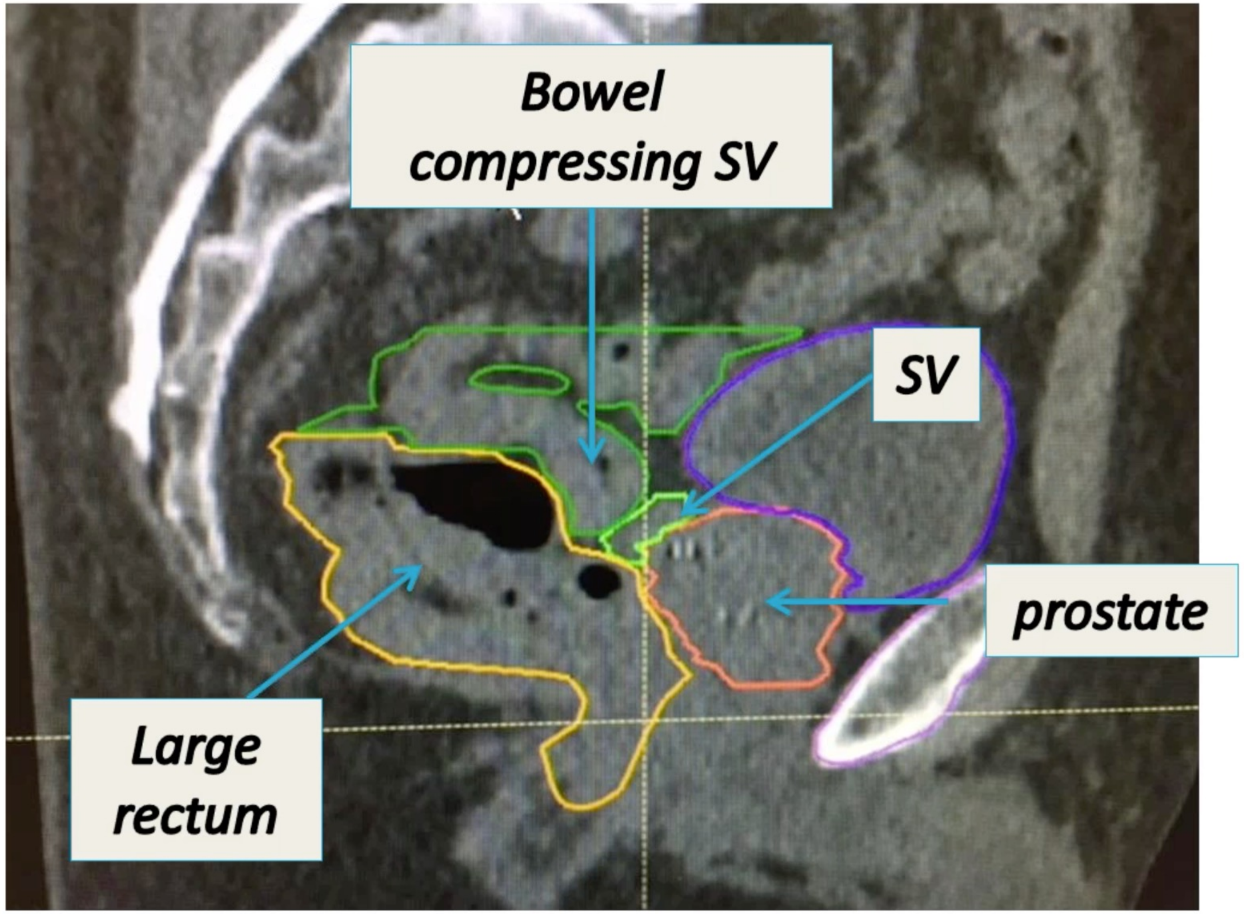


UMC Utrecht

Elekta Unity with Comprehensive Motion Management (CMM)
has CE mark and U.S. FDA 510(k) clearance. Not available in all markets.

Current status and future developments

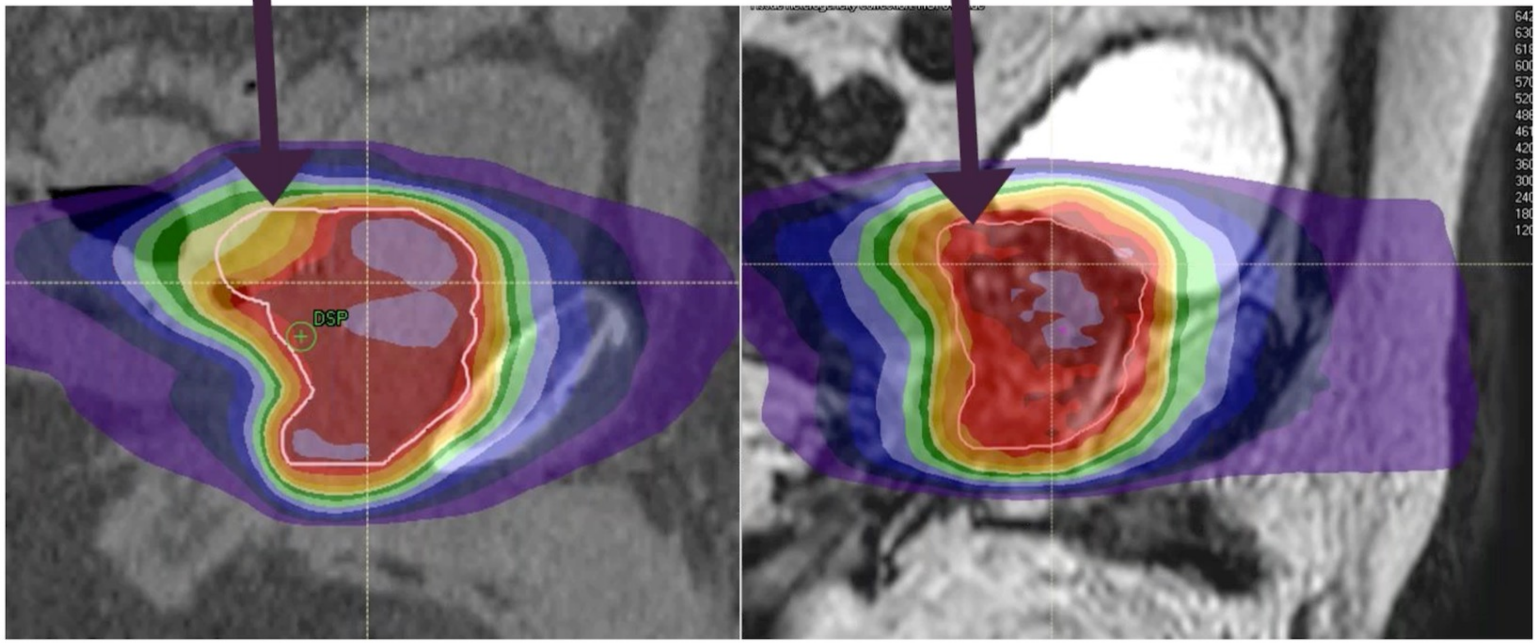
Adaptive MR-guided RT
Patient 3- the perfect/worst candidate?

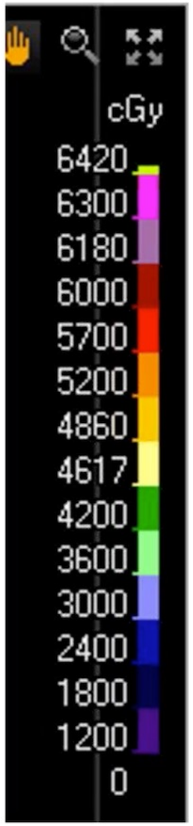


Adaptive MR-guided RT
Patient 3- the perfect/worst candidate?

Significant undercoverage of the target

Target well covered

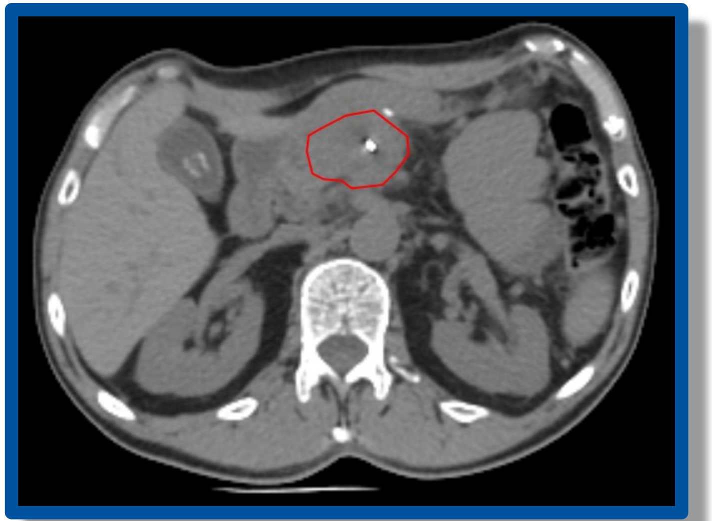


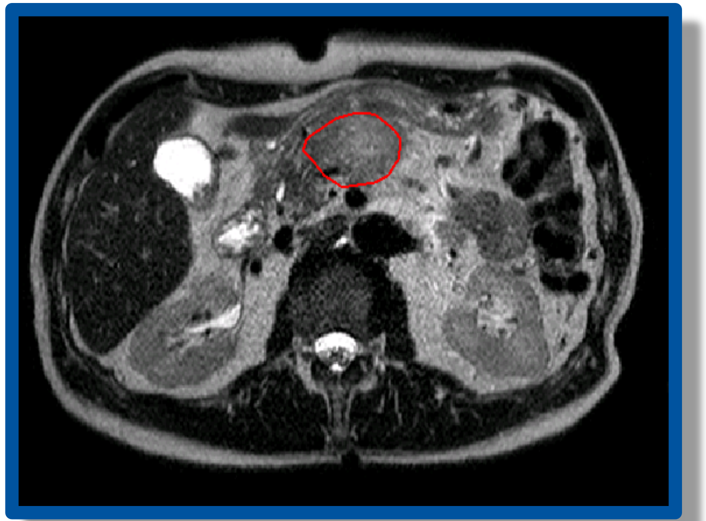


Tumor-background contrast

Pancreas

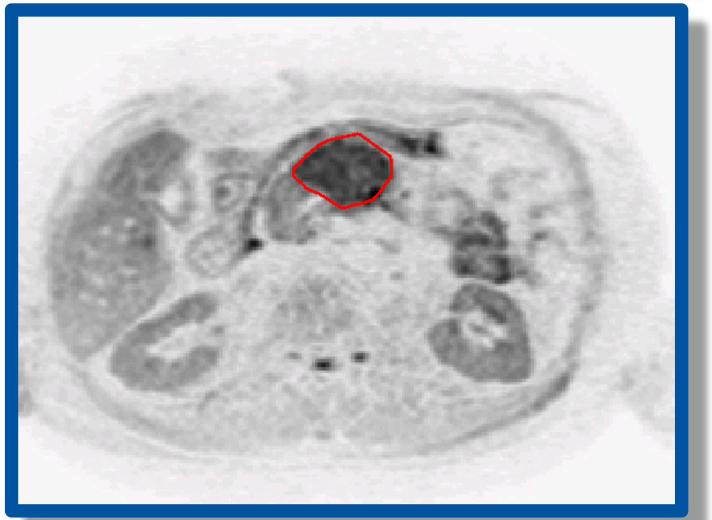
CT

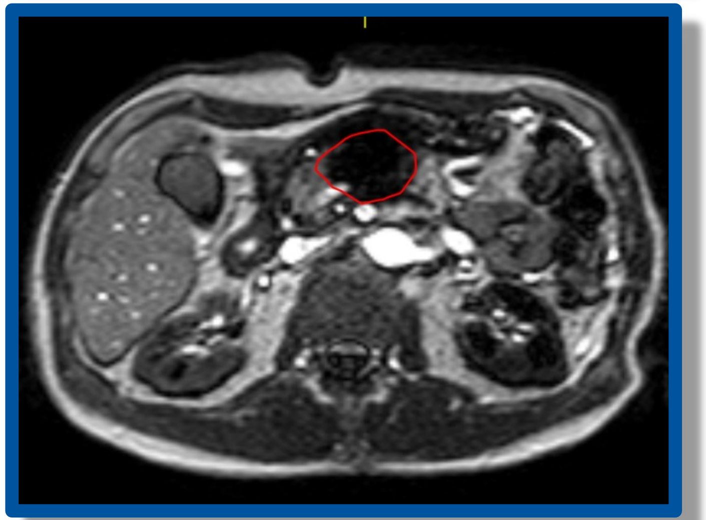




T2 MRI

DWI MRI

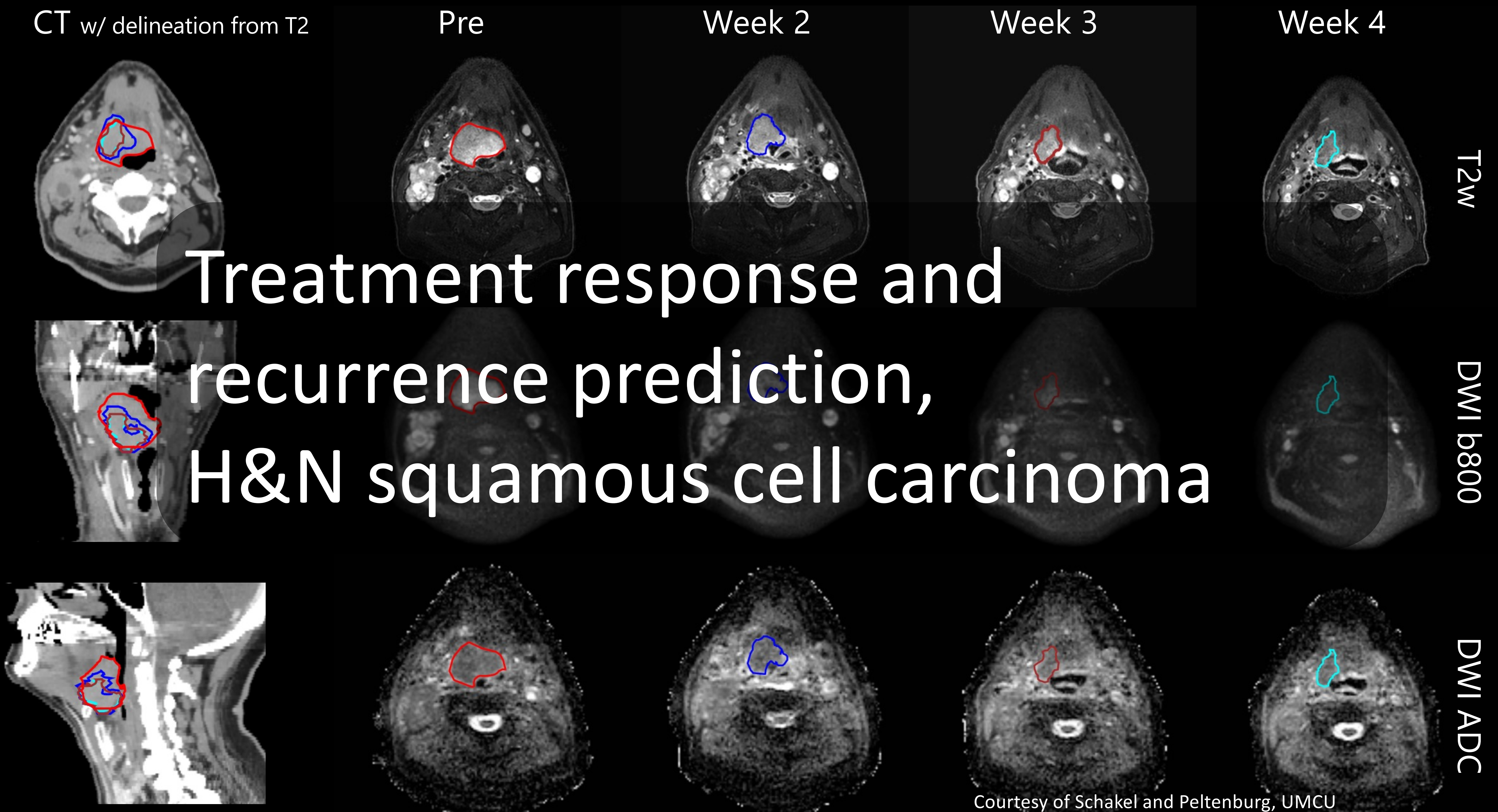




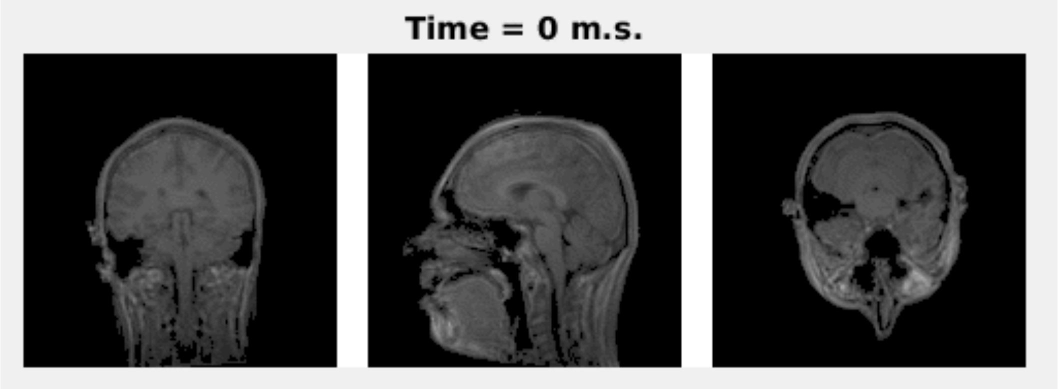
T1 MRI

versatile MRI for automatic contouring

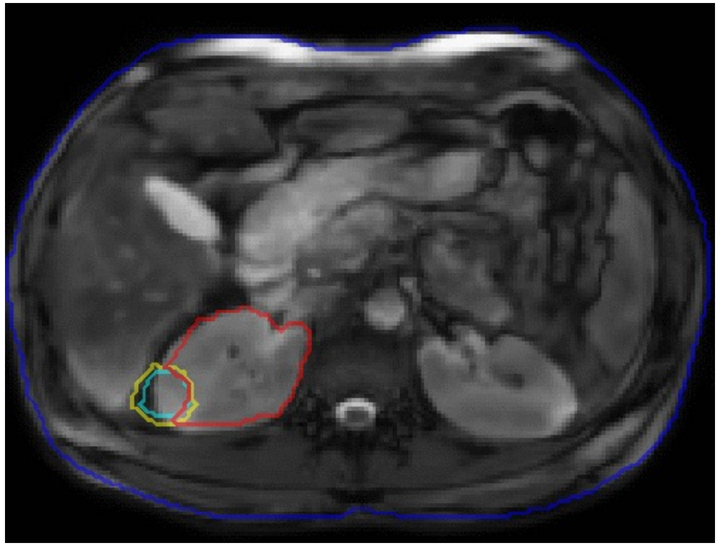
Treatment response and recurrence prediction, H&N squamous cell carcinoma



Towards real-time MRI guided adaptive radiotherapy: treating moving targets as if they are static



MRI can acquire real-time 3D updates (see Huttinga et al. Phys Med. Biol. (2020)**)**



Continuous re-planning on moving anatomy converges to acceptable dose distribution (see Kontaxis et al. Phys Med. Biol. (2015 and 2017)**)**

MRI can acquire the heart beat for cardio-respiratory tracking and gating (see Akdag et al. Phys Med. Biol. (2022)**)**

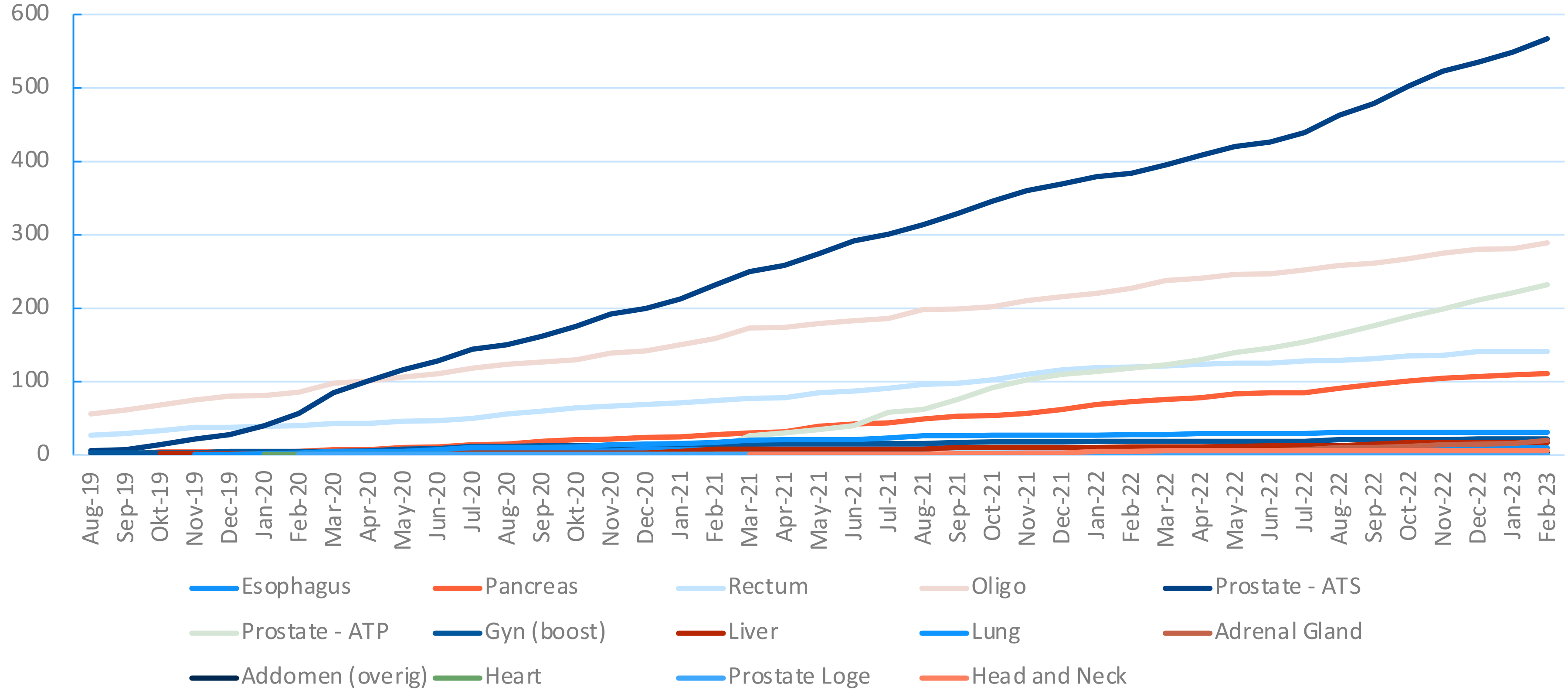
Is the dream real?

- Start radiotherapy immediately
- See cancer clearly before and during treatment
- Change radiotherapy as often as the internal anatomy moves
- Alter dose day by day depending on anatomy/biology
- Few fractions

- Full optimisation in 5 mins
- MRgRT
- CMM gating and baseline shift
- Powered by (fMRI) imaging and AI
- Zeker!

Elekta Unity treatments at UMC Utrecht

~1500 patients in ~10000 fractions



1. Prostate ATS
2. Lymph Nodes
3. Prostate ATP
4. Rectal Cancer
5. Pancreas

UMC Utrecht

52 Unity systems in clinical use

Elekta Unity

>120 orders

as of February 2023

100% treatments adapted

>40 indications treated

>55% SBRT

0.4% ≥ Grade 3 toxicity using full online adaptive workflow

<30 min to treat **Adaptive Radiotherapy**

99% uptime

Global network of **650 engineers and 165+** remote support specialists

MOMENTUM

3700+ patients recruited in MOMENTUM, a multi-center clinical registry

~12 patients per day are treated on a Unity system

>580 peer reviewed publications

22 open clinical trials

Only **2 RTT's** required for Elekta Unity utilizing **remote review** and **approval**

Elekta

[1] Patterns of Care and Safety in 1800 patients treated on a high-field MR-Linac platform registry. J. Westerhoff et al, ESTRO 2022 Abstract OC-0419 ESTRO. 0.4% treatment related toxicity for treatments using full online adaptive workflow CTCAE Grade 3; no Grade 4 or 5. Based on 1000 ATS patients

Conclusion

- MRI is the best, most flexible, fastest imaging option for RT
- Physics tests and results are well established
- Deformations and geometrical uncertainty are small.
- Unity and MRIdian provide MRgRT throughout the world
- Unity has 1.5 T MRI soft-tissue contrast and unprecedented plan adaptation.
- Fast imaging to enable automatic gating, tracking and adaptation
- Entirely new treatments become possible (targeted lymph nodes, pancreas etc)
- A new era
  - From elective to **ablative**
  - From invasive to **non-invasive**
  - **Personalized** radiotherapy