ICTP School of Medical Physics for Radiation Therapy: Dosimetry and Treatment Planning for Basic and Advanced Applications

LINAC MRI

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Benefits and Challenges of MRI

The challenge in radiotherapy is delivering dose to the tumour while the dose to the surrounding tissues is kept as low as possible

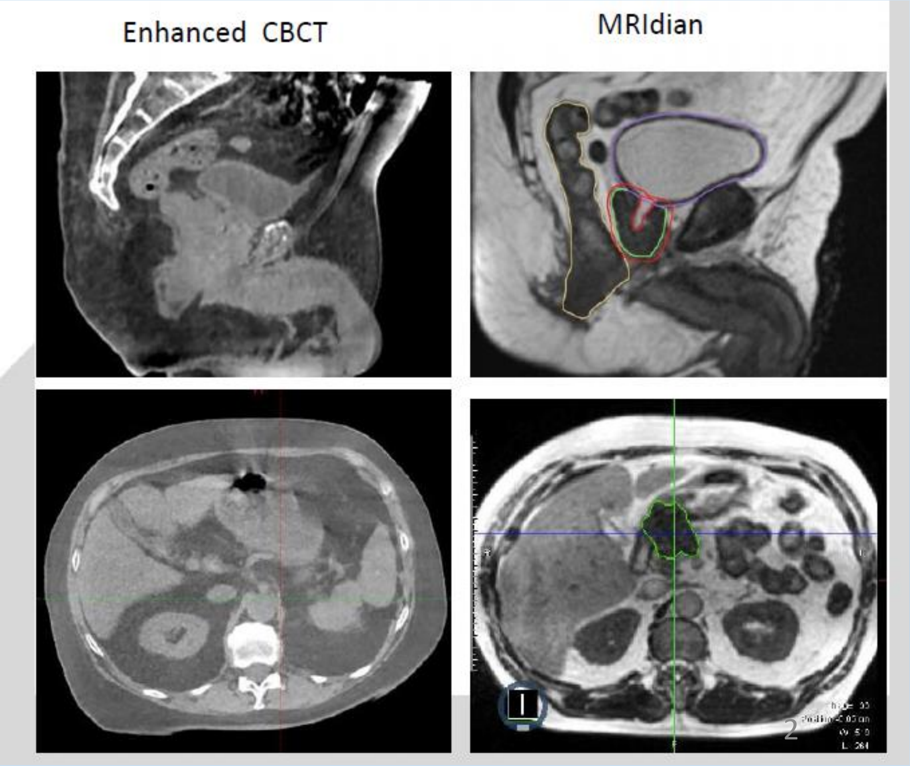
Tumour and OAR have inter-fractions and intra-fractions movements and modifications - inter-treatment shrinkage

Image guided radiotherapy (IGRT) is the key to optimize this process as it allows the localization of the tumour and organs at risk (OAR) while the patient is on the treatment table.

MRI is the most versatile and suitable candidate for IGRT as it provides soft-tissue contrast to enable direct tumour visualization as well as OAR localization

The best CBCT doesn’t compare with MRI for soft tissue delineation

Better inter and intra-fraction control



Incorporating MR for simulation & treatment planning increase the targeting precision and allows reproducible millimeter accuracy in soft tissue definition : **Potential to reduce Margins**

MR OBI (on board imaging) allows target and critical structure localization & tracking based on **gold-standard anatomy rather than fiducial markers**, bony anatomy or other surrogate as in CT

MRI in RT planning to the superior soft tissue differentiation added the capability of **functional imaging.**

Functional imaging (DCE/DWI) allows **dose painting** to high risk tumor volume for greater tumor control

Intra-fraction anatomic and functional imaging allows early **evaluation of tumor response** and **adaptive** treatment **escalation or de-escalation** to improve tumor control or treatment toxicity

To image biological and functional aspects of the body has the potential to provide **imaging biomarkers** of therapy response of tumor and normal tissue or both.

Towards a precise & personalized RTtherapy

Pancreas & liver : Avoidance of OARs suchas duodenum, small bowel,and stomach by studying the best approaches with cine MRIs and monitoring within-room MRI could allow significant increase in overall dose.

H&N :The availability of in-room MRI would address the issue of changing **hypoxia volumes** and locations within tumors and would allow for **online dose painting** of hypoxic areas if desired.
Volume adjustments would be routine as would be **individualization of dose**, which makes sense given the large variation of tumor size and burden in patients with head and neck cancers,and the **biologic differences of individual tumors**
Adjustments would allow better normal tissue sparing, particularly salivary gland sparing.
DWMRI could also allow for assessment of changes within the salivary glands predicting for late effects

MR LINAC SYSTEM

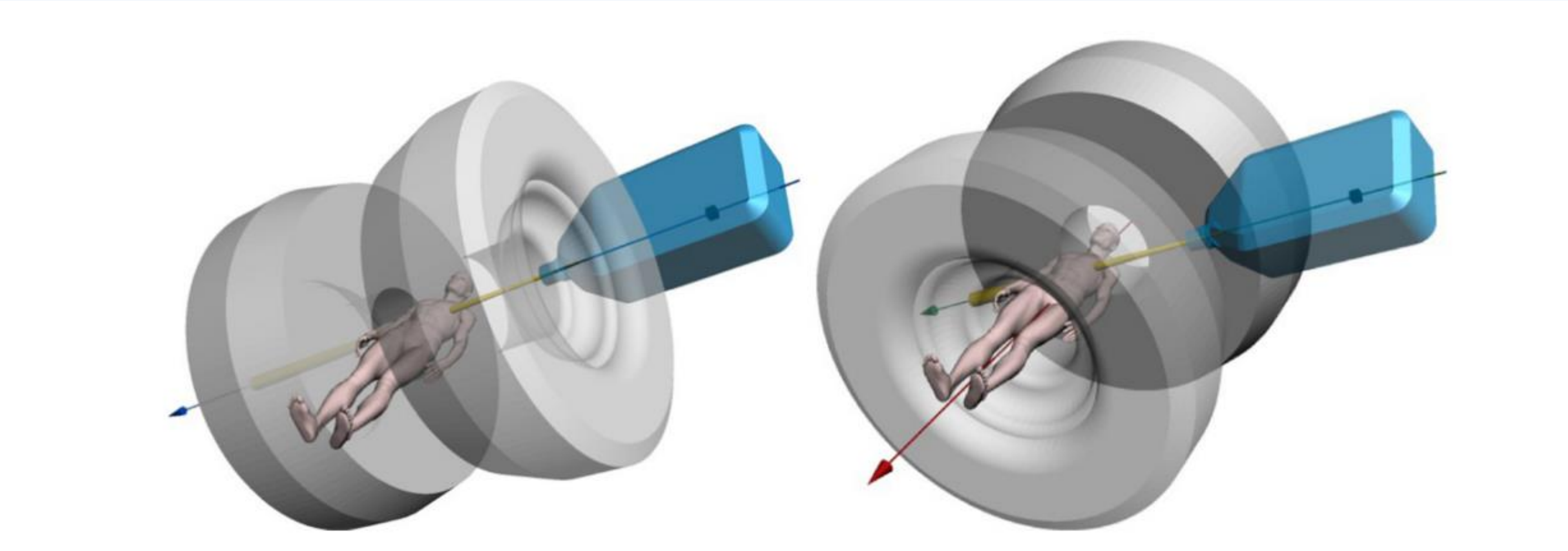
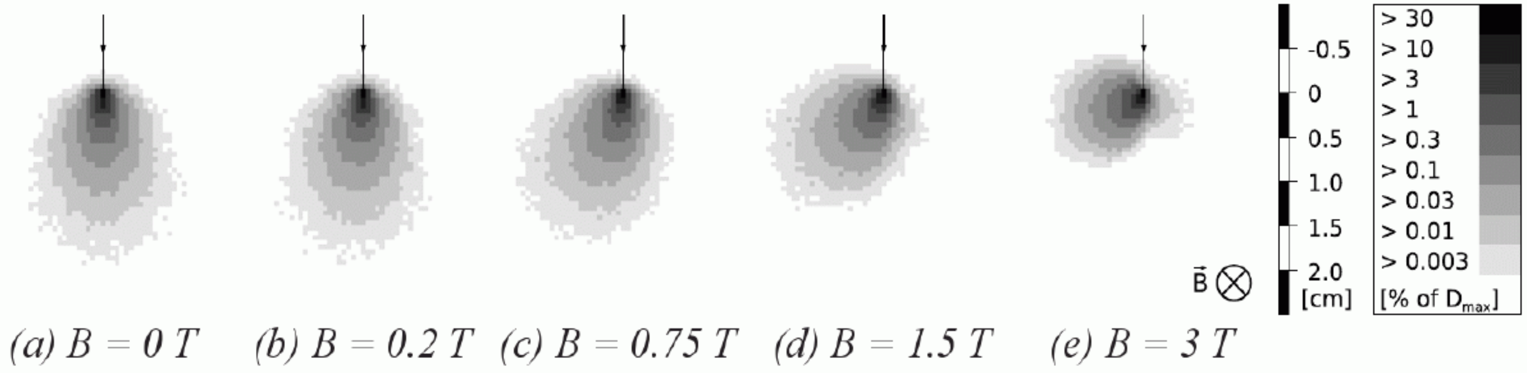


Table 1
Configuration details of each of the current MRI-linac systems in order of magnetic field strength

System (manufacturer)	Radiation	Field strength (T)	Magnet type	Orientation
Unity (Elekta)	6 MV	1.5	Closed superconductor	Perpendicular
Australian	4 & 6 MV	1	Open superconductor	Both
Aurora-RT (MagnetTx)	6 MV	0.5	Biplanar, high-temp superconductor with steel yoke	Inline
MRIdian (Viewray)	Co or 6 MV	0.35	Split superconductor	Perpendicular

Point dose kernels with and without a magnetic field



Raaijmakers et al. PMB 2008

The kernel of the secondary particles become more **asymmetrical** for increasing B field strength.

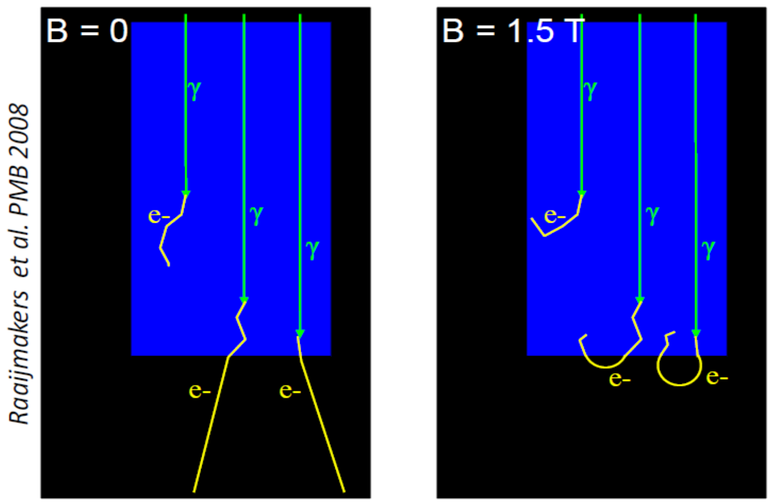
The penetration of the electrons becomes smaller

$$\boldsymbol{F}_{Lorentz} = q\,\boldsymbol{v} \times \boldsymbol{B} \qquad \boldsymbol{F}_{centripetal} = \frac{m\,\boldsymbol{v}^2}{r} \qquad q\,\boldsymbol{v} \times \boldsymbol{B} = \frac{m\,\boldsymbol{v}^2}{r} \qquad r = \frac{m\boldsymbol{v}}{q \times B}$$

Table 1. In-vacuum electron trajectory radius (in mm), depending on the electron energy and magnetic field strength.

Electron energy (MeV)	Magnetic field strength 0.2 T	0.75 T	1.5 T	3 T
0.5	14.5	3.9	1.9	1.0
1.0	23.7	6.3	3.2	1.6
1.5	32.4	8.6	4.3	2.2
2.0	41.0	10.9	5.5	2.7

The Electron Return Effect (ERE)



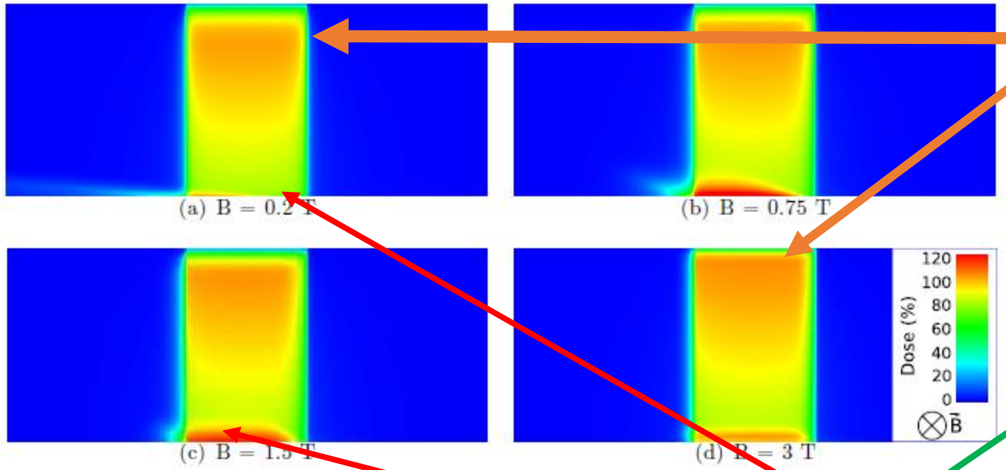


Figure 4. Dose distributions for a 5 × 5 cm^2 6 MV photon beam at the indicated magnetic field strengths.

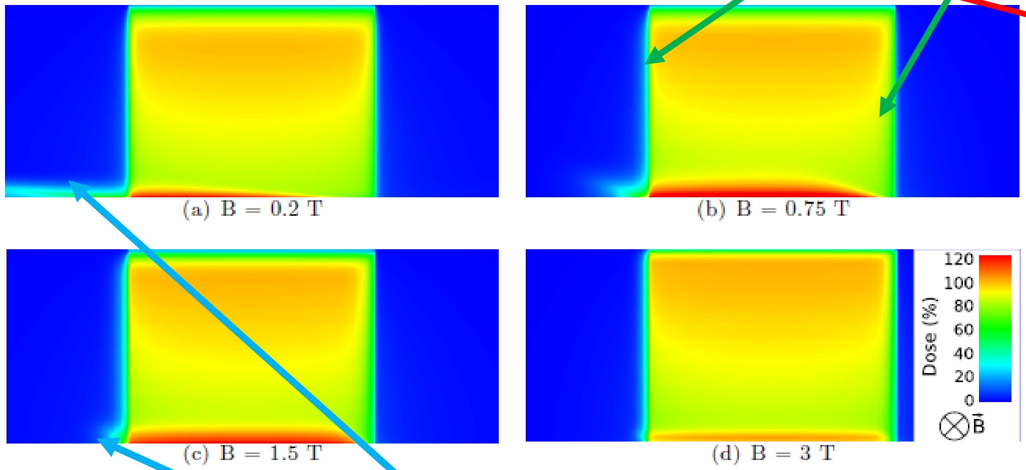


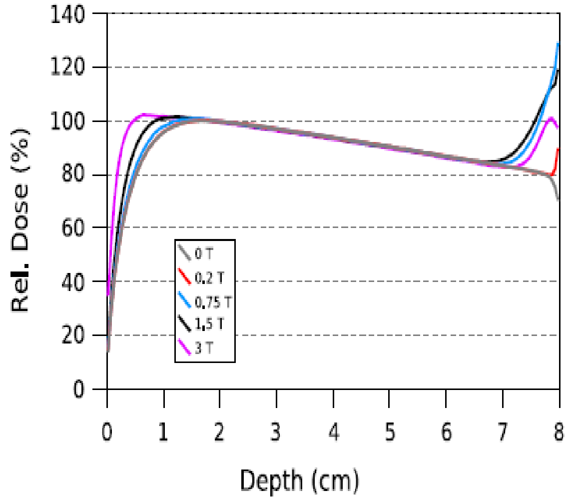
Figure 5. Dose distributions for a 10 × 10 cm^2 6 MV photon beam at the indicated magnetic field strengths.

The build-up distance decreased with the MF due to the ERE (the r is reduced)

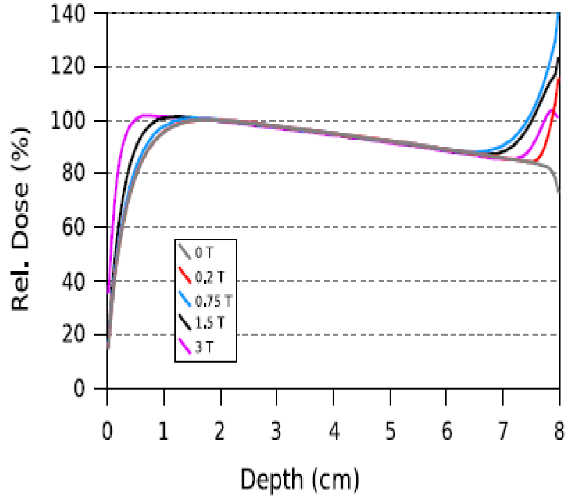
The penumbra is slightly shifted and asymmetrical

At tissue air interfaces, electrons can re-enter the tissue and increase the dose

At low MF the radius is the biggest one so the ERE effect is reduced

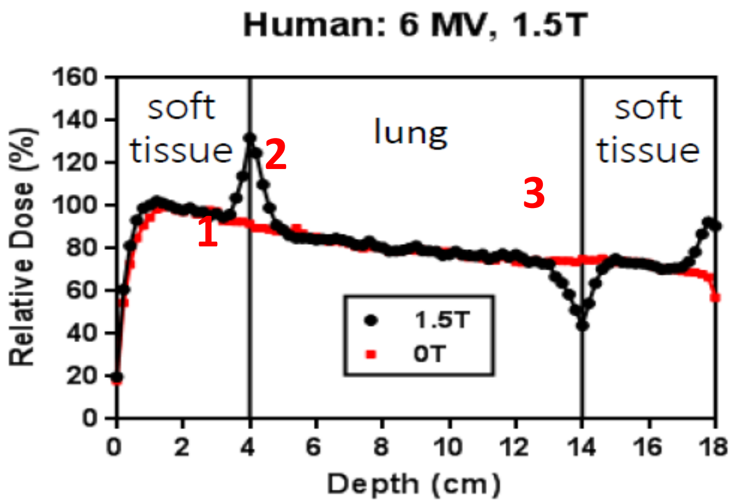


(a) 5×5 cm^2, central axis



(c) 10×10 cm^2, central axis

At Low MF the dose increase inside the field is reduced but the radius is large enough to deposit dose outside the filed



Rubinstein et al, *Med Phys*, 2015

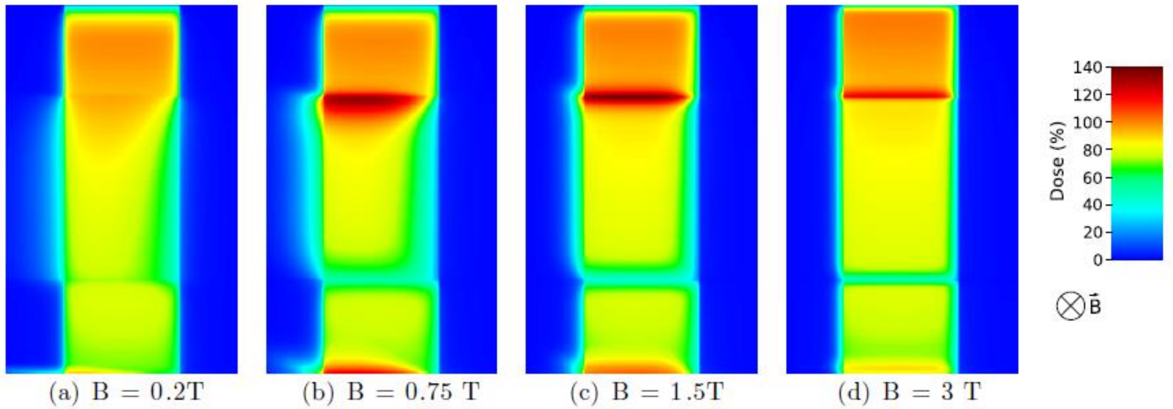
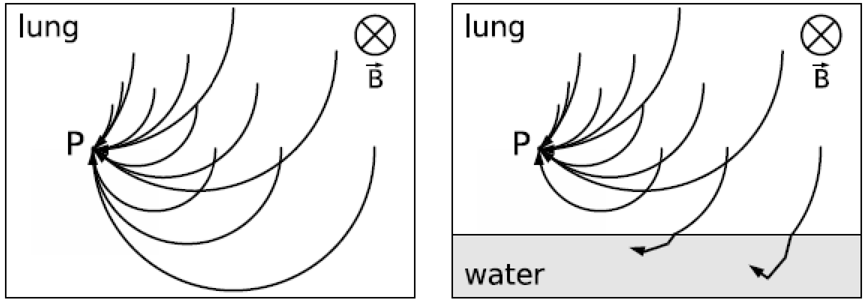


Figure 10. Dose distributions for a 5 × 5 cm^2 6 MV photon beam on a water–lung–water phantom at the indicated magnetic field strengths.

1 : increase due to the ERE
2 : increase for energy deposit by ERE scatter electron while returning to water
3 : decrease as some scattered electrons are intercepted in water



(a) (b)

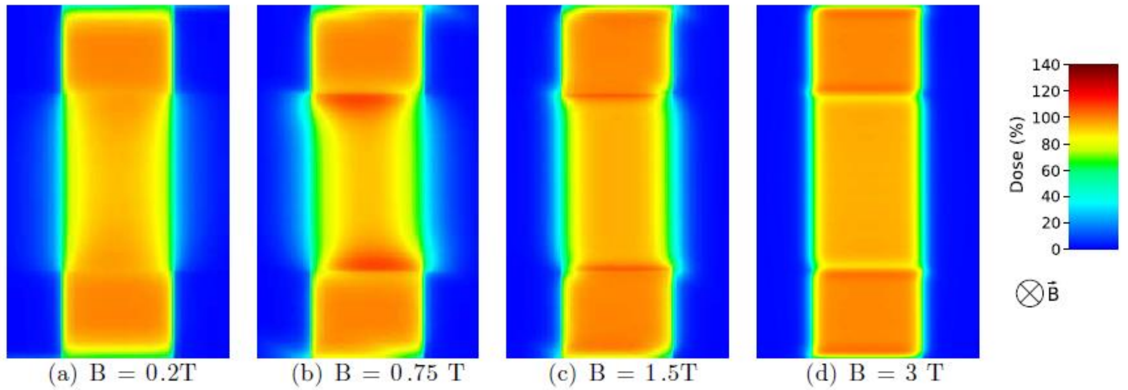


Figure 13. Dose distributions for two opposing 5 × 5 cm^2 6 MV photon beams on a water–lung–water phantom at the indicated magnetic field strengths.

Opposit beams can compensate

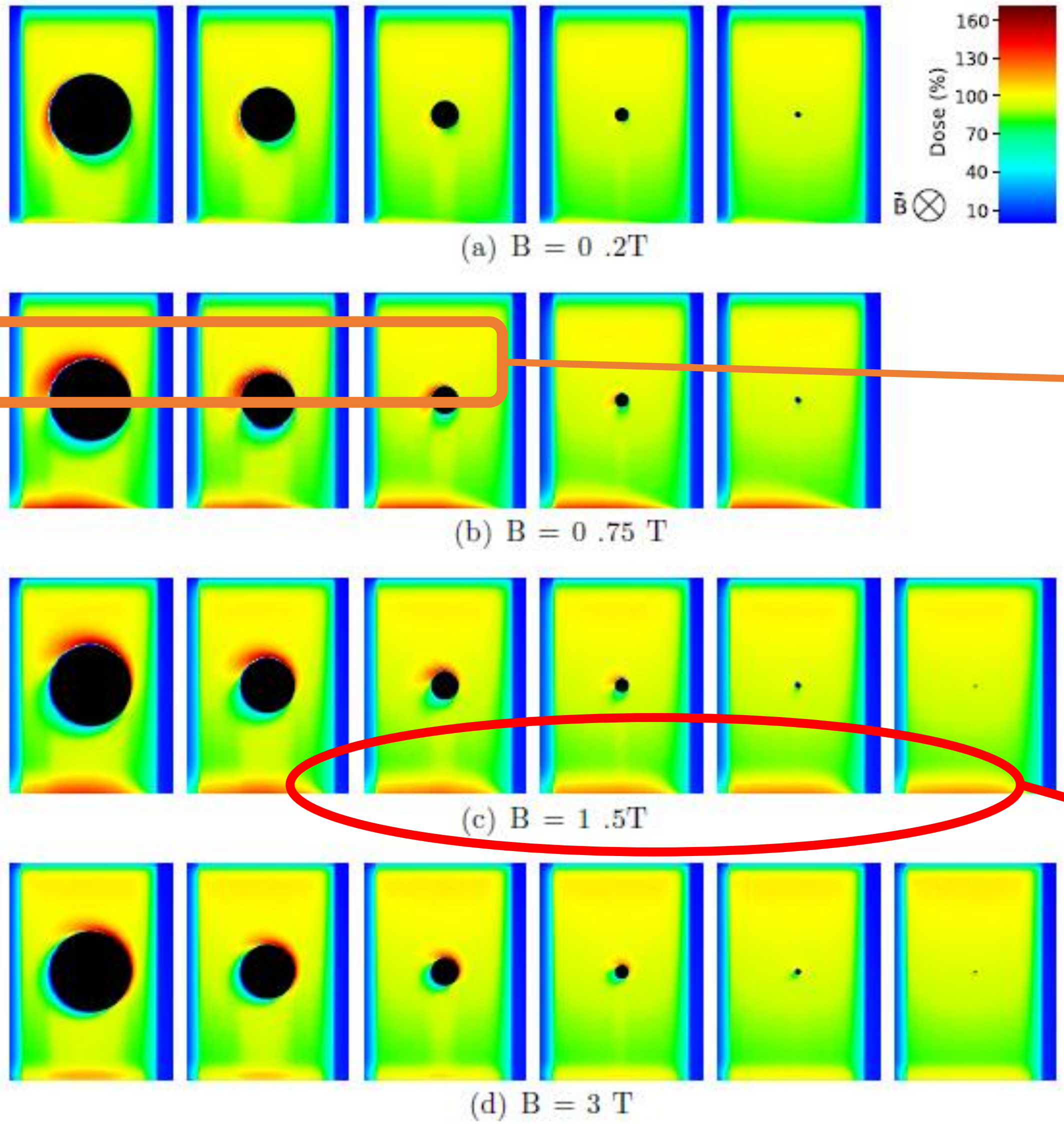
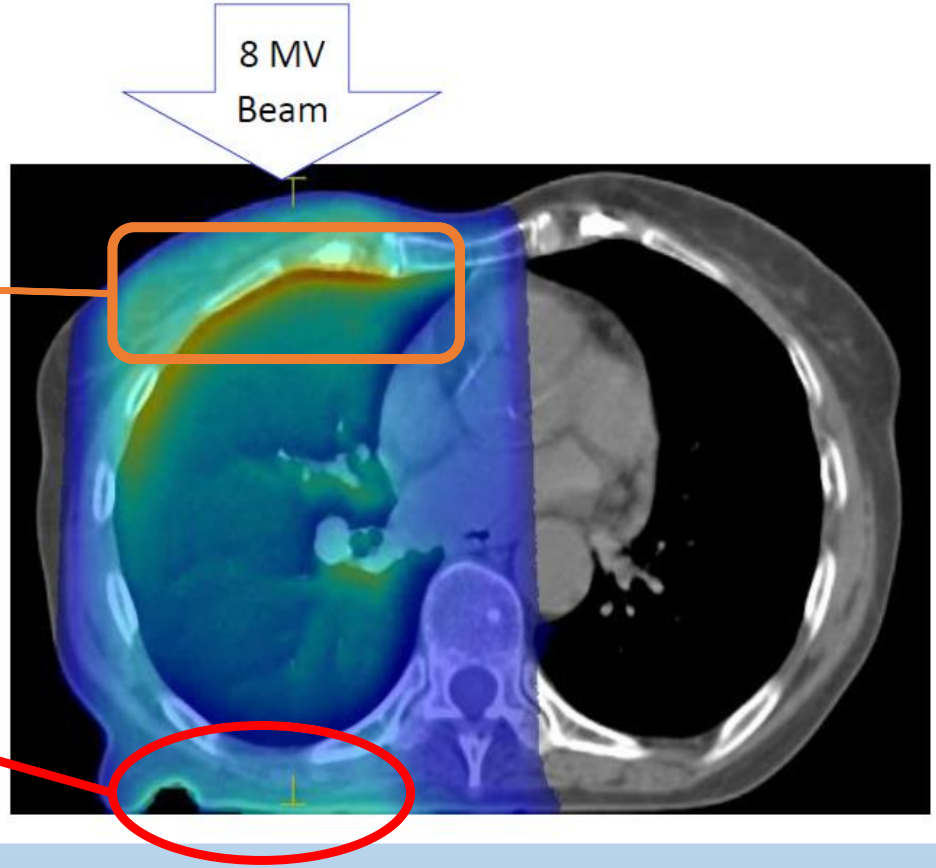
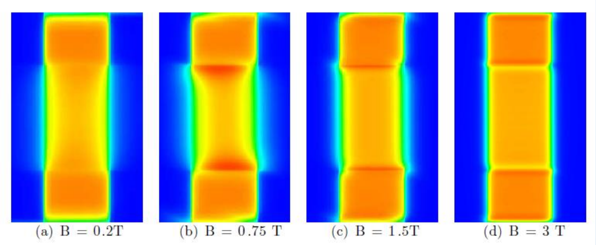


Figure 9. Dose distributions for a 5 × 5 cm^2 6 MV photon beam on a water phantom with air cavity (diameter: 30, 20, 10, 5, 2 and 1 mm) at the indicated magnetic field strengths.



Account for perturbations in treatment planning

1. Parallel opposite fields



2. IMRT

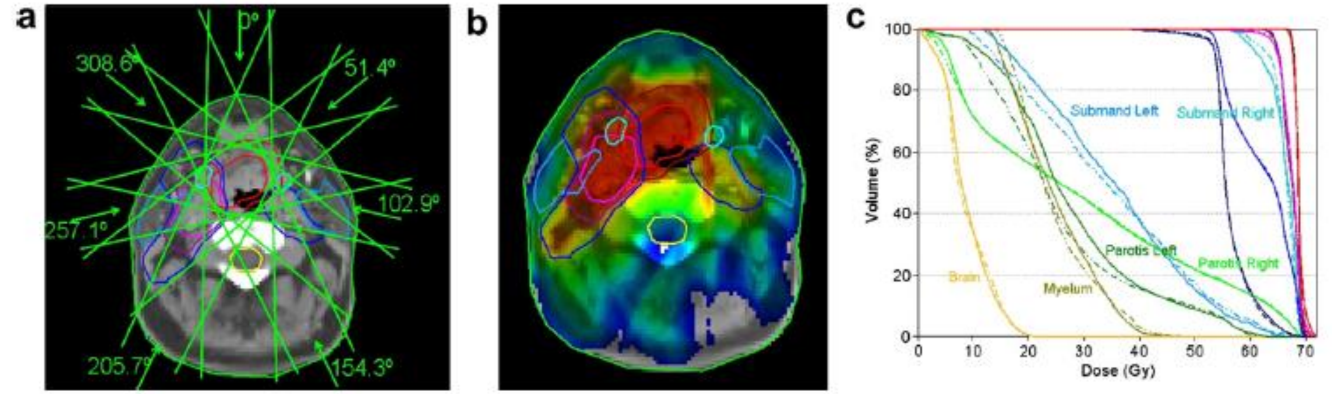
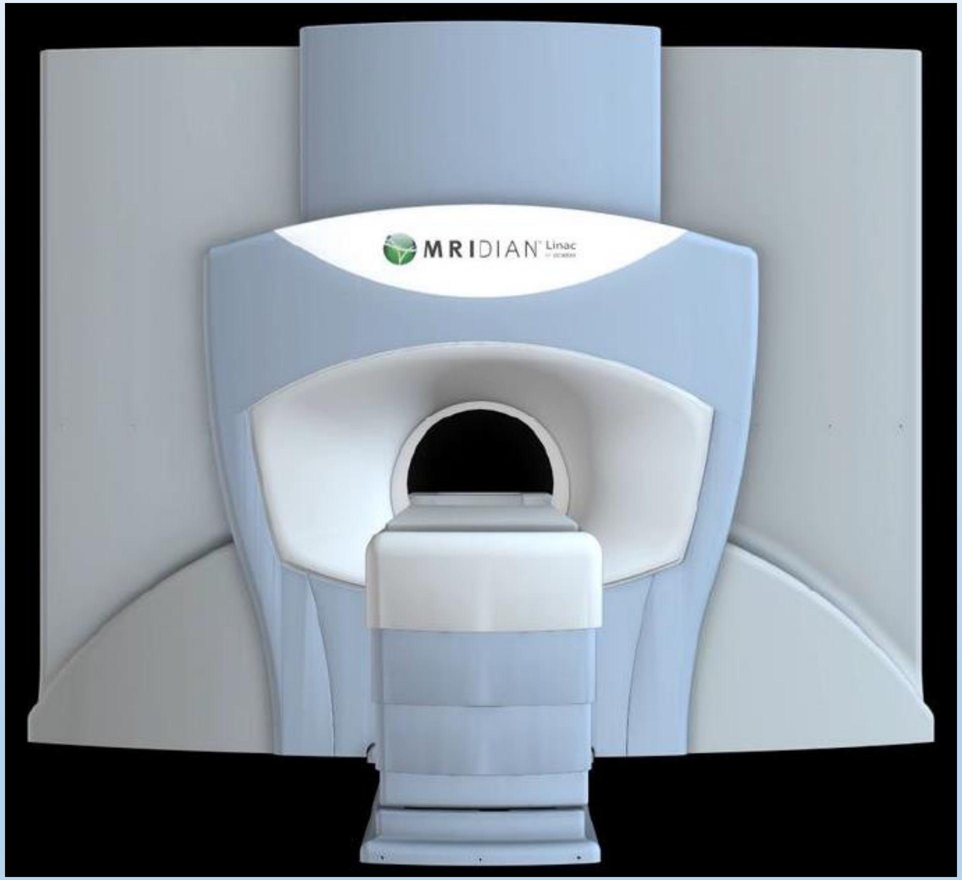


Fig. 3. Oropharynx, seven beam IMRT, Orbit RaySearch optimization, beamlets computed with Geant4. (b) IMRT dose distribution in a 1.5 T MRI, (c) DVH comparison of $B = 0\,T$ to $B = 1.5\,T$.

3. Monte Carlo based treatment planning

MRIdian - Viewray



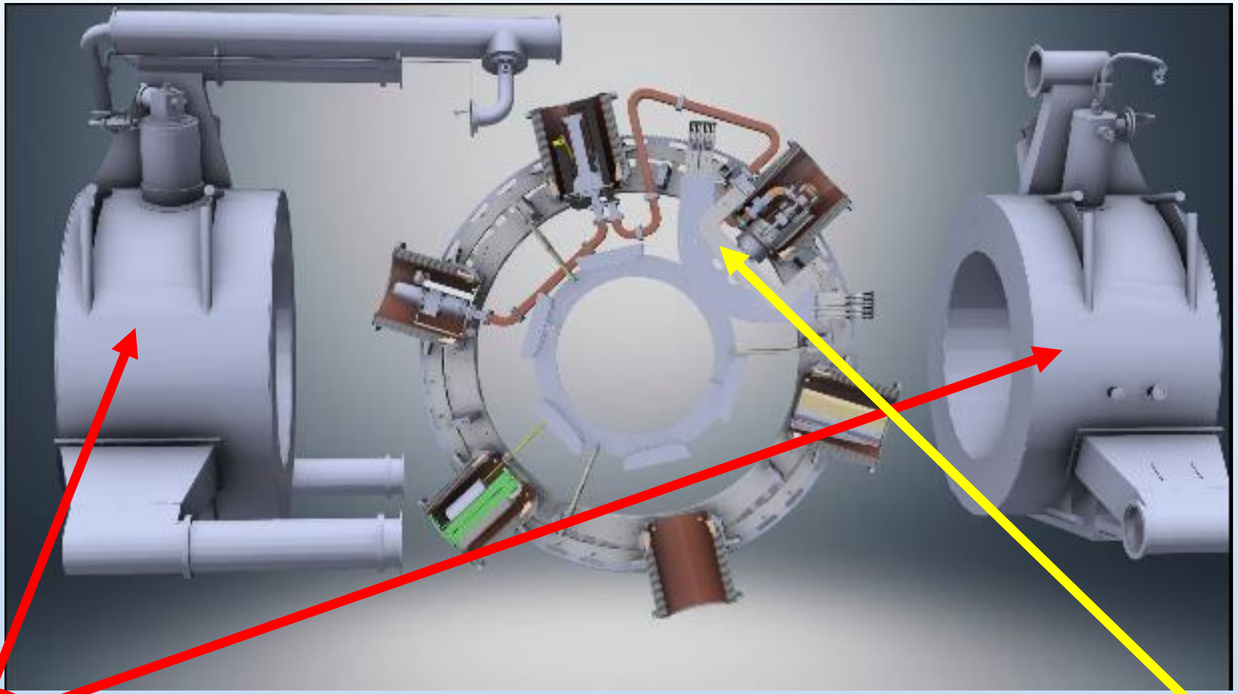
Is an integrated magnetic resonance (MR)–guided radiation therapy (RT) system

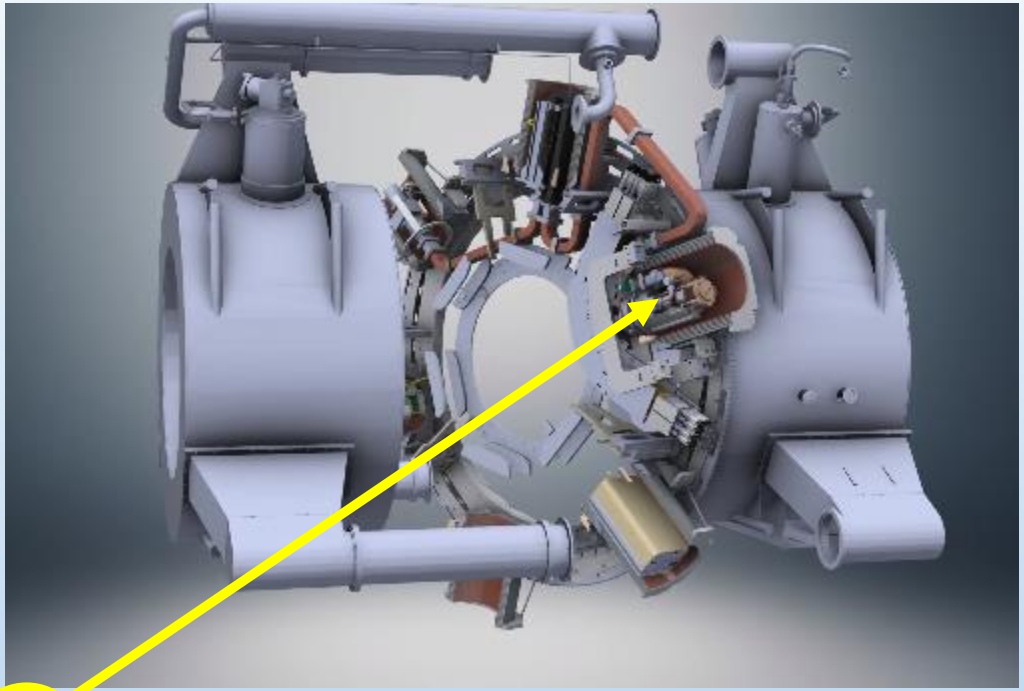
designed to provide

simultaneous MR imaging(MRI)
&
external-beam RT

at the same isocenter.

MRIdian - Viewray





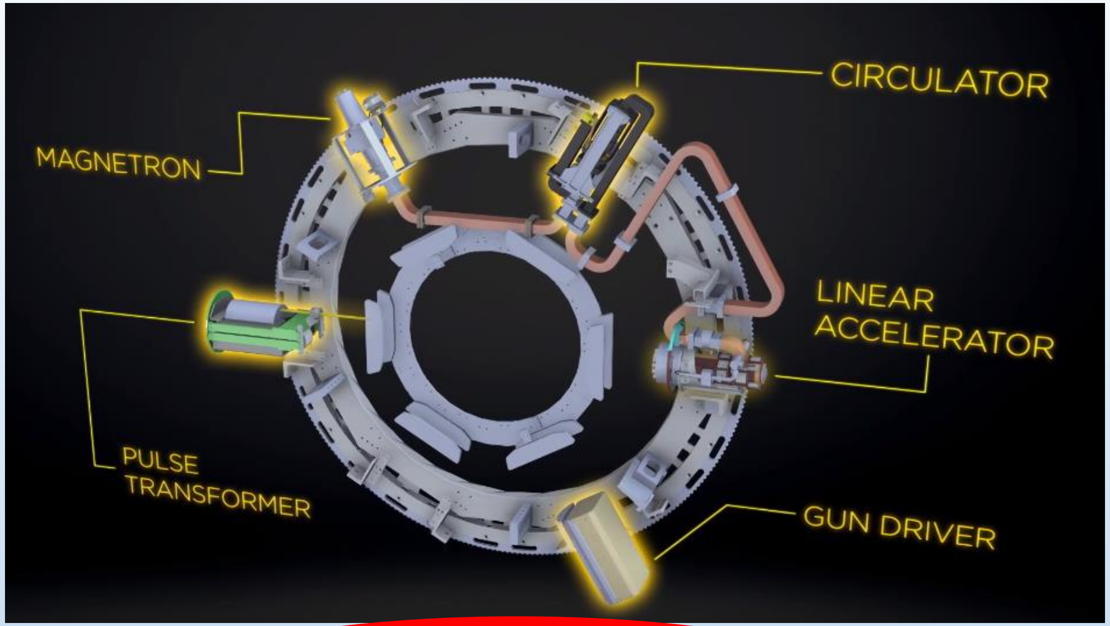
1. Split magnet design to allow beam penetration : gap equal to the maximum field aperture B =0,35T

2. A gantry ring for LINAC components: 6 bays where magnetic field sensitive elements can be placed

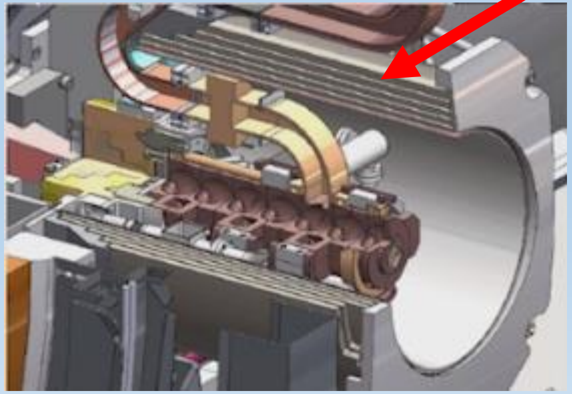
A system developed to minimize the interferences between MRI & LINAC:

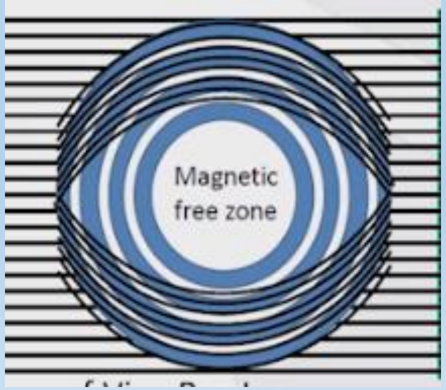
- Effects of the magnetic field on the electrons: Hide the linac from the MRI
- Effects of LINAC components on MR image quality : Shielding linac and its components

MR on Linac effects

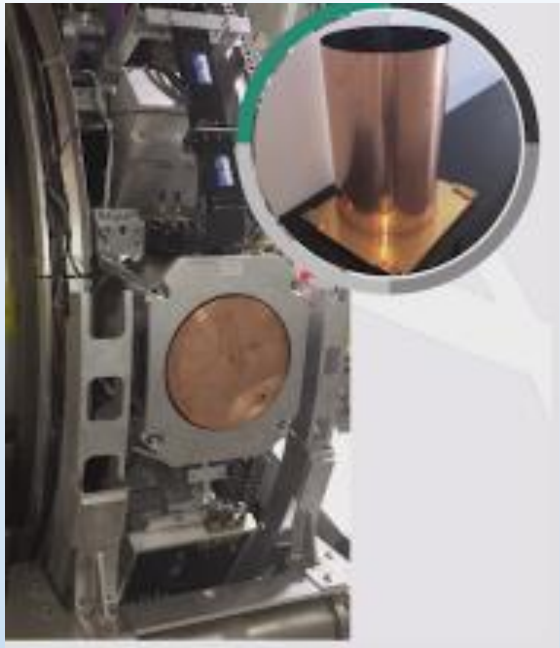


HIDE THE LINAC FROM THE MR
5 concentric cylindrical ferromagnetic (steel) shields + 3 mu-metal





LINAC on MRI effects



1. RF shielding elements :sleeve made of layers of reflecting and absorbing materials (carbon fibers and copper)

2. Add Shimming system to eliminate non static component

3. Image acquired only at static MLC and gantry

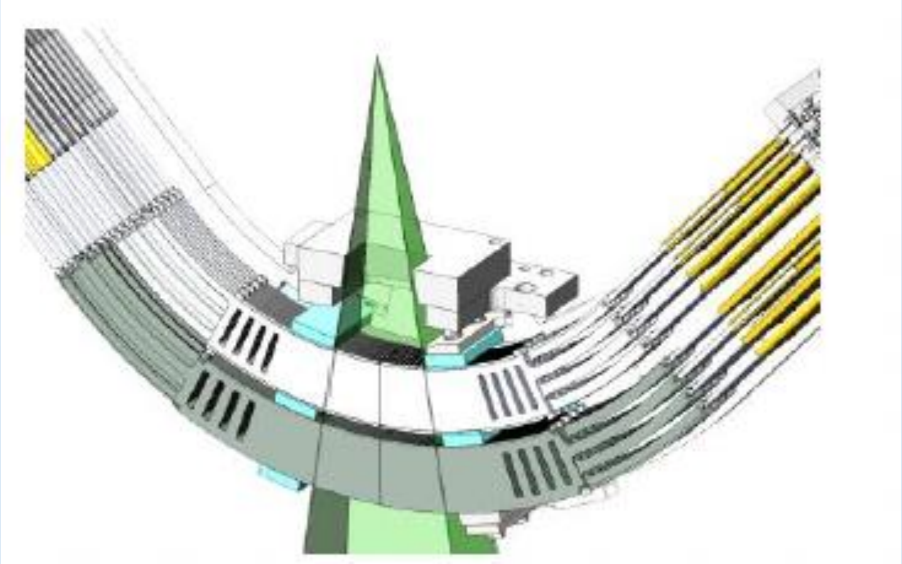
MRIdian Specifications

- Compact inline S-Band 6 MV Linac
- Flattening filter free
- Isocenter distance: **90 cm**
- 360^o treatment around patient
- Dose rate: > **600 cGy/min** in water @ 90 cm SAD
- 138 leaf Double-focus, Double-stack MLC
- 68 leaf upper stack; 70 leaf lower stack
- Leaf width **4 mm**
- Upper stack offset by ½ leaf width
- Leaf width at the isocenter **2 mm**
- 4 cm/sec leaf speed
- Full leaf overtravel and interdigitation capability
- Maximum field size: 27.4 cm x 24.1 cm
- Minimum field size 2mm x 4mm
- Delivers IMRT, SBRT, Conformal therapies

- **0.35 T** Split superconducting magnet
- Bore size: 70cm

MRIdian Functionality

- Image during treatment
- Daily Adaptive Replanning
- Real-time imaging with gated delivery



MRIdian : Advantages of 0.35T MRI for RT

- Minimal perturbations of the dose distributions and surface doses

  Dose distortion from Electron Return Effect (ERE) is clinically insignificant $r \propto {}^{1}/_{Bo}$

  ➡ TPS, MC calculation, takes into account the effect even if small

- No SAR (tissue heating) issues from repeated MRI

- Sub-millimeter chemical shift and susceptibility distortions $\Delta x \propto B_0$

- Short T1 tissue relaxation time enables fast MRI

- MRIdian Linac setup images and cine show no artifacts

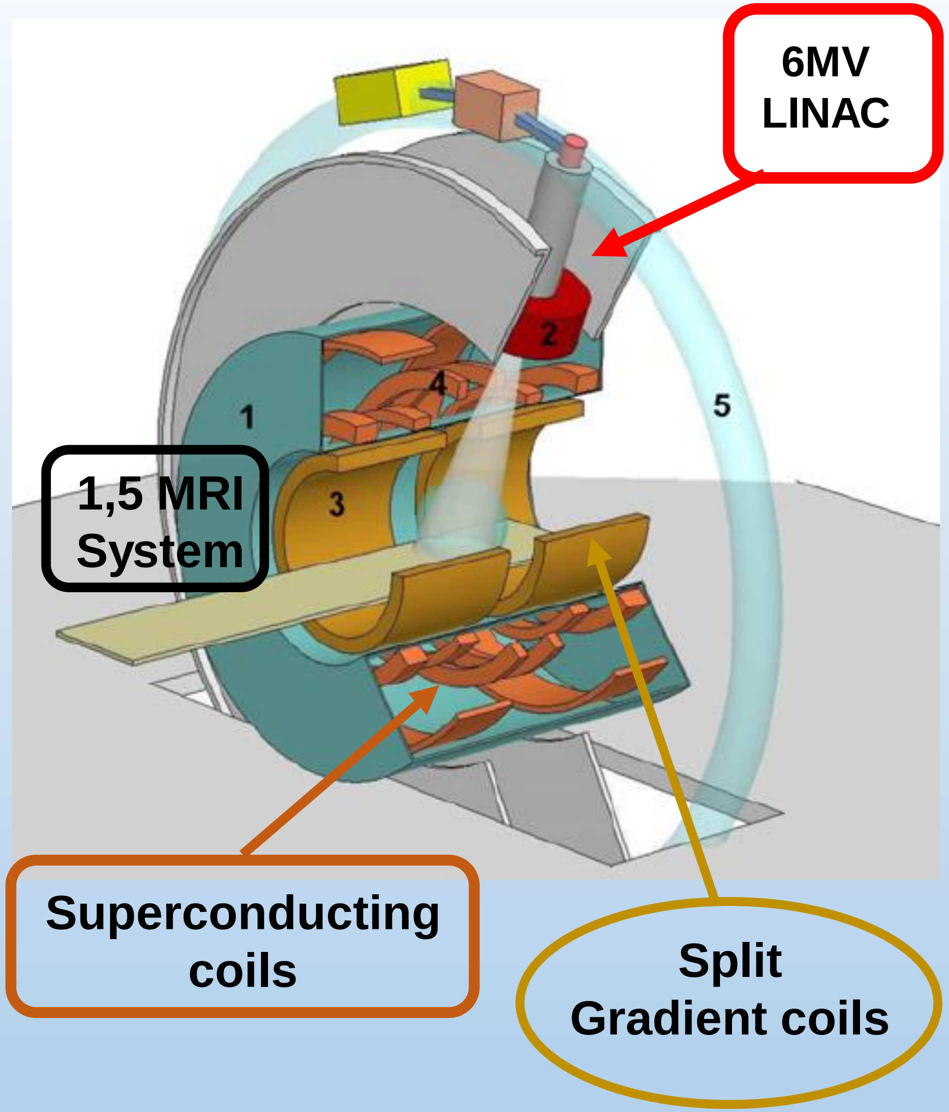
Unity - Elekta

Is an integrated magnetic resonance (MR)–guided radiation therapy (RT) system

designed to provide

simultaneous MR imaging(MRI)
&
external-beam RT

at the same isocenter.

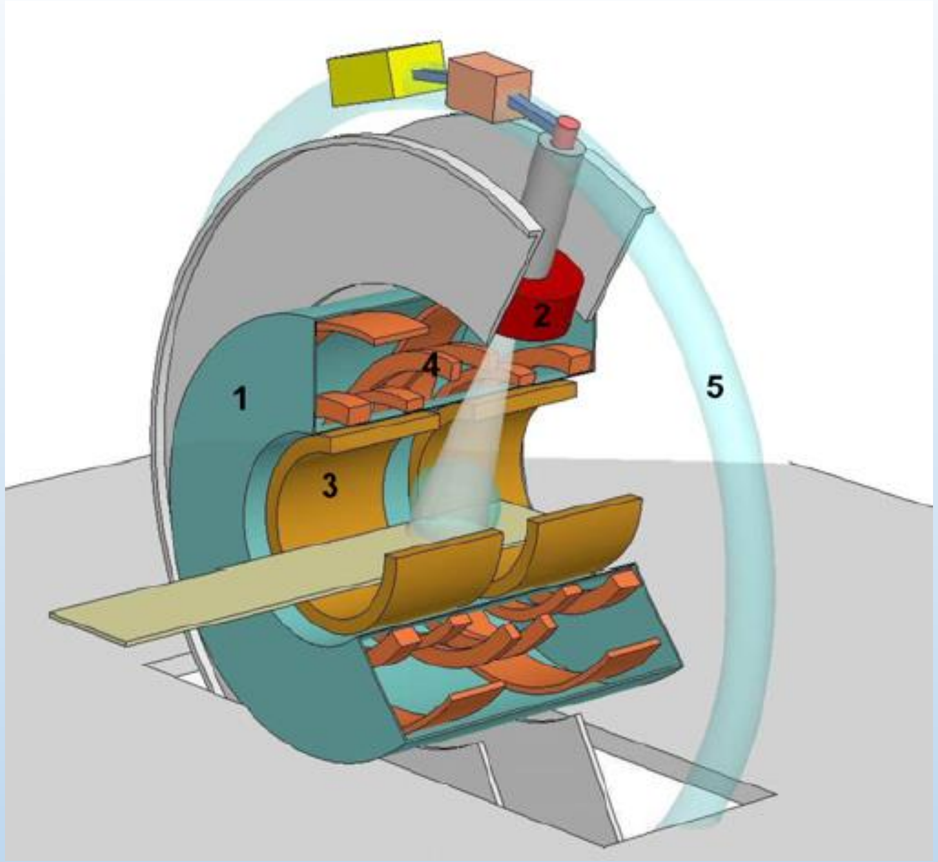


Unity MRI is composed by a 6 MV Elekta (Crawley, UK) accelerator mounted on a ring around a modified 1.5 T Philips Achieva (Best, The Netherlands) MRI system.
SAD =1,5 m

The Philips Achieva is replaced by the the 1.5 T magnet built by Magnex (Oxford, UK) modified to make the system compatible with a linear accelerator in perpendicular configuration

A ring gantry, which holds all the beam generating components, such as the magnetron, waveguide, a standing wave linear accelerator, and the Multi Leaf Collimator (MLC), is positioned around the cryostat.

The accelerator is modified by replacing various steel components by non-ferromagnetic copies.



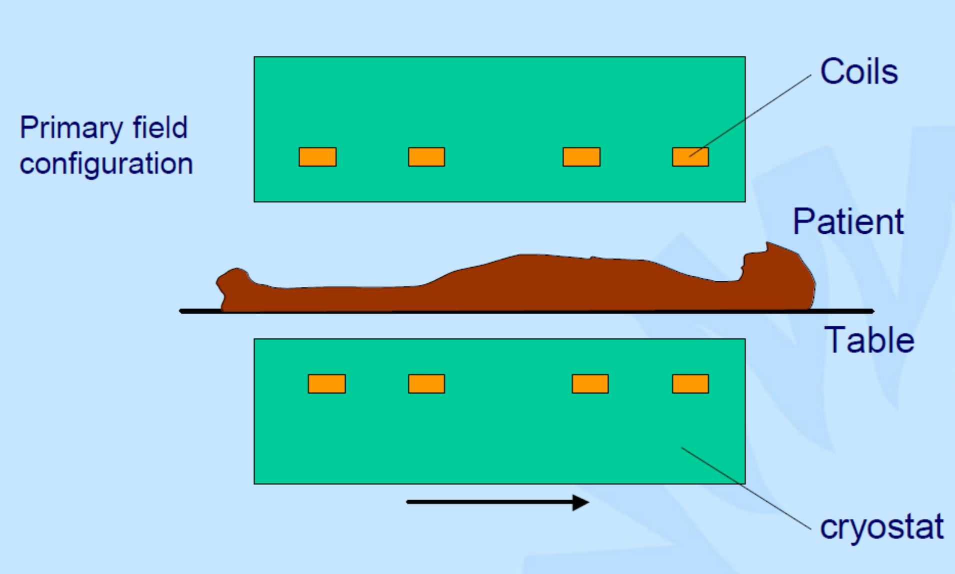
The active shielding of the magnet has been modified to create a torus of near zero magnetic field around the magnet at the location of the sensitive electronic components, waveguide, and the gun of the Linac.

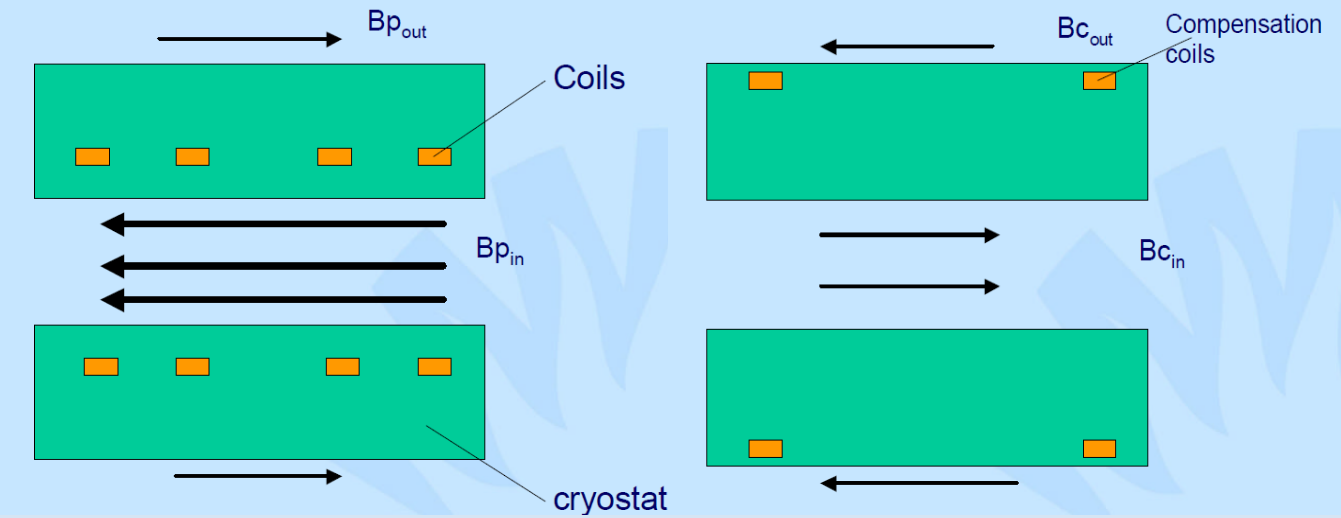
The cryostat has been integrated into the Faraday cage to minimize radiofrequency interference of the Linac components on MR signal acquisition.

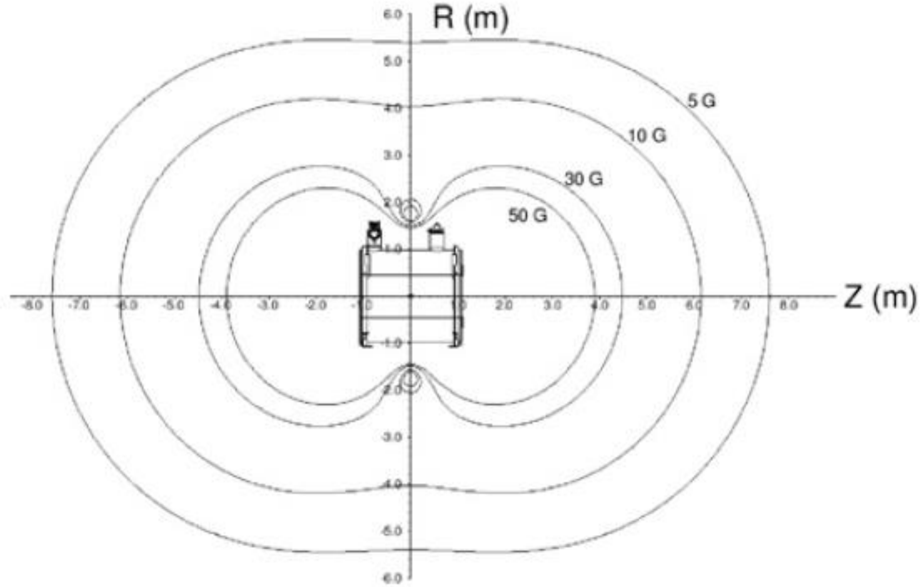
The cryostat and B0 coils have been modified to minimize beam attenuation, and the gradient coils are physically split, which creates a radiation window of 22 cm at isocenter.

The radiation beam travels through the closed-bore MRI before it enters the patient.

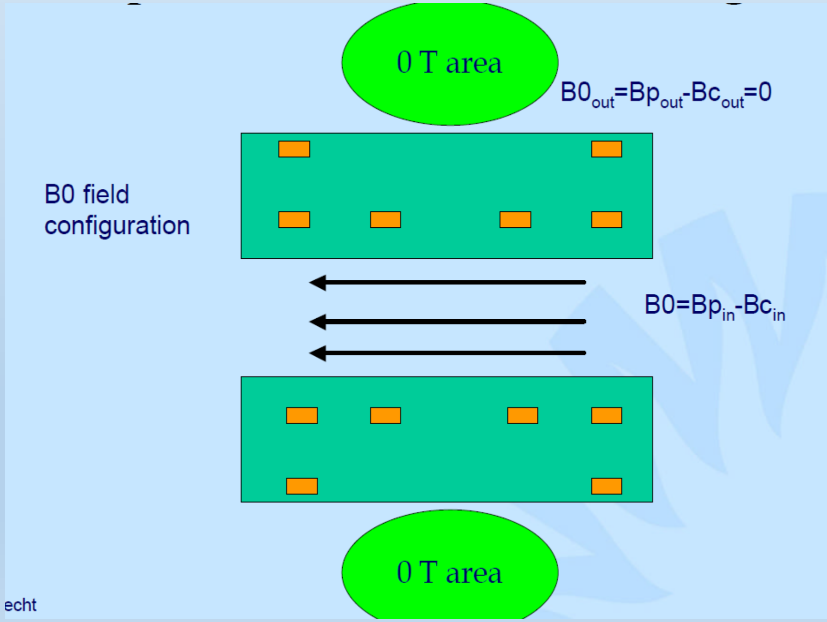
The system is equipped with a 2 4 channel radiolucent receive array (coil), with electronic components placed outside the radiation window to minimize attenuation and radiation induced currents that may impact image quality

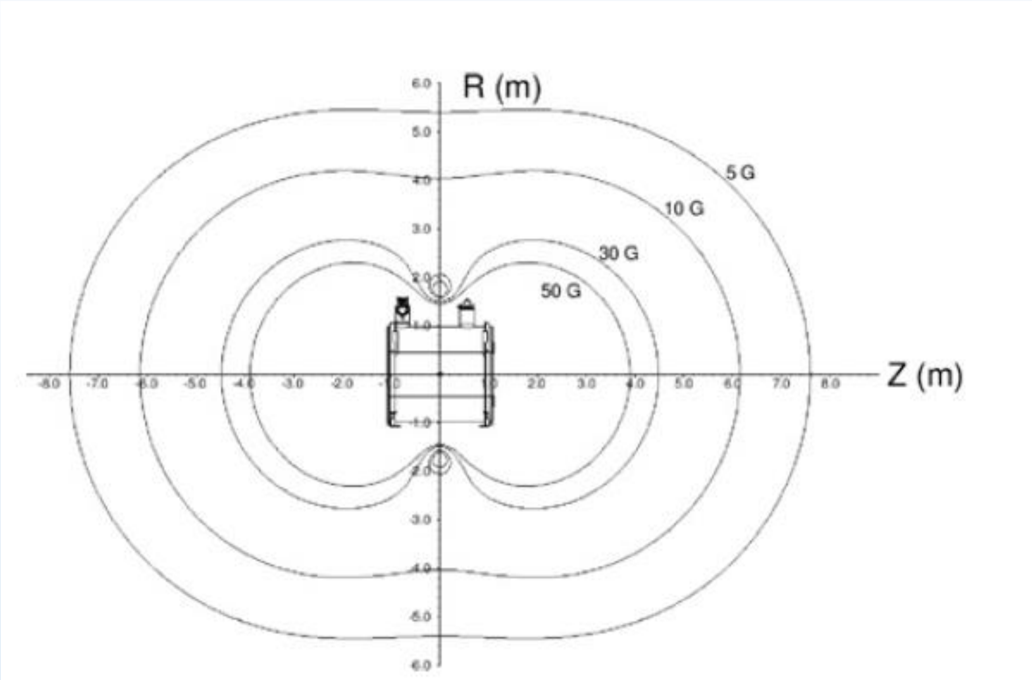


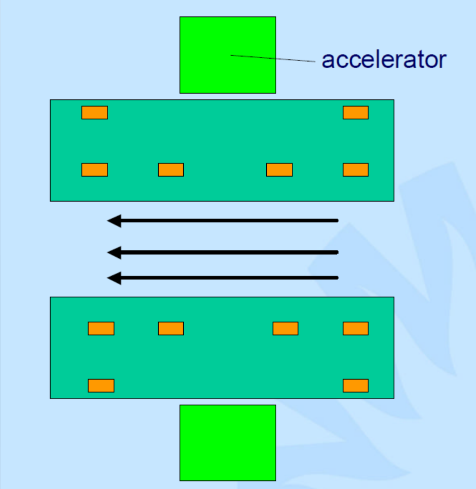


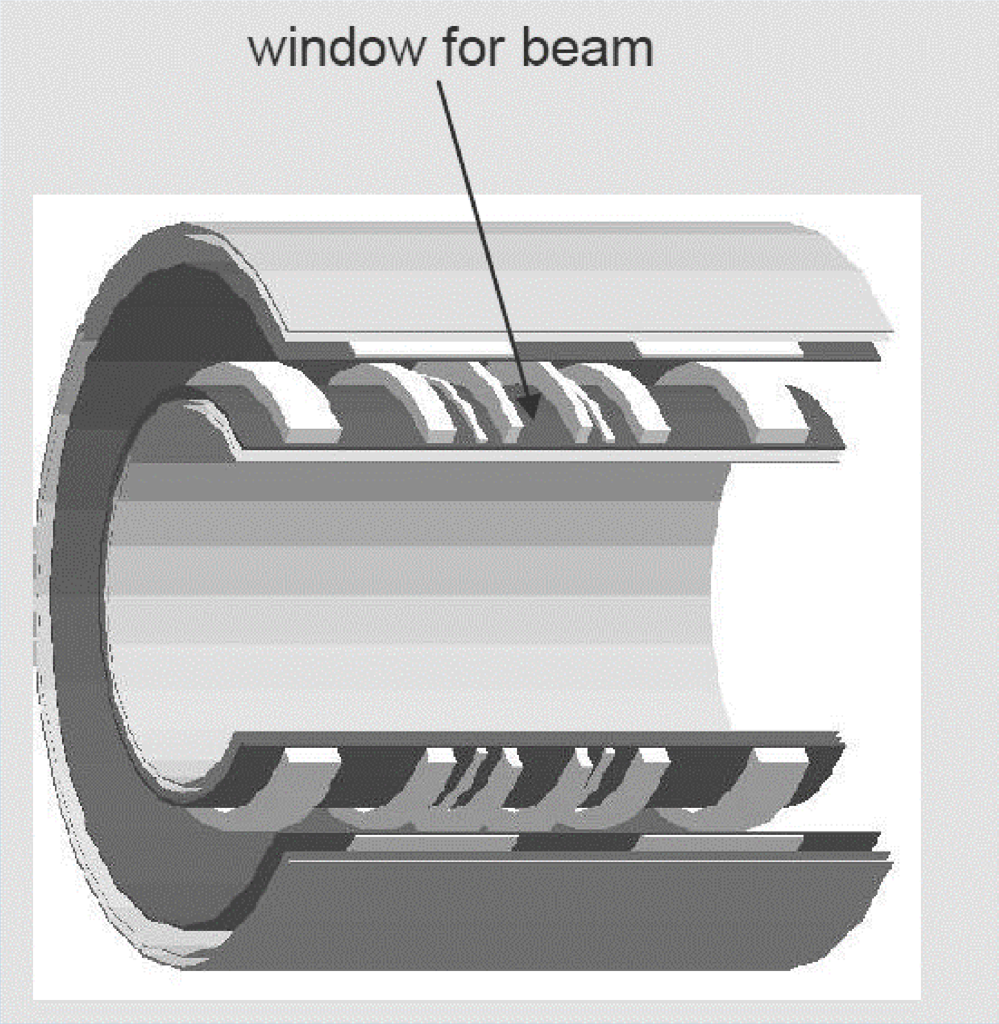


(b) Fringe field around the magnet.




R (m)
Z (m)
5 G
10 G
30 G
50 G


accelerator


window for beam

MRIdian Linac Specifications

- Compact inline S-Band 6 MV Linac
- Flattening filter free
- Isocenter distance: 90 cm
- 360º treatment around patient
- Dose rate: > 600 cGy/min in water @ 90 cm SAD
- 138 leaf Double-focus, Double-stack MLC
- Leaf dimension 4 mm /2 mm at isocenter
- 4 cm/sec leaf speed
- Full leaf overtravel and interdigitation capability
- Maximum field size: **27.4 cm x 24.1** cm
- Minimum field size **2mm x 4mm**
- Delivers IMRT, SBRT, Conformal therapies

- **0.35 T** Split superconducting magnet
- Bore size: 70cm

Unity Linac Specifications

- 6 MV Linac
- Flattening filter free
- Isocenter distance: **143,5 cm**
- 360º treatment around patient
- Dose rate: > 450 cGy/min at dmax & SAD
- MLC Agility
- leaf dimension =7 mm at the isocenter
- 6 cm/sec leaf speed
- Full leaf overtravel and interdigitation capability
- Maximum field size: **22 cm x 57,4** cm
- Minimum field size **5mm x 5mm**
- Delivers IMRT, SBRT, Conformal therapies

- **1,5 T** Split superconducting magnet
- Bore size: 70cm

QC _Hybrid test

The direction of the main magnetic field must be verified as it determines the direction of dose kernel tilt and the electron return effect (ERE).

Measure the B_0 homogeneity as a function of gantry angle. Because the gantry contains large amounts of ferromagnetic material, the gantry can introduce spatially varying offsets to the B_0 field, which could lead to image artifacts.

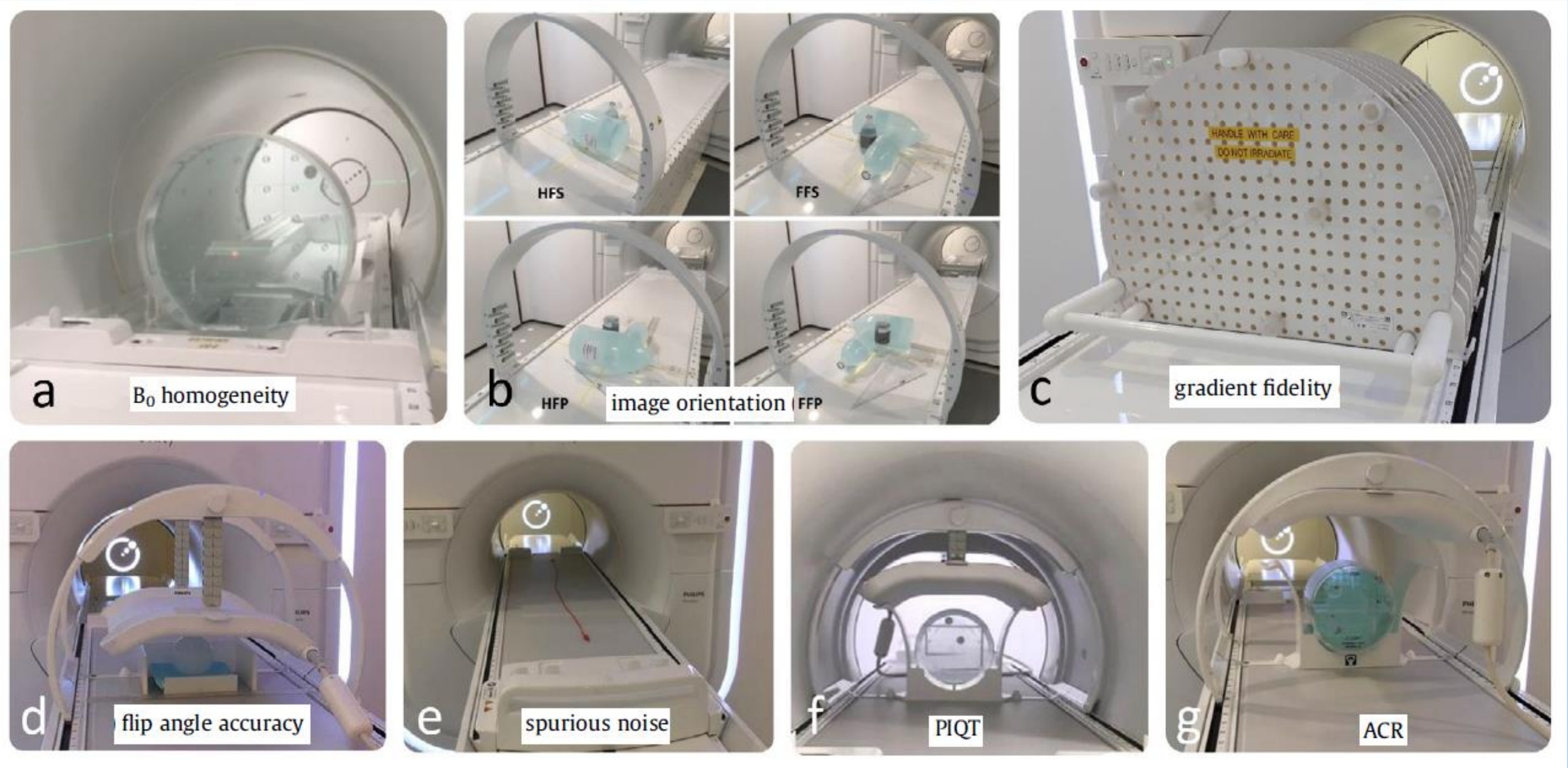
RF interference produced by the Linac is tested.

Noise only scans (i.e., images acquired without RF excitation) are acquired

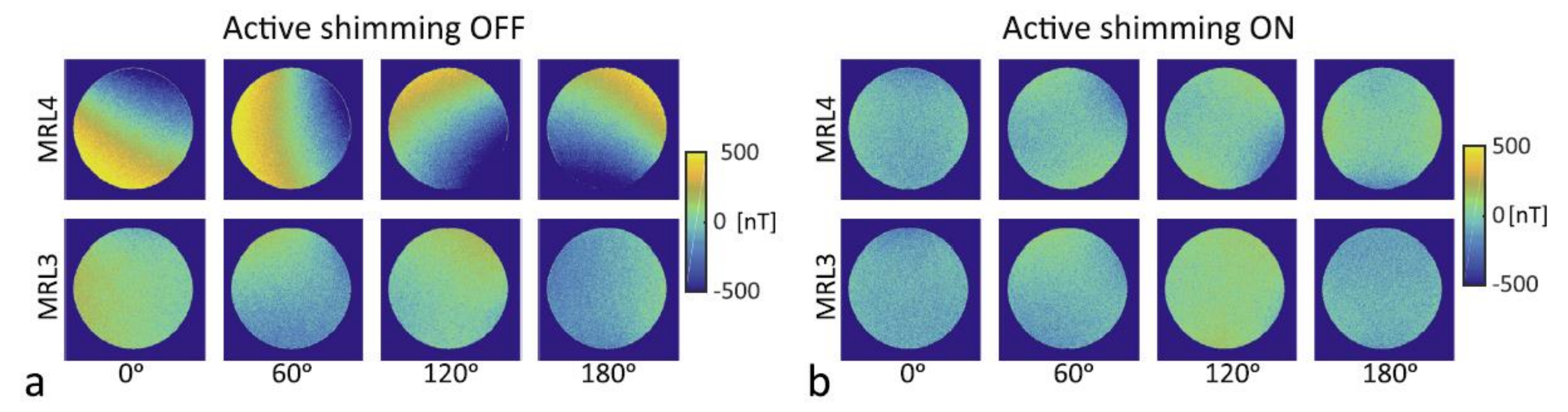
1) with the Linac turned off,
2) with the magnetron turned on, but without radiation,
3) with moving MLCs

Additionally, phantom scans and noise only scans were performed during irradiation of various field sizes to test the effect of pulsed radiation on the receiver coils

Suggested Test



B0 homogeneity as a function of gantry angle



The B0 field maps, with and without active shimming, at various gantry angles

MRL#4 shows an apparent linear field offset that rotates with the gantry angle when no active shimming is performed (top row, panel a).
The dependency is largely mitigated after active shimming (top row, panel b).

MRL#3 (second row) : effect of gantry angle was not observed for, excellent B0 homogeneity with and without active shimming.

#1 Clinical applications MRIdian Viewray

Inter- and intra-fractional organ changes entail major problems for the safe delivery of intended doses in EBRT for tumours located in the abdominal and pelvic region, especially for hypofractionated schemes.

- ❖ Variability in rectum and bladder filling has been observed for patients treated for prostate cancer
- ❖ lower biochemical tumour control was reported for patients with larger rectum volumes at the time of the CT simulation presumably because of geographic misses.

- ❖ Mean prostate displacements of up to 9mm between fractions with the largest deviation found in the anterior-posterior (AP) direction are reported by interfractional prostate variability investigations

- ❖ Seminal vesicles, included in the target volume for intermediate and high risk disease patients, are subjected to even larger inter-fractional shifts than the prostate

- ❖ Intra-fractional rotations and deformations of prostate and seminal vesicles because of variable rectal filling have been reported.

Daily image-guided radiotherapy (IGRT) improves the precision and accuracy of treatment delivery for prostate cancer

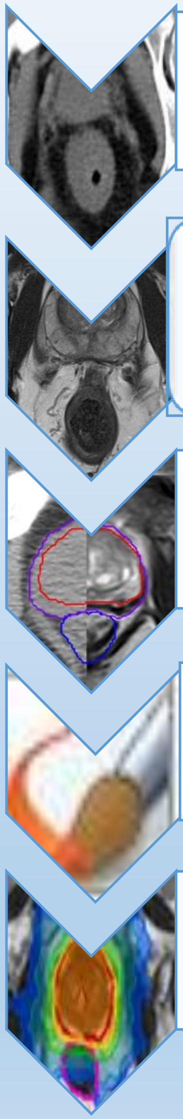
- MR-guided radiation therapy (MRgRT) allows for superior visualization of the prostate, base of the seminal vesicles and adjacent OARs such as the rectum and bladder **prior to- and during treatment delivery**.

- Proper management of inter- and intra-fractional variations allows for treatment **with small uncertainty margins** and in combination with daily plan re-optimization may result in relevant reductions of doses to normal tissues

.

Viewray -workflow

Simulation



- CT scan

- MR1 scan
- FISP short TR and TE=TR/2
- TR/TE =3,37/1,45 FA 60°

- CT-MRI Deformable registration

- Contouring
- Map density registration

- MC Baseline plan

Each fractions: on line adaptive

- MR##

- Rigid Registration MR## & MR1

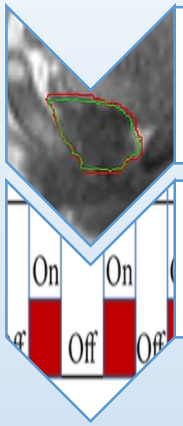
- Contouring CTV

- Deformable registration MR## & MR

- CT Deformable registration
- Deformed electron density map.- pseudo CT

- Predicted Plan
- Adapted Plan
- MC QA

Treatment



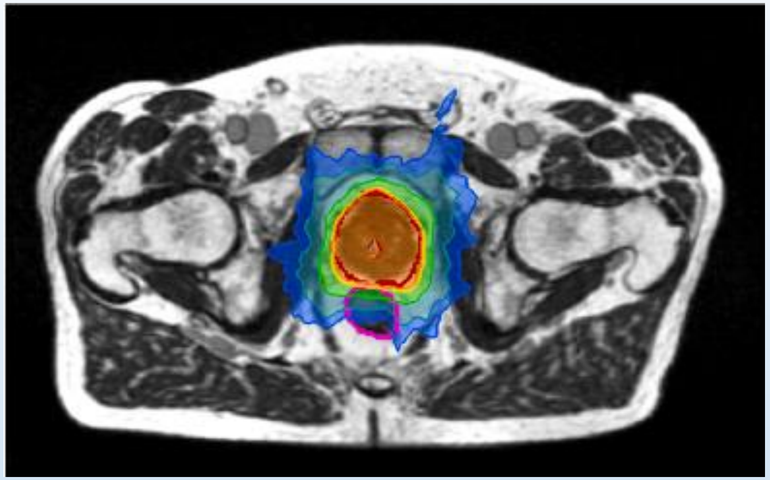
- Cine acquisition
- Only sagittal plane

- CTV out of PTV more than %
- Beam off- beam on

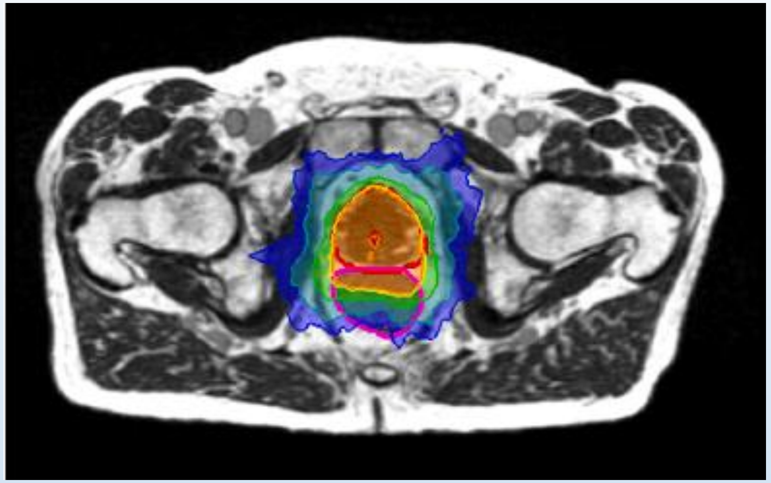
SMART step	Time (min)
Patient setup	7.6
Registration	6.1
Delineation	10.7
Re-optimization	2.9
Plan QA	1.5
Beam-on Tx	15.9
Total	44.7

S.U. Tetar, et al. "Clinical implementation of magnetic resonance imaging guided adaptive radiotherapy for localized prostate cancer" Physics and Imaging in Radiation Oncology 9 (2019)

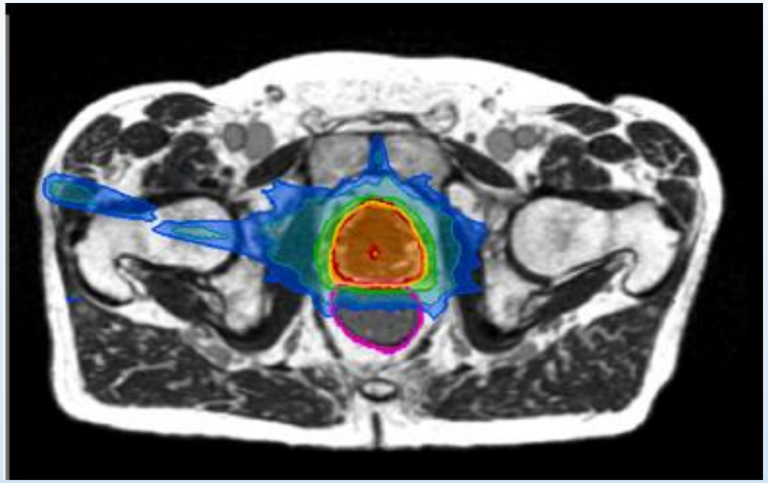
Baseline

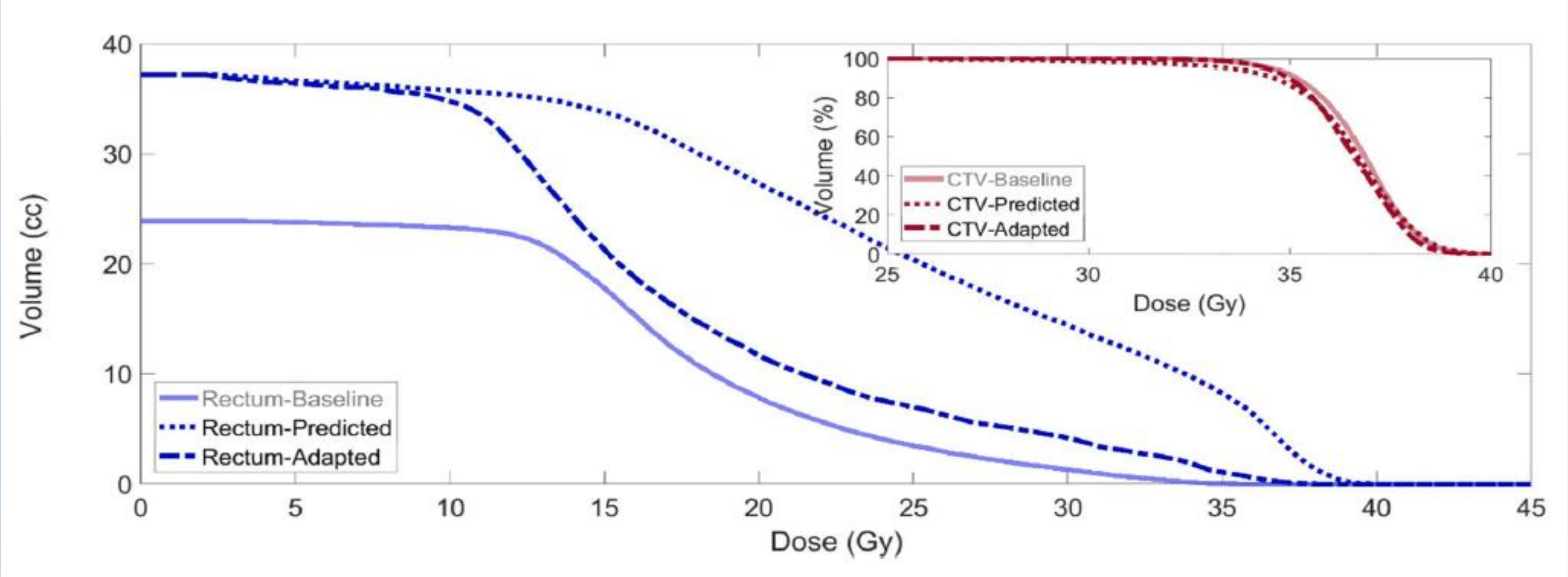


Predicted



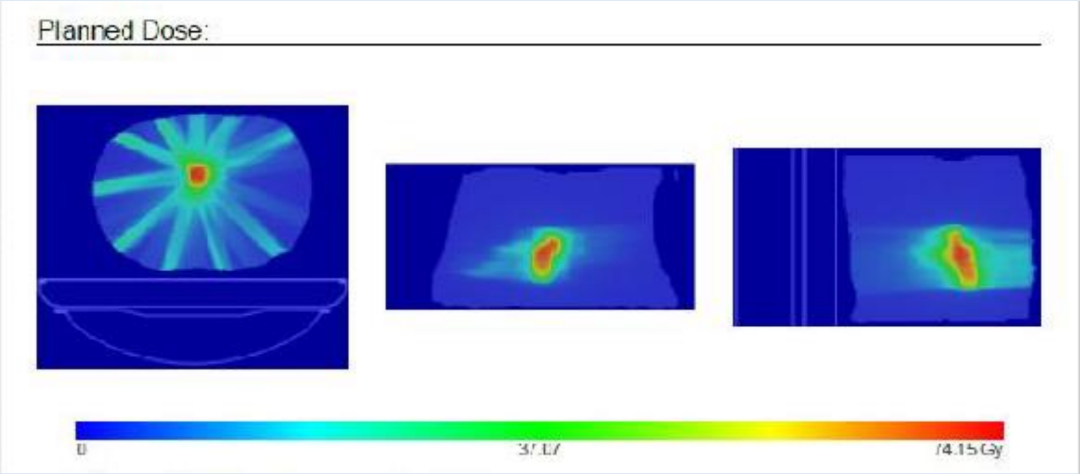
Adapted

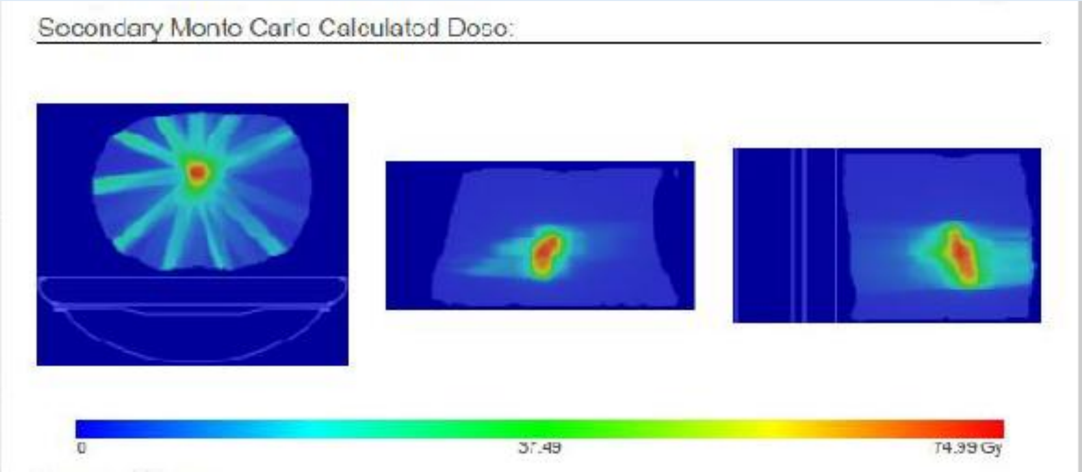


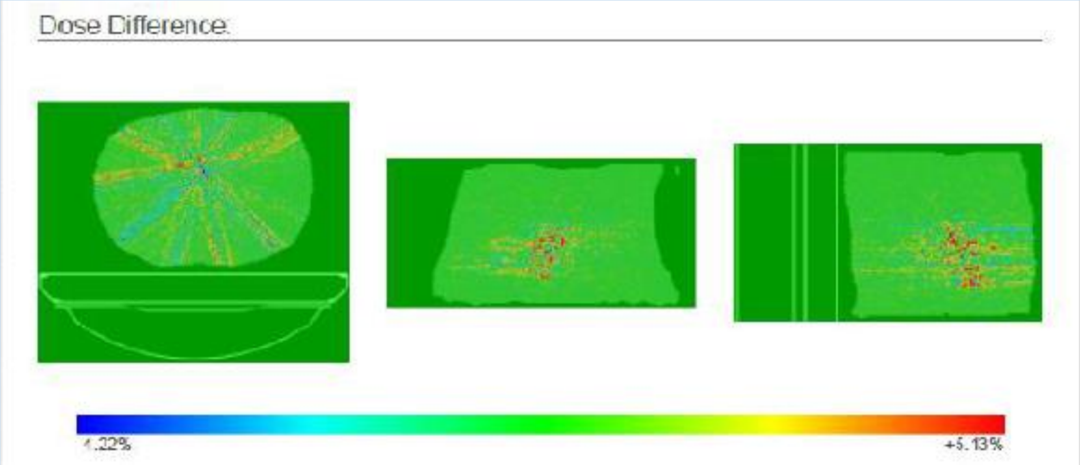


Adaptive QA is performed with an independent Monte Carlo dose calculation

- Magnetic field can be included in calculation
- Gamma Analysis is reported
- Process take 1-2 minutes

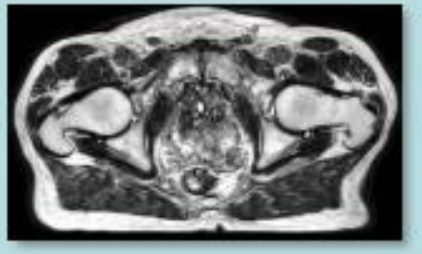


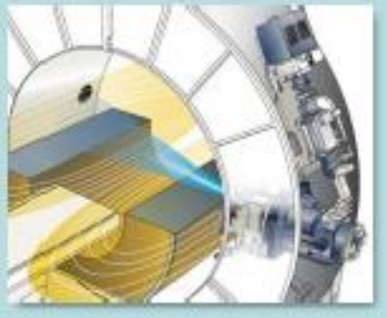




Scan-Plan-Treat with Adapt to Position

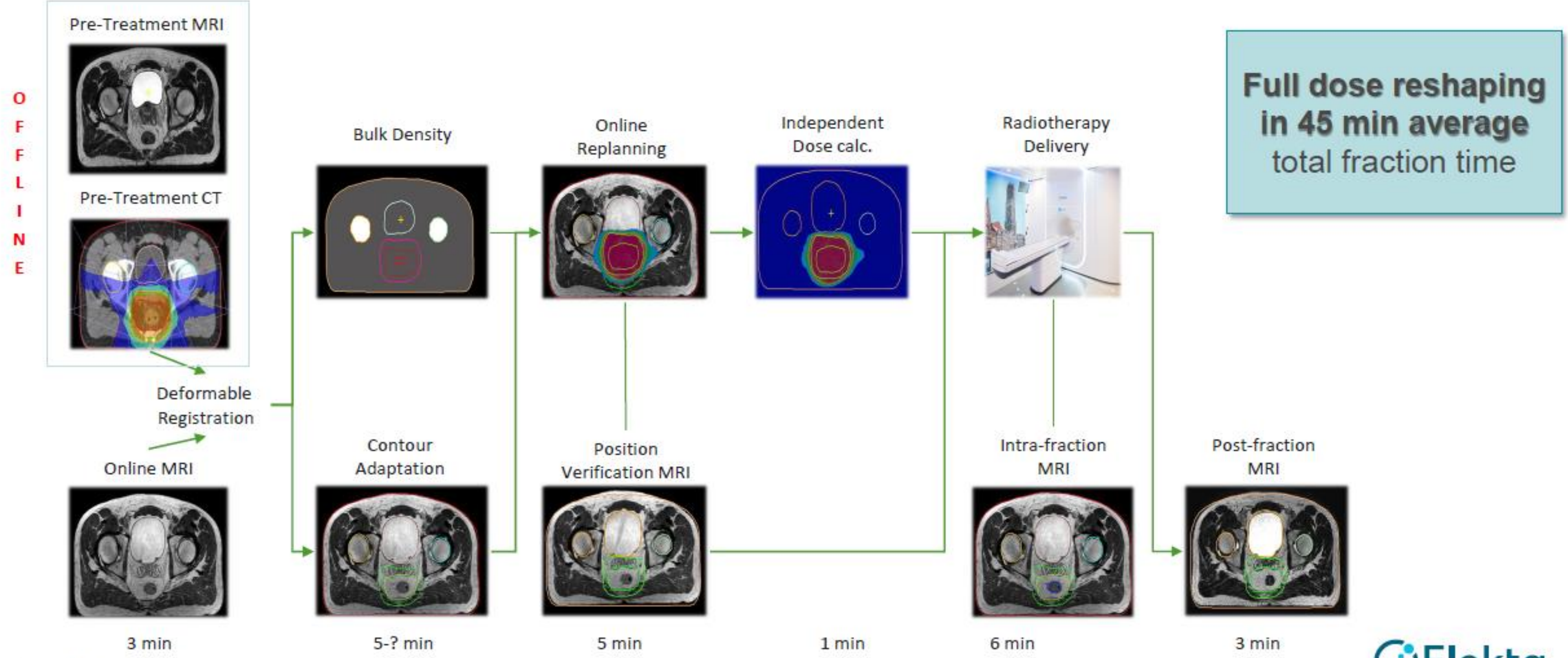
16 minutes total fraction time*





Patient arrival ▶ Patient setup ▶ Daily MR ▶ Adapt to Position ▶ Beam delivery ▶ Patient departure

Scan-Plan-Treat with Adapt to Shape



Focus where it matters.

See clearly

Monitor motion

Adapt real-time

Assess response

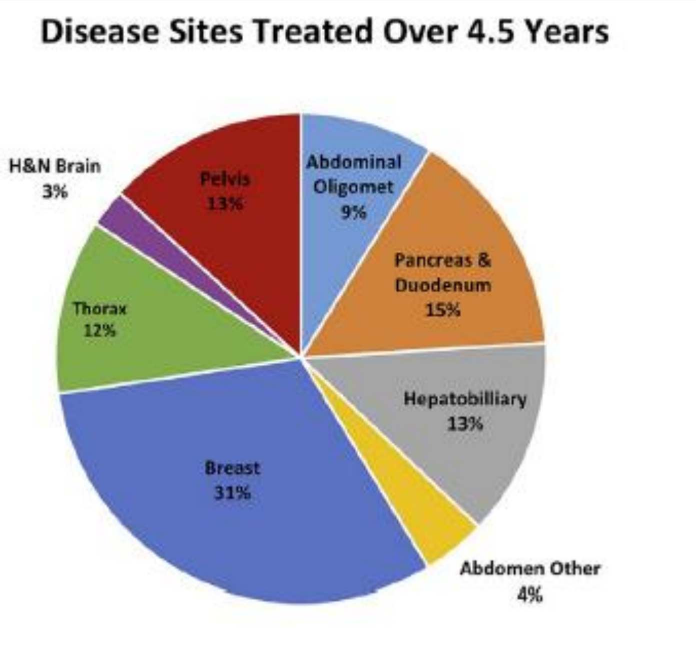
Improve local control → Stereotactic regimes

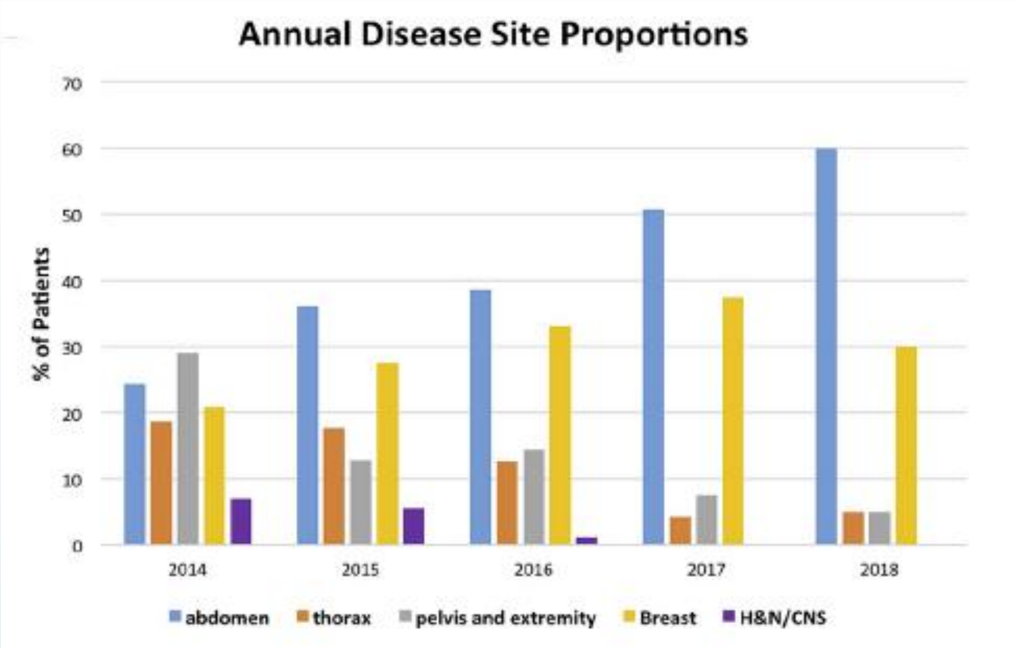
Reduce margins → Minimize OAR toxicity

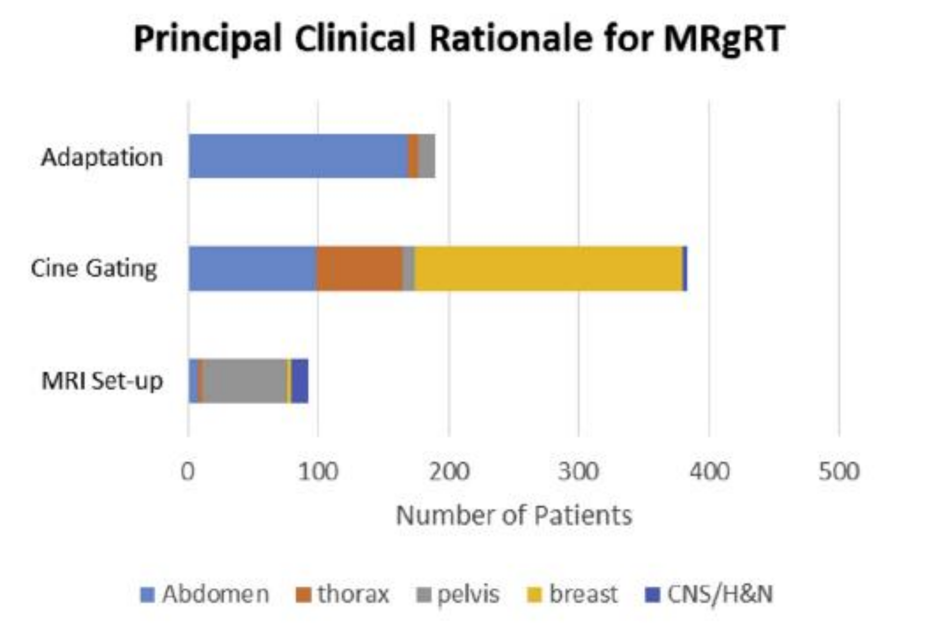
Inter-fractional changes → Daily plan optimization

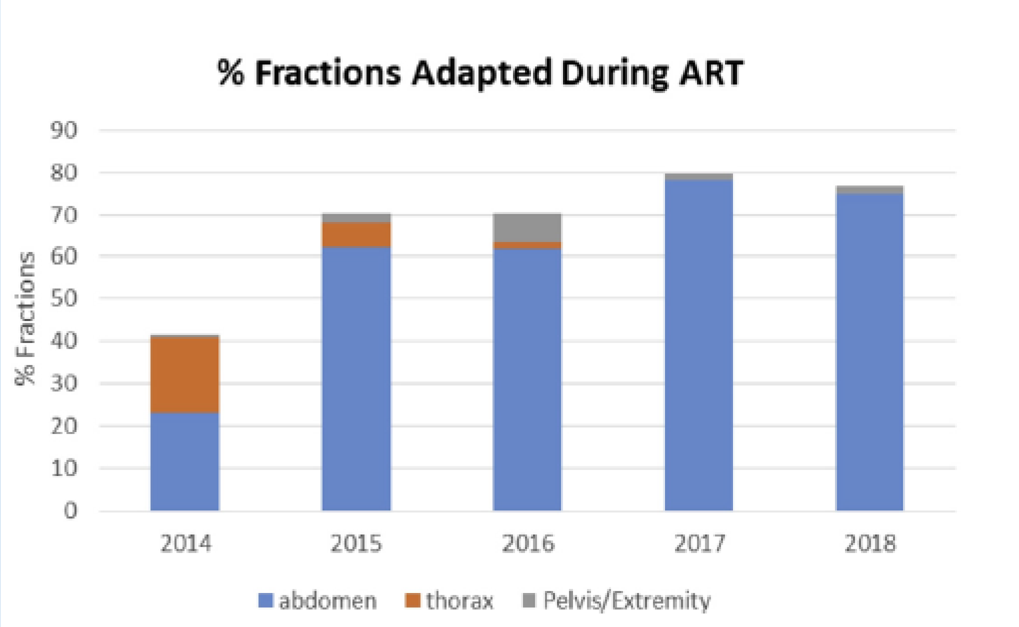
Biological information → Earlier treatment adaptation

Clinical experience at the Radiation Oncology Department Washington University St. Louis





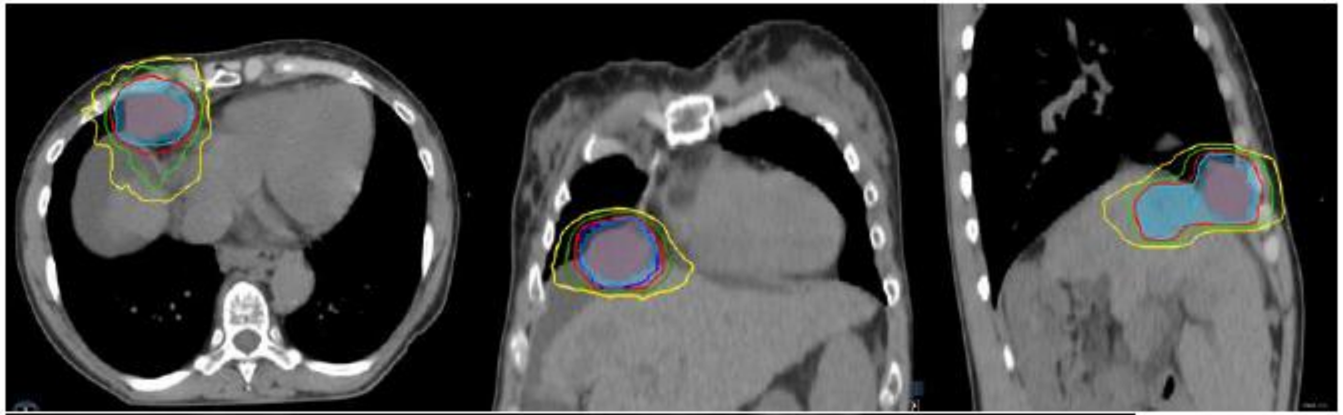




Henke LE, et al., Magnetic Resonance Image-Guided Radiotherapy (MRIgRT): A 4.5-Year Clinical Experience,Clinical Oncology (2018)

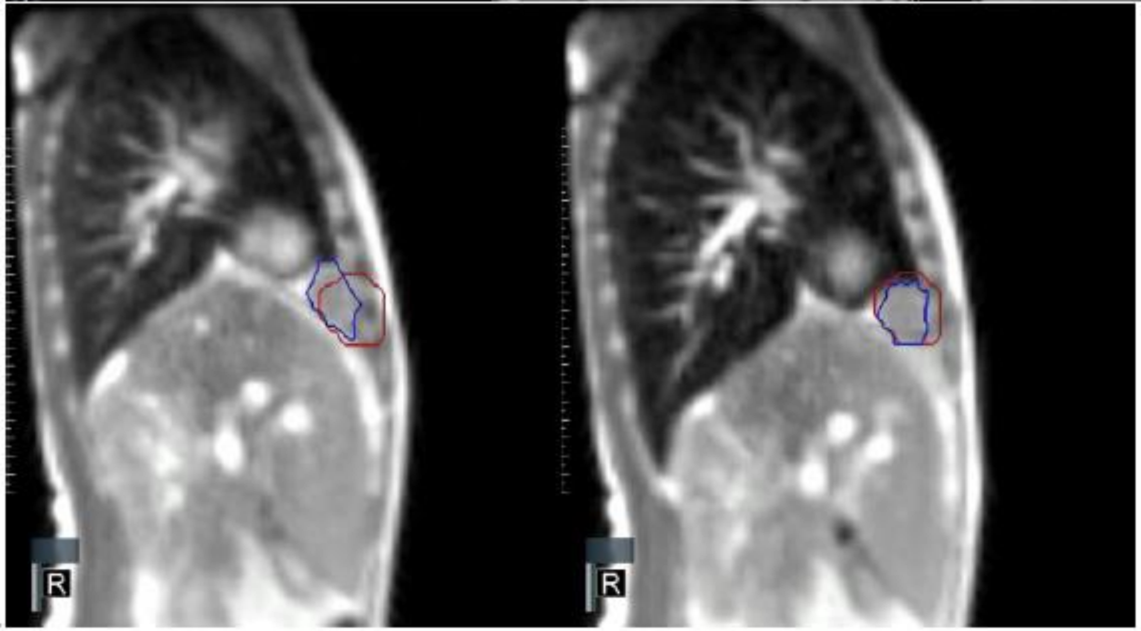
SBRT for Liver and Supra-diaphragmatic Metastasis

Planning CT



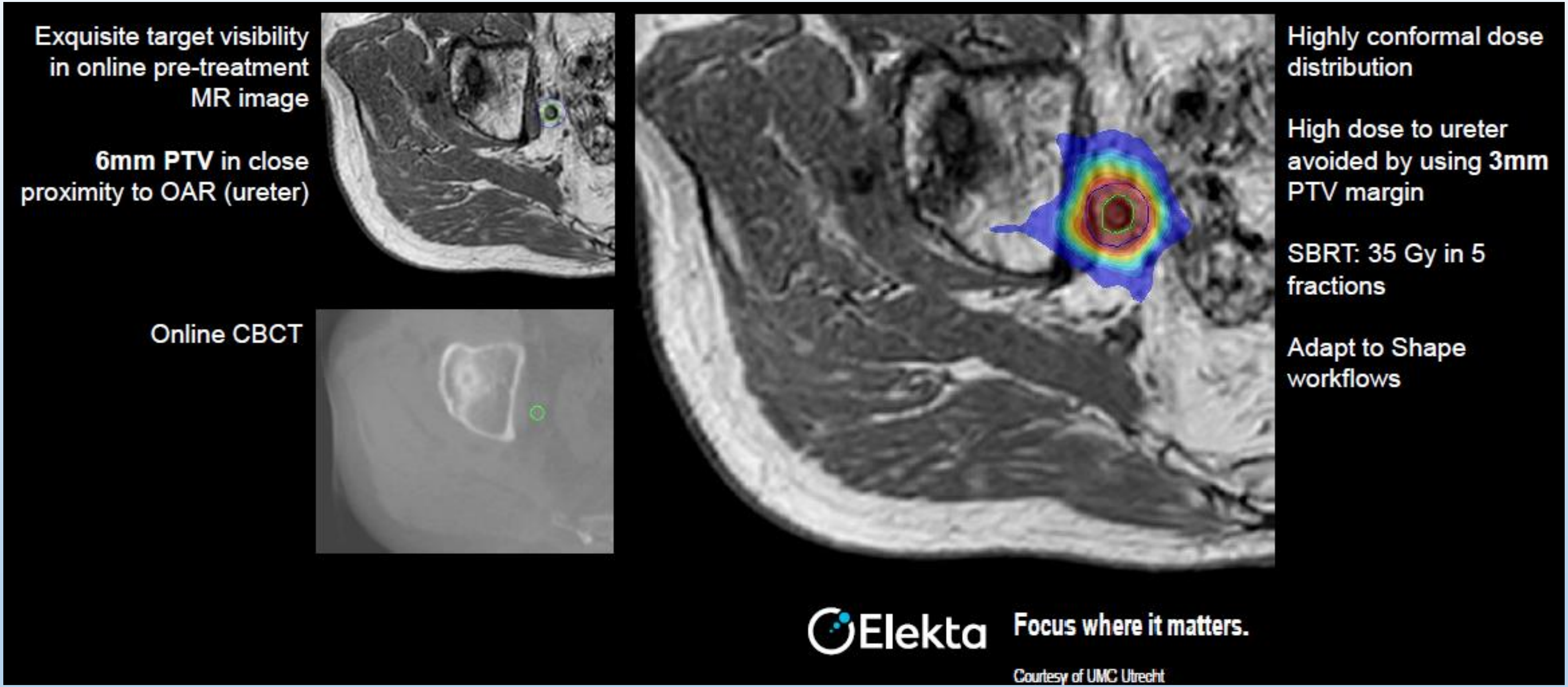
Prescription:
4500 cGy in 5 Fx

Daily MRI Guidance



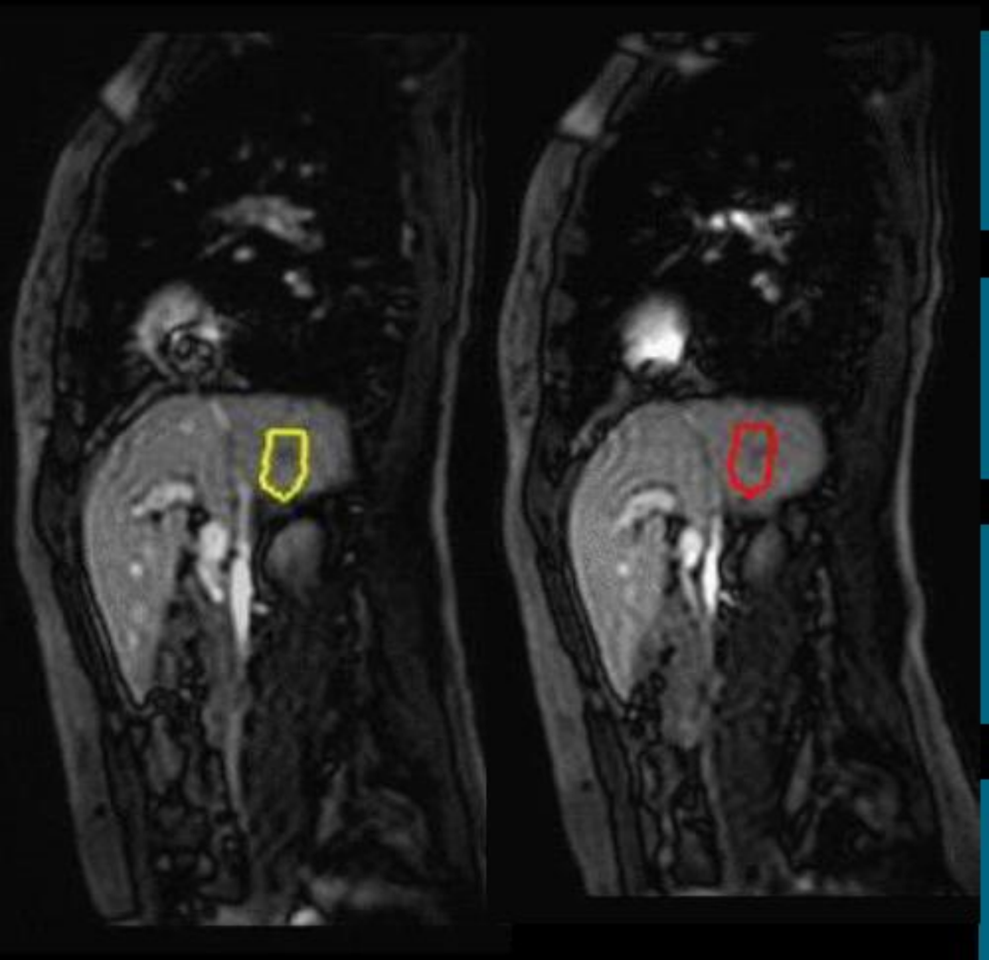
Exhale Inhale

Note: Target is out of bounds during exhale


Exquisite target visibility in online pre-treatment MR image
6mm PTV in close proximity to OAR (ureter)
Online CBCT
Highly conformal dose distribution
High dose to ureter avoided by using 3mm PTV margin
SBRT: 35 Gy in 5 fractions
Adapt to Shape workflows
Elekta
Focus where it matters.
Courtesy of UMC Utrecht

Real-time motion monitoring during treatment

Beam-on cine imaging

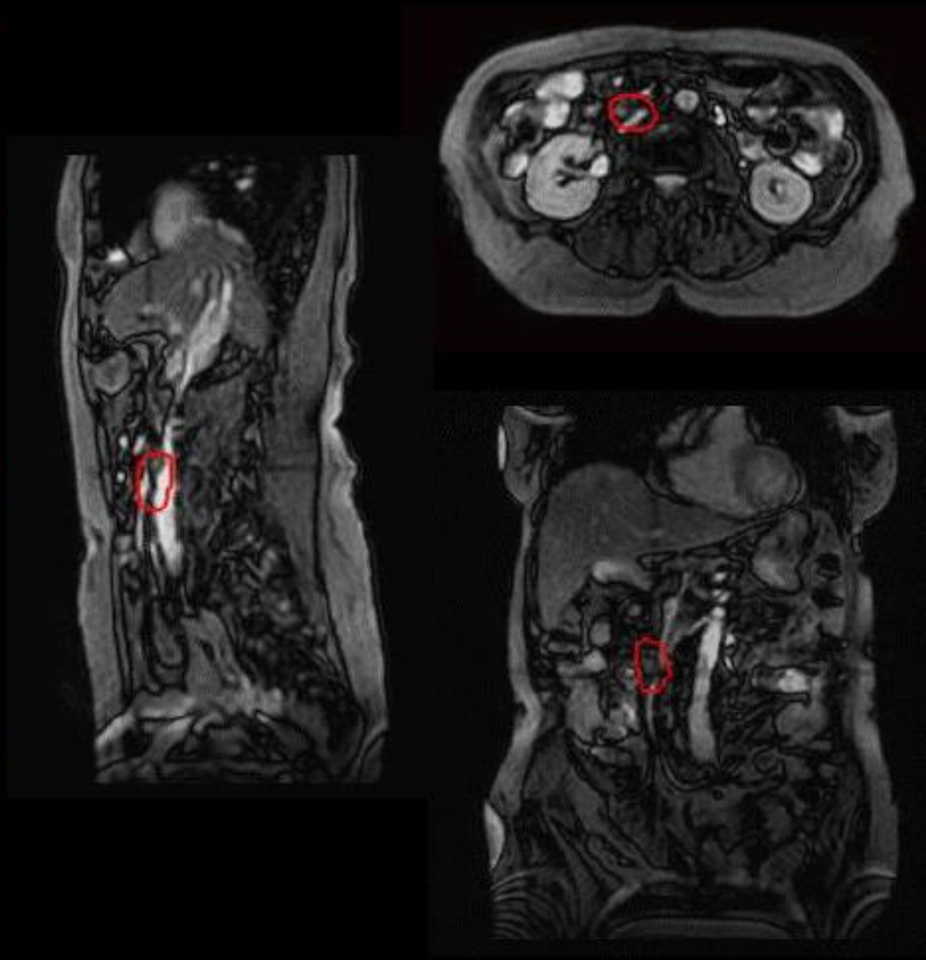


5 frames per second
temporal resolution

Contour of interest
visualization during real-time cine imaging

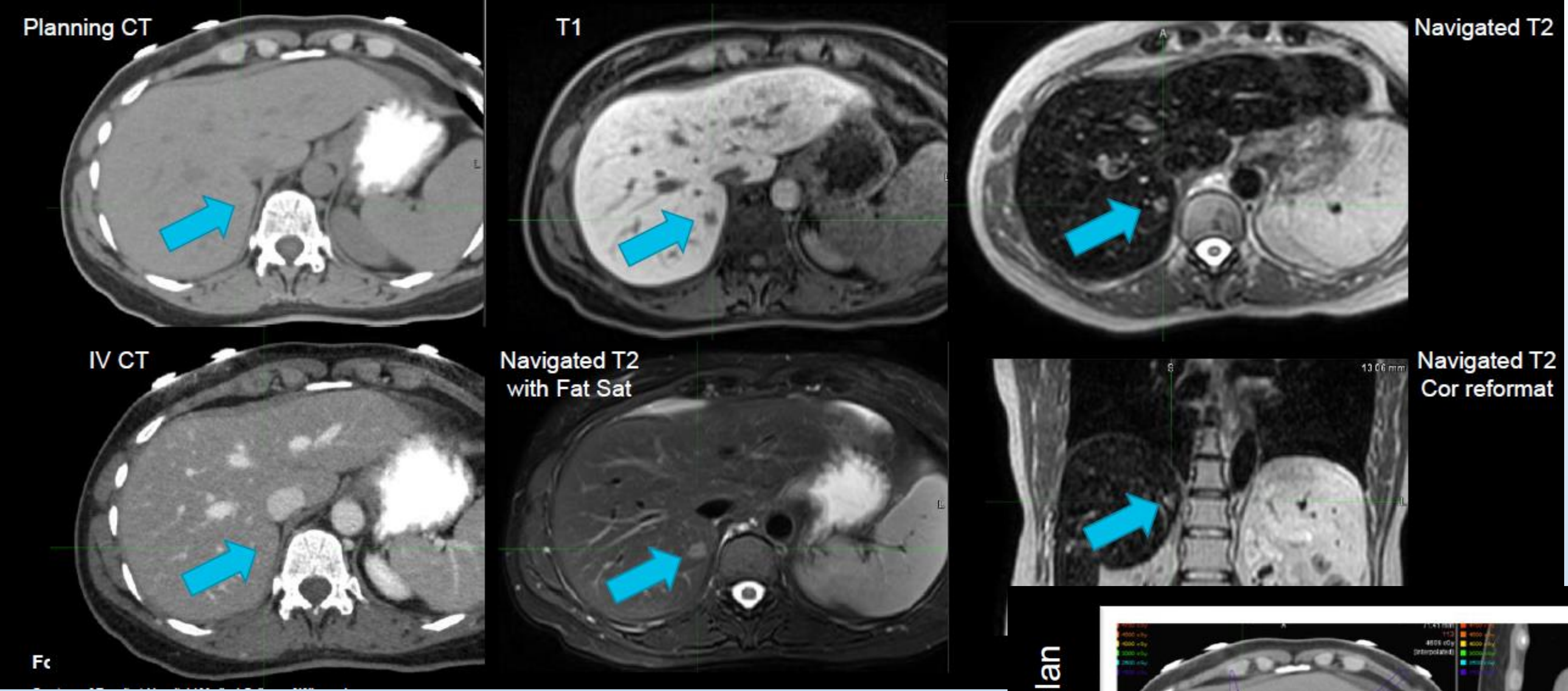
Simultaneous 3-planar
motion capture

Continuous MR scanning
during irradiation and gantry rotation



Focus where it matters.

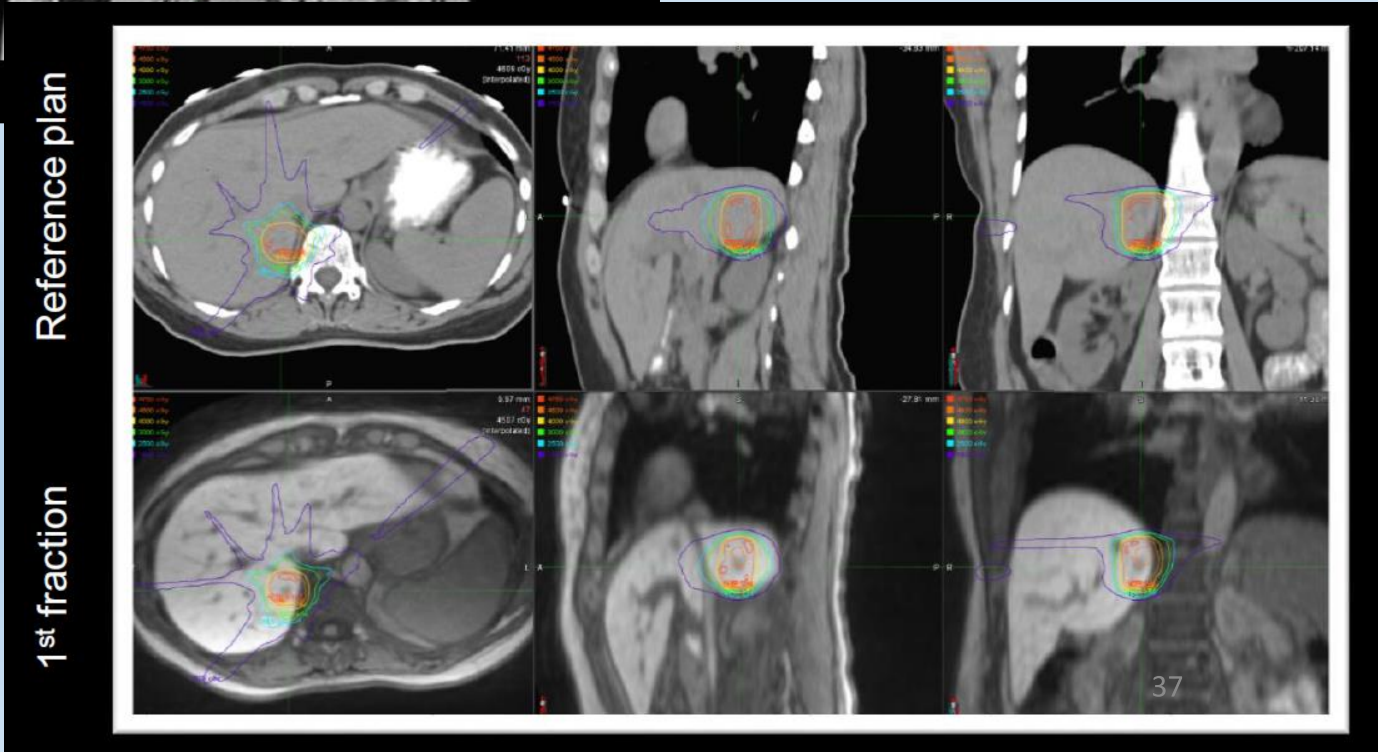
Courtesy of Froedtert Hospital/Medical College Wisconsin



SBRT visualization

Lesion not visible on CT

Adapt to position workflow
Daily targeting with 4D MRI
Beam-on motion monitoring



Acknowledgements

Dr. Marco Fusella Medical Physics Department IOV

Dr.ssa Ludovica Mei   Radiustech- Viewray

Dr. GianLuca degli Stefani Elekta S.p.A

WHY MRIgRT

This technology offers

- improved soft-tissue visualisation
- daily imaging and intra-fraction real-time imaging without added radiation exposure
- adaptive radiotherapy (ART) to adjust for anatomical changes