UMC Utrecht

The promise of the MRI linac:
simultaneous 1.5 T MRI and irradiation

(and the role of Monte Carlo)

Bas Raaymakers

Acknowledgements and disclaimer

Physics Team MRI in RT UMCU

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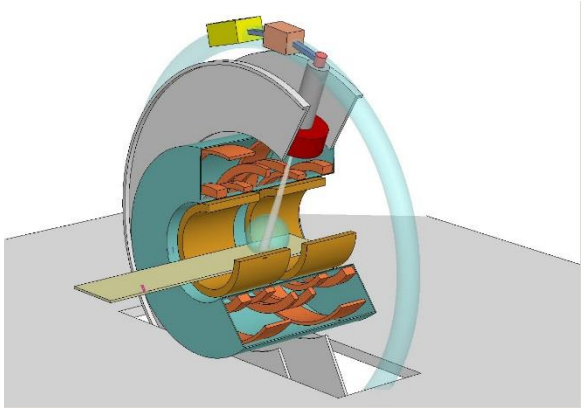
The 1.5 T MRI linac: Simultaneous MRI and irradiation

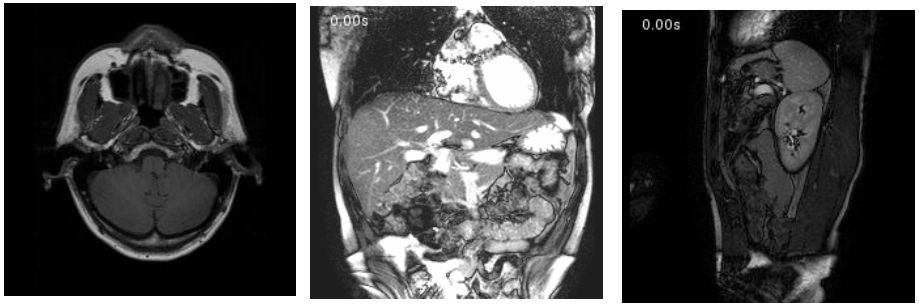
- MRI linac and (Monte Carlo for) clinical introduction
- Monte Carlo for dosimetry in presence B fields
- Monte Carlo to get towards real-time adaptive

1.5 T MRI accelerator: Simultaneous beam on and MRI

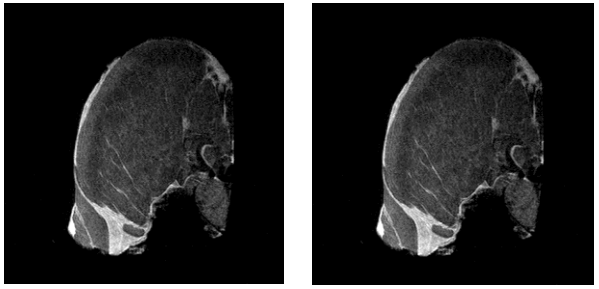


Artist impression

First prototype MRI accelerator



1.5 T diagnostic MRI quality



No impact of beam on MRI

From Raaymakers et al. PMB (2009)

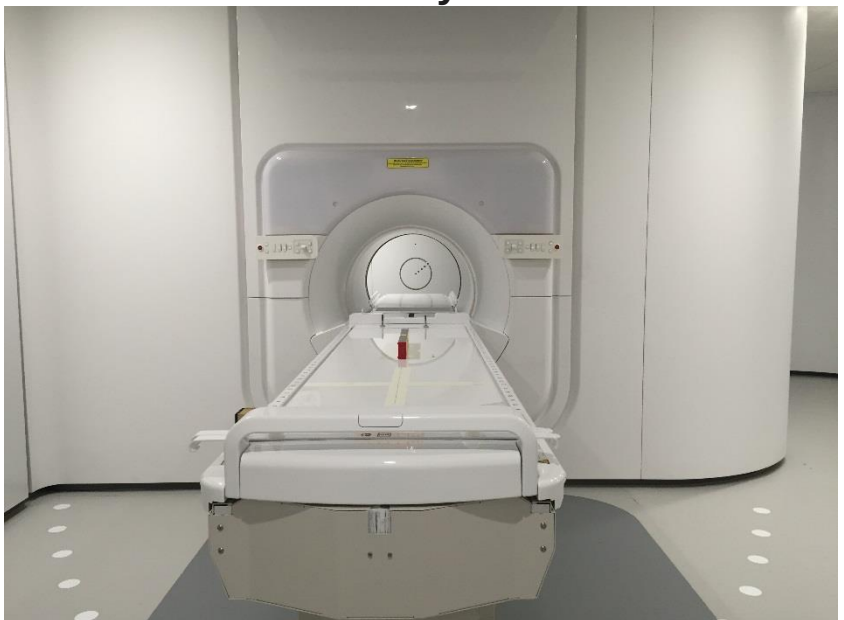
1st, 2nd, 3rd and 4th generation MR linac: from proof of concept to clinical system

Proof of concept simultaneous MRI and irradiation

Rotating gantry and MLC

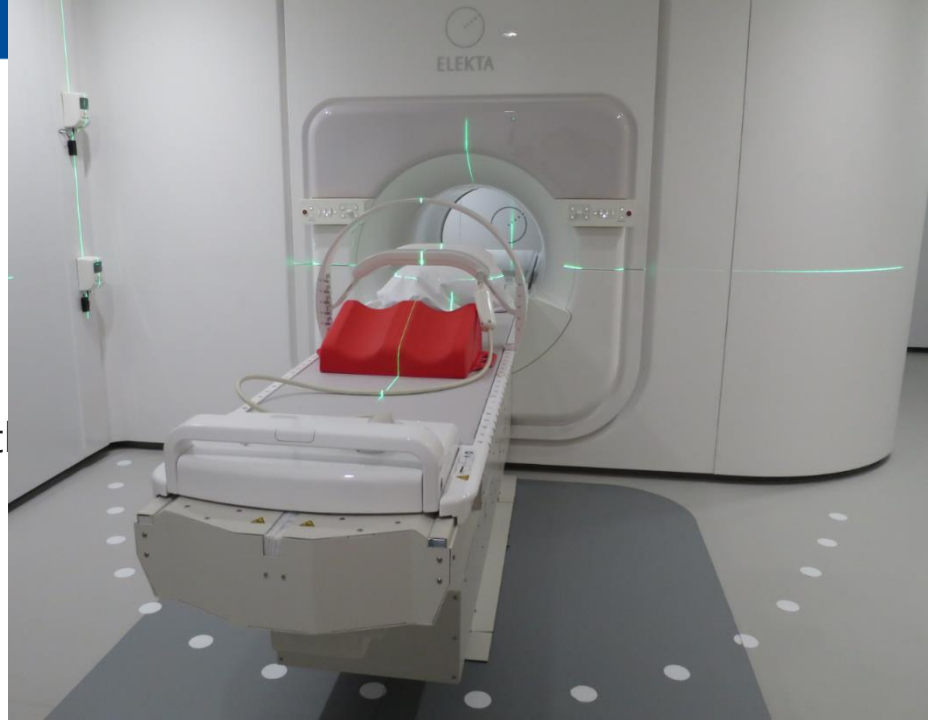
Pre-clinical prototype

Clinical system

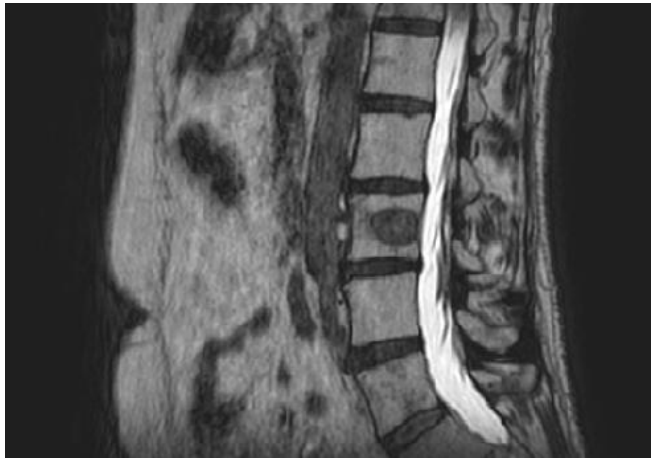


First patient on the MRL

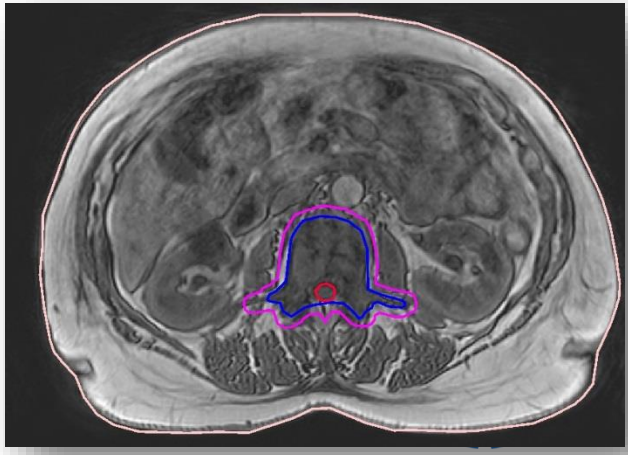
Bringing push to shove



- Patient population
  - Patients with bone metastases treated wit palliative intention
- Treatment
  - 8 Gy in a single fraction
  - 3 or 5 field IMRT
- Goal:
  - Demonstrate technical accuracy and safety in the clinical setting



3D T2 TSE

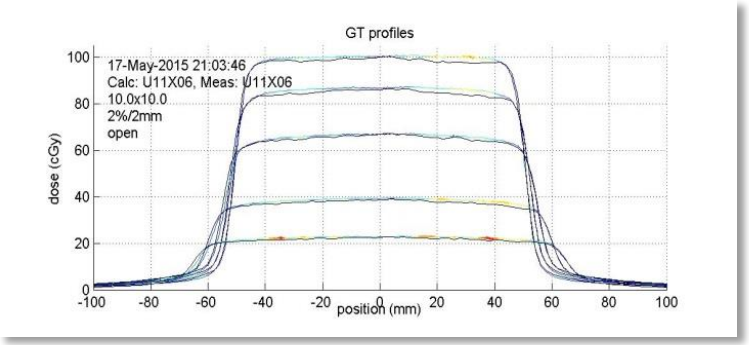


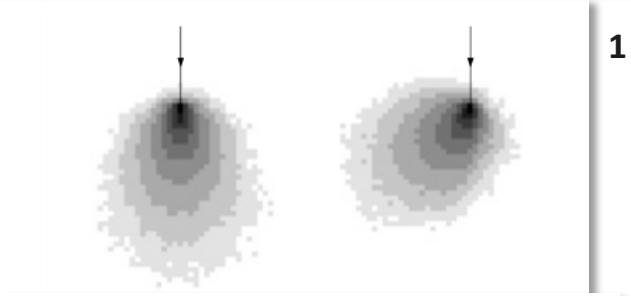
Commissioning Monaco for the MR-linac

Beam model
- Energy of photons
- Profile of beam

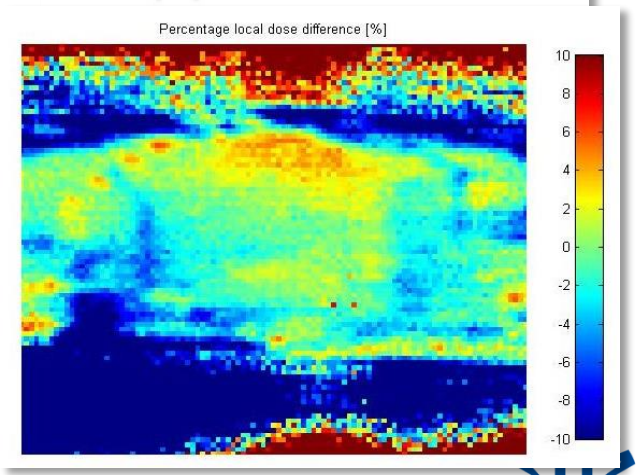
Algorithm
- Inhomogeneities (i.e. not water)
- Oblique beams / missing tissue
- Off-axis fields

Checking
- IMRT treatments (multiple patients)



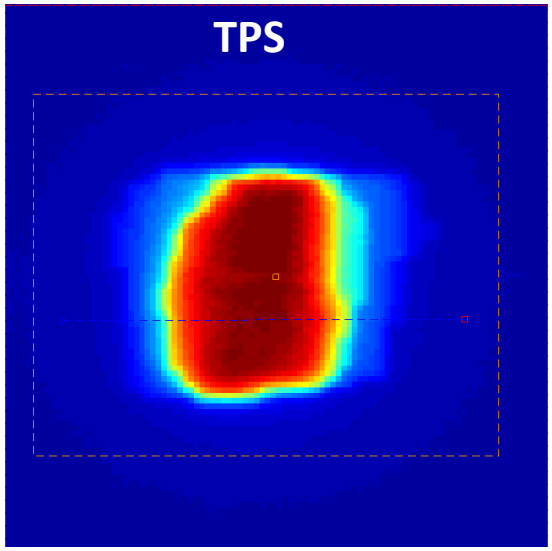


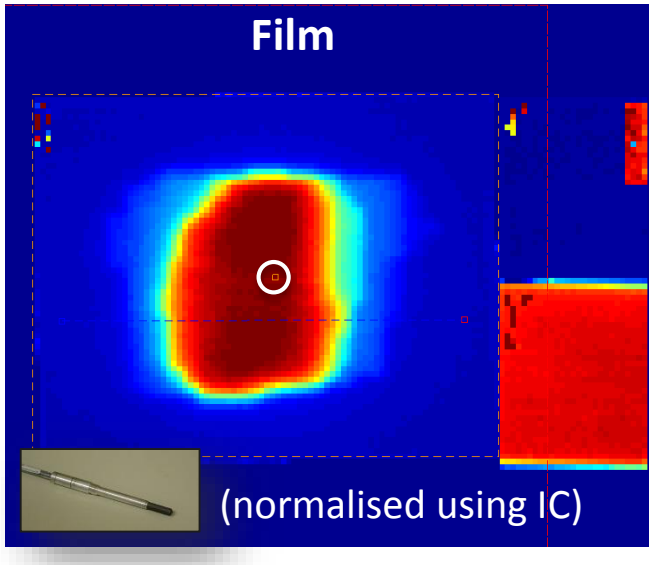
[1]

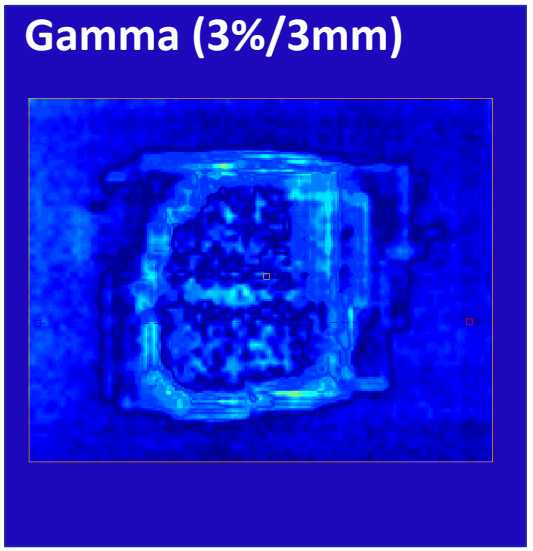


[1] Raaijmakers *PMB* 2008

Film and point measurement
First patient

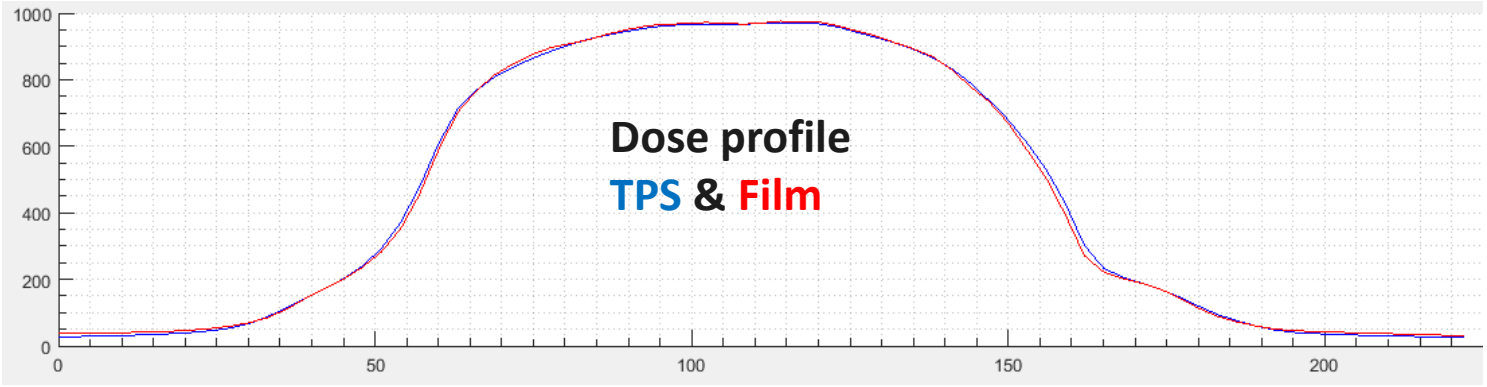






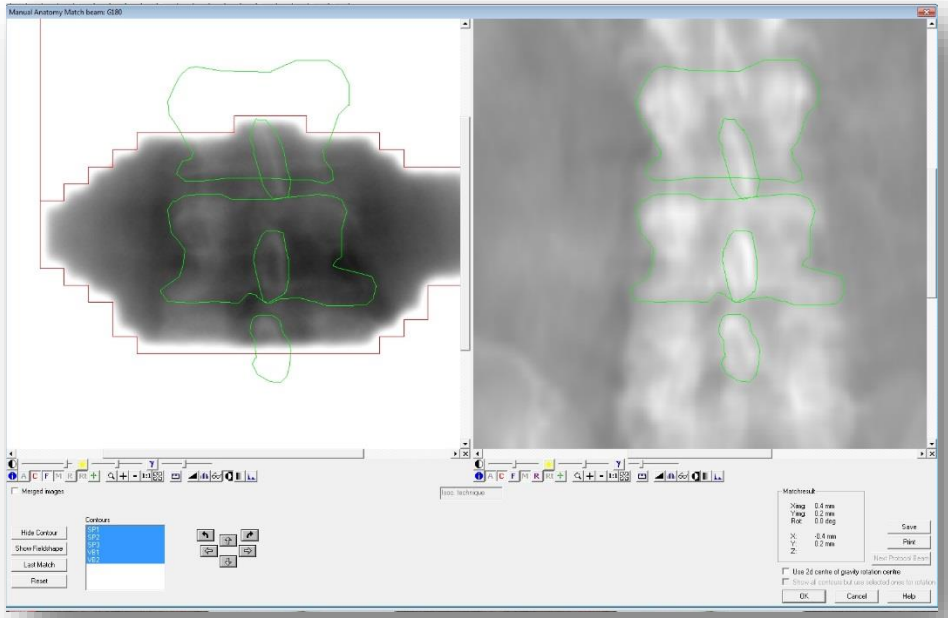
IC vs. TPS: 1%

$D_{10}(\gamma<1)$: 100%
$D_{60}(\gamma<1)$: 98.8%

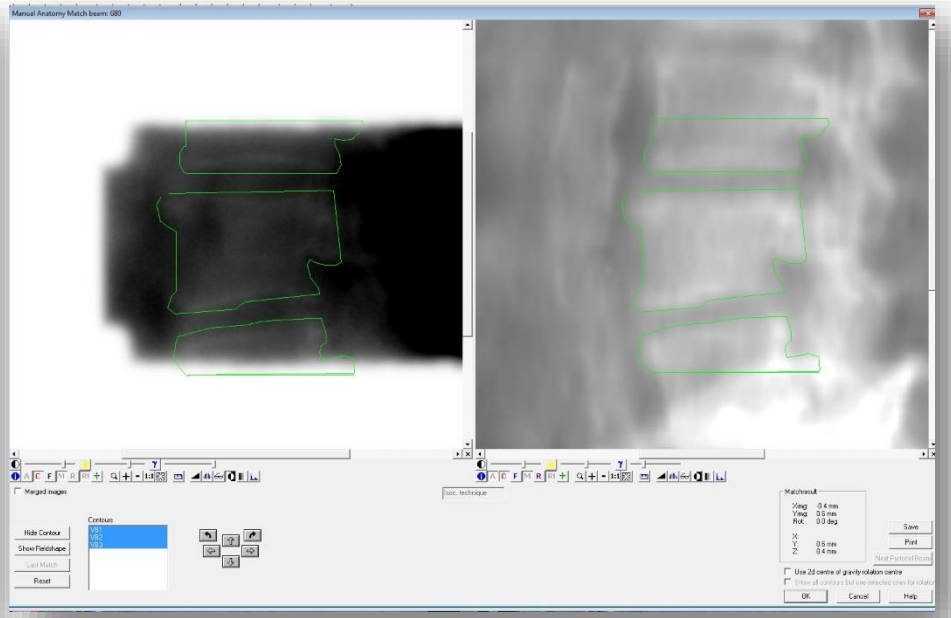


Geometrical accuracy FIM
First patient

- Bone match using EPID and pseudo CT DRR
- Theraview software
- Displacement vector (3D): ***0.2 mm***

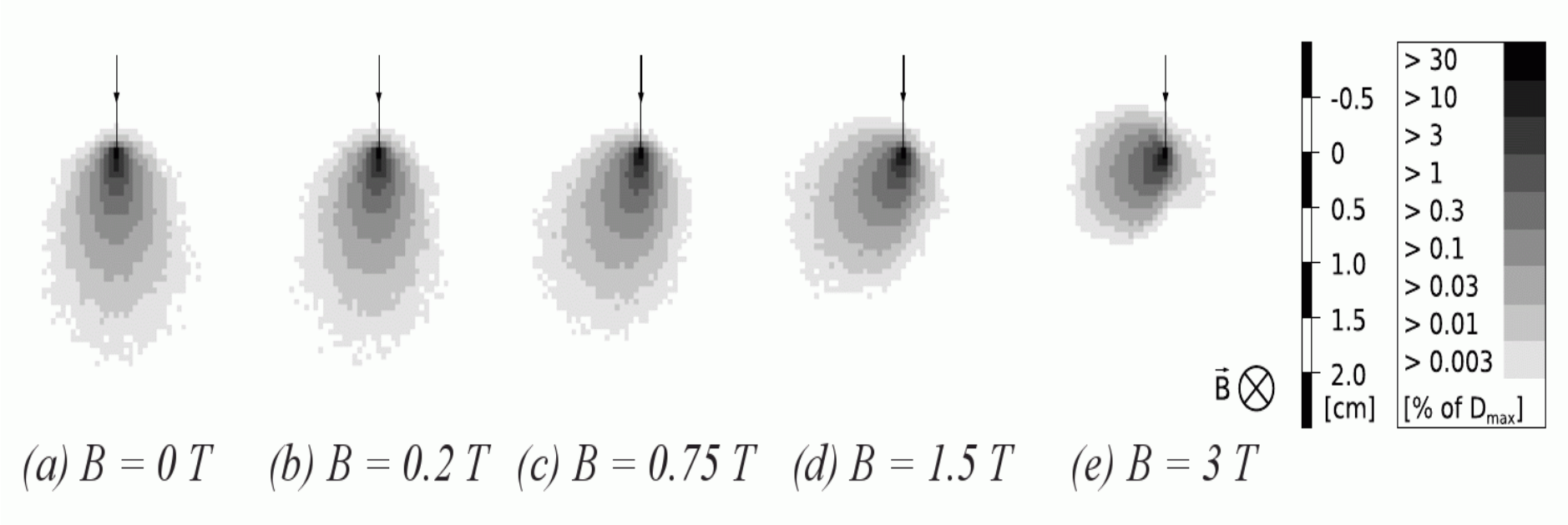


MV and MRI projection for PA beam



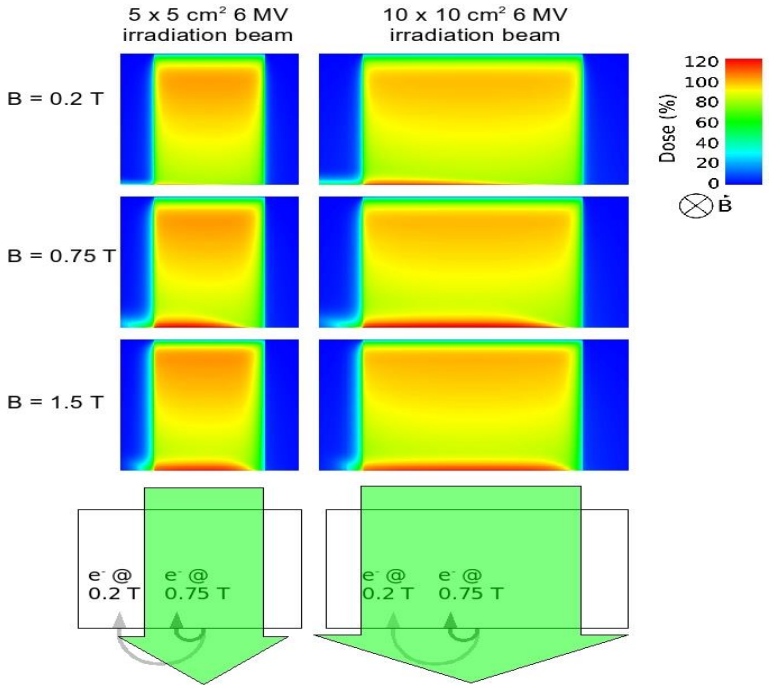
MV and MRI projection for oblique beam

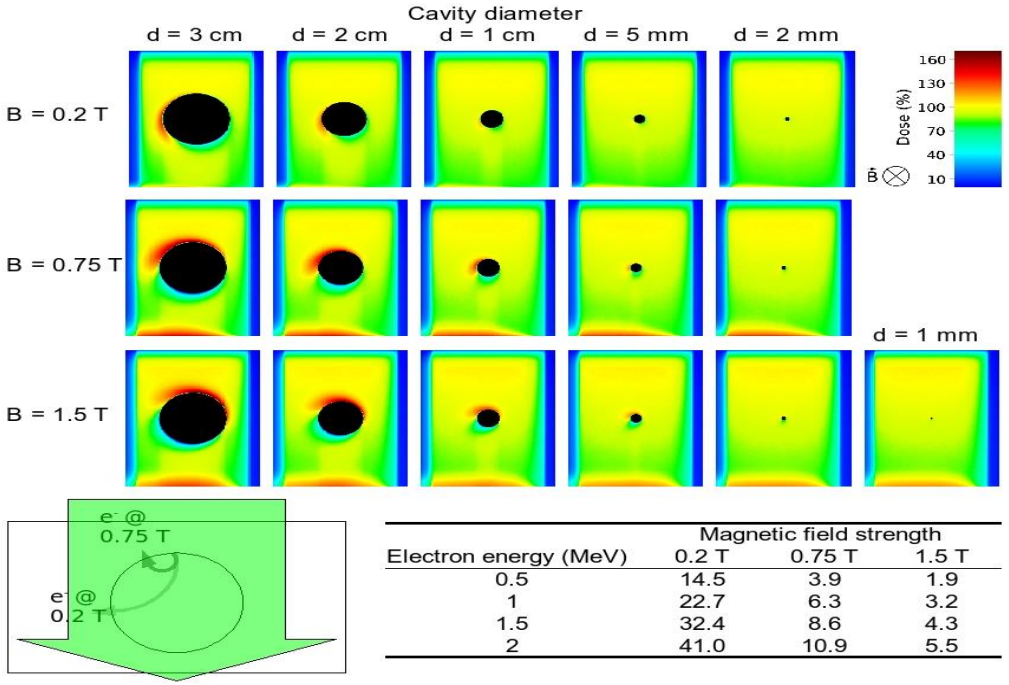
Impact of perpendicular B-field on point spread kernels in homogeneous water



From Raaijmakers et al. *PMB* 2008

Impact depends on field size, B-field strength, orientation, tissue density and geometry

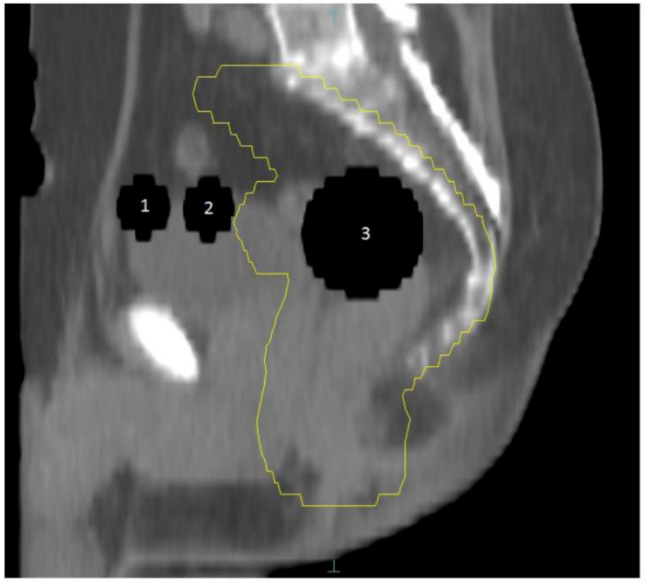




Electron energy (MeV)	Magnetic field strength 0.2 T	0.75 T	1.5 T
0.5	14.5	3.9	1.9
1	22.7	6.3	3.2
1.5	32.4	8.6	4.3
2	41.0	10.9	5.5

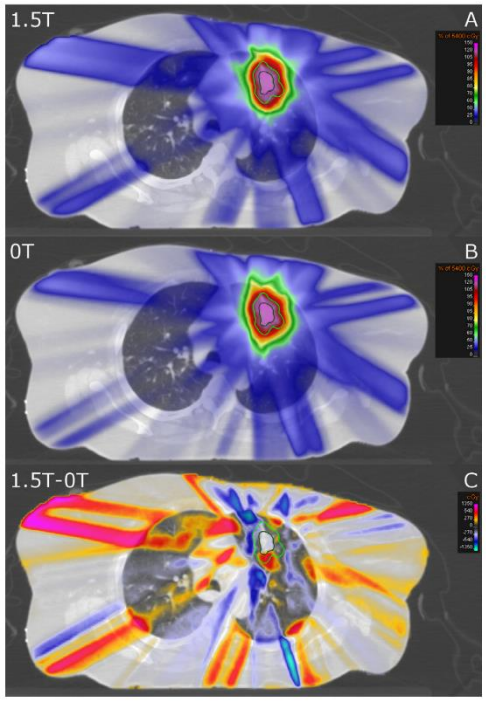
Raaijmakers et al. *PMB* (2008)

IMRT in presence of 1.5 T magnetic field: e.g. rectal cancer and lung



- For **Rectum**:
- Impact transient air bubbles
- There is impact of B field
- Impact clinically acceptable

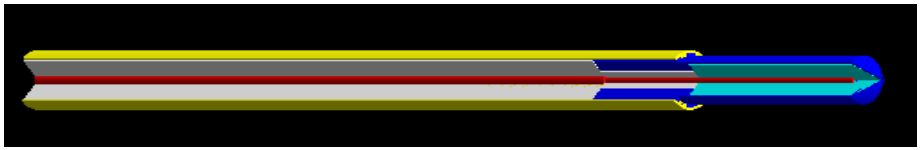
Uilkema et al. Med Phys (2015)

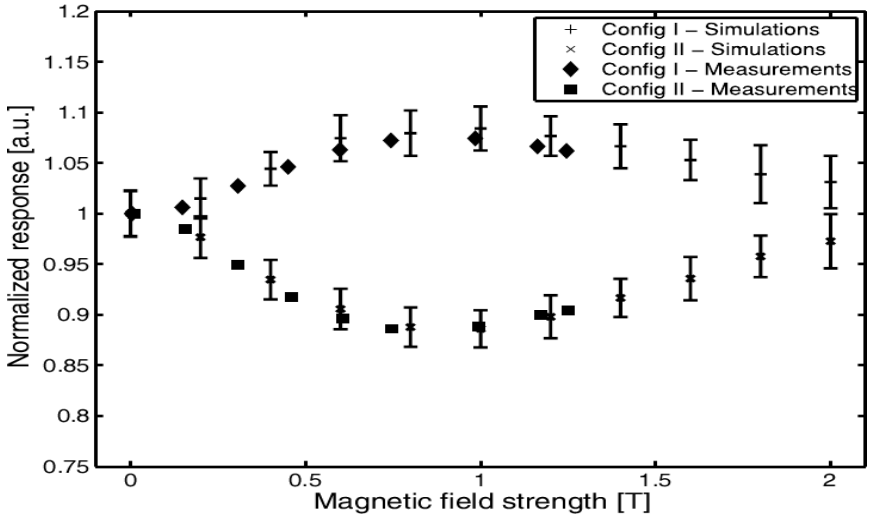


- For **Lung**:
- Impact on lung stereotactie irradiation
- There is impact of B field
- Impac ically acceptable
- MLC t ıg not affected by B field

Menten et al. Radiother. Oncol. (2016)

Farmer chamber in magnetic field: Measurements and Monte Carlo simulations



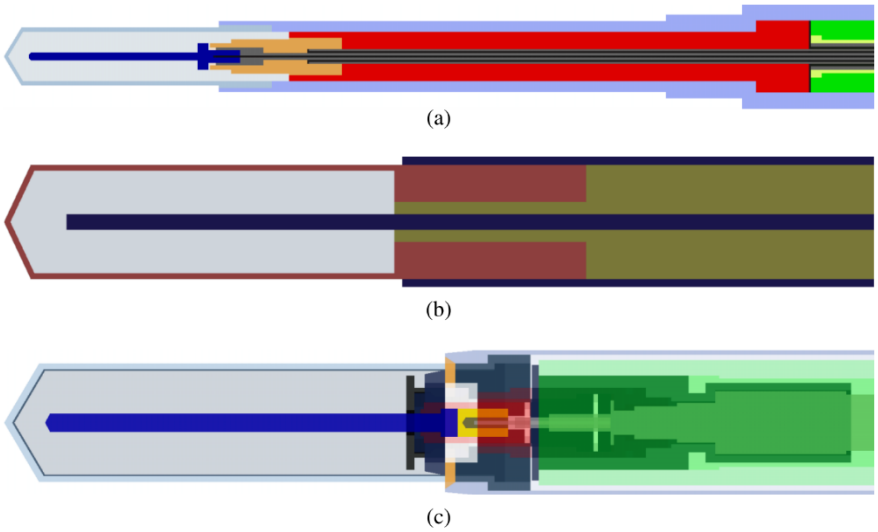


From Meijsing et al 2009

Reference dosimetry in magnetic fields

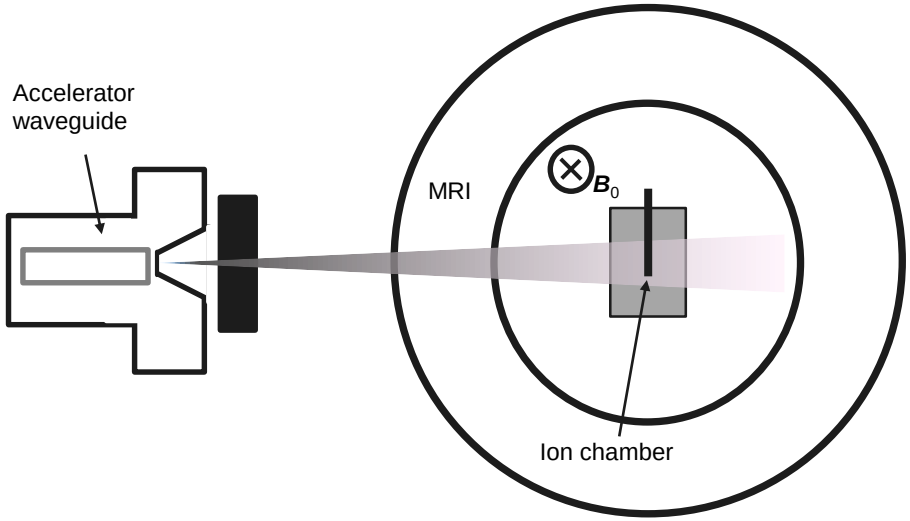
- Geant 4
- Full head model
- 6 chambers
- 3 configurations

- Correction factors needed
- Uncertainties with B fields similar to conventional formalisms



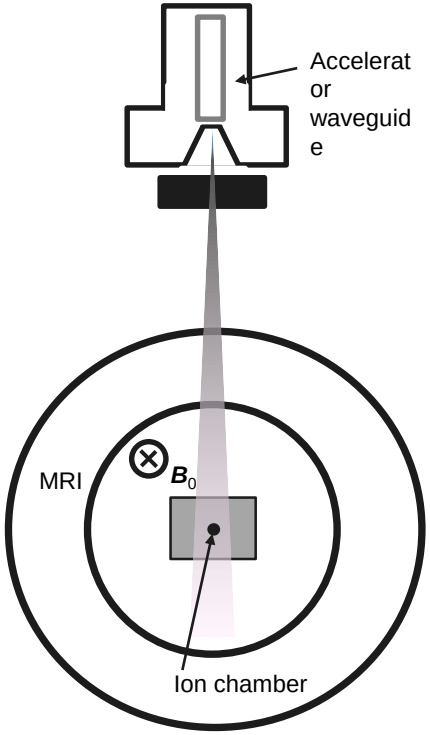
From o Brien et al. Med Phys (2016)

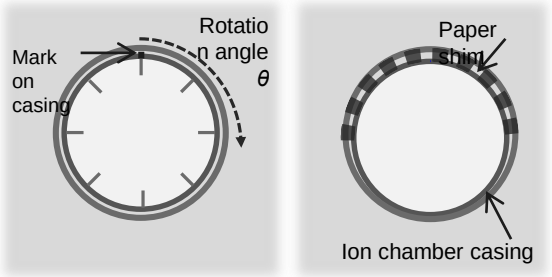
The chamber response on an MR-linac was 0.6% to 1.3% higher with water rather than air around the chamber

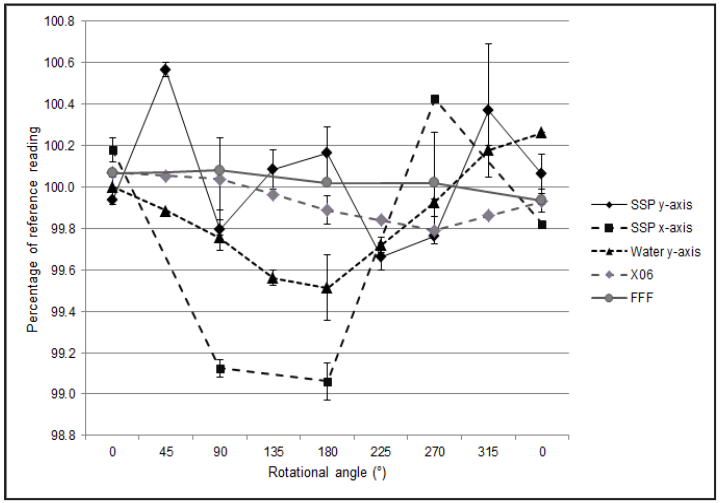


Hackett et al. Med Phys (2016)

The chamber response varied by up to 2% when the distribution of air around the chamber was altered

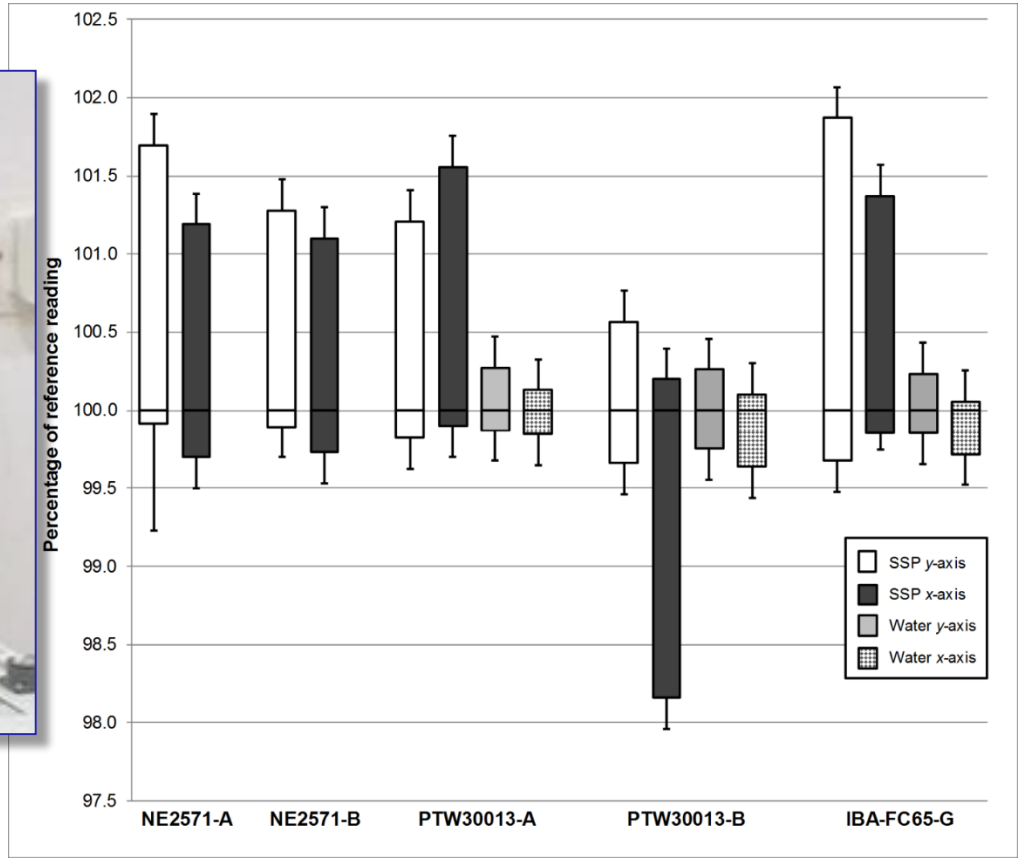






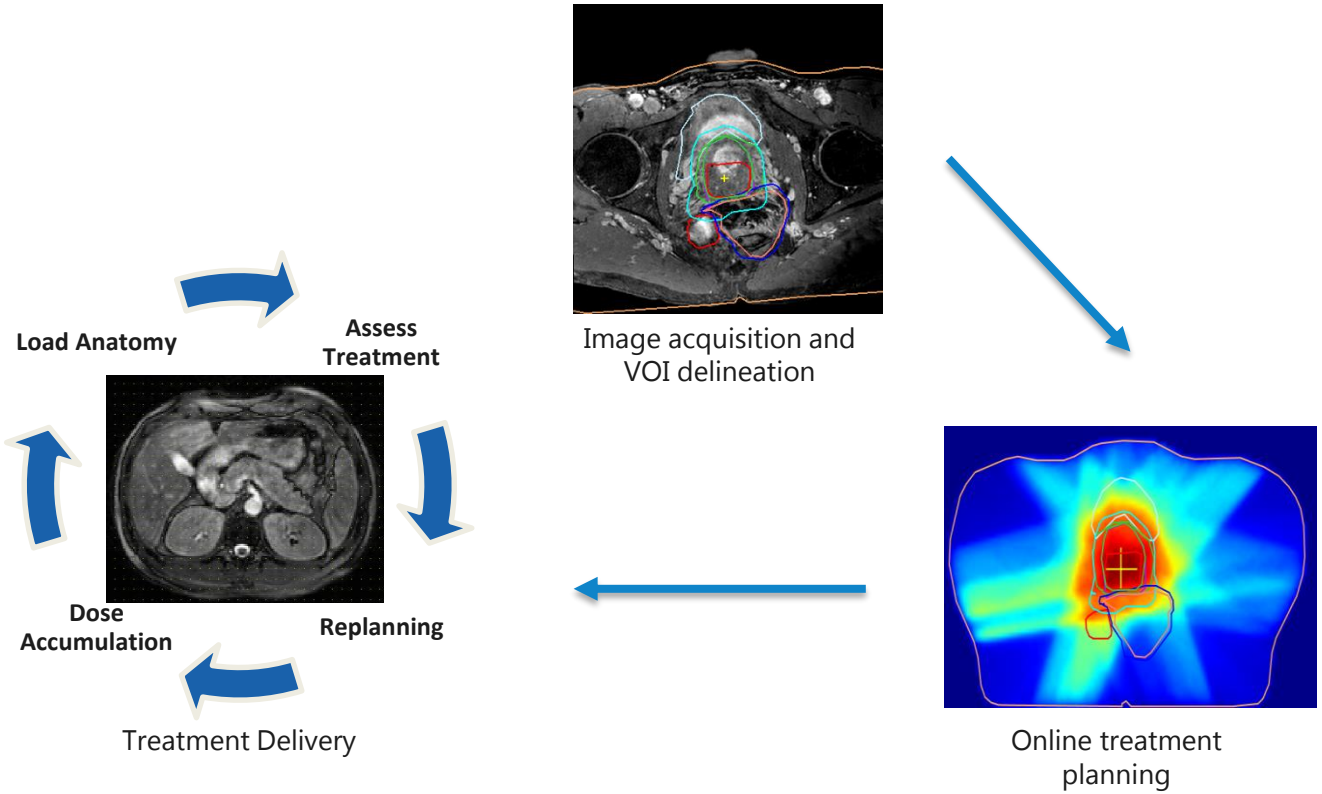
Hackett et al. Med Phys (2016)

Consequences of air layer around an ionization chamber



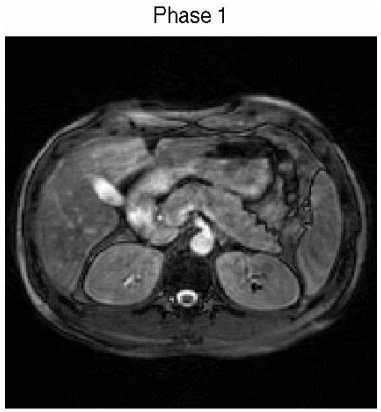
Hackett *et al.* Med. Phys. (2016)

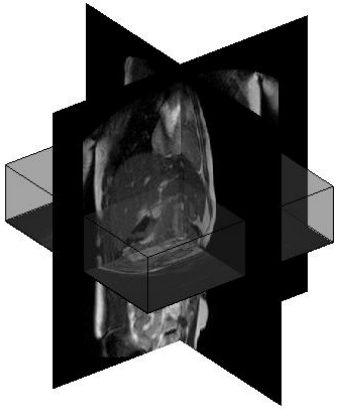
MR-linac: from on-line to real-time adaptive treatment

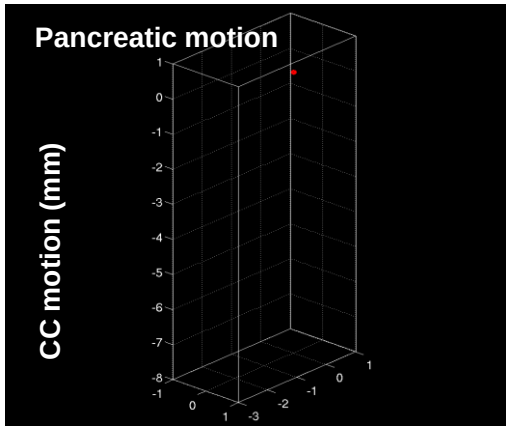


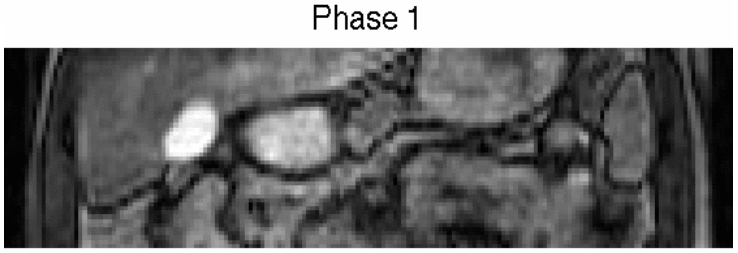
Kontaxis et al 2015 PMB 60 2493

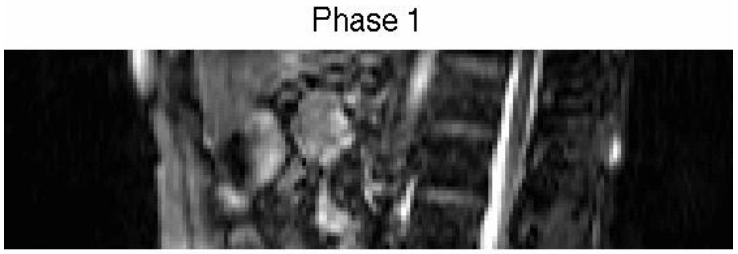
MRI tracking of 3D anatomy and deformation field at 5Hz
e.g. pancreas tracking by combining pre-treat 4D MRI and on-line MRI

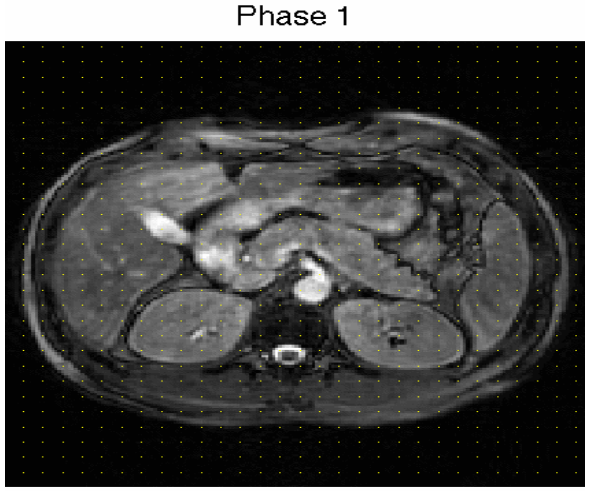






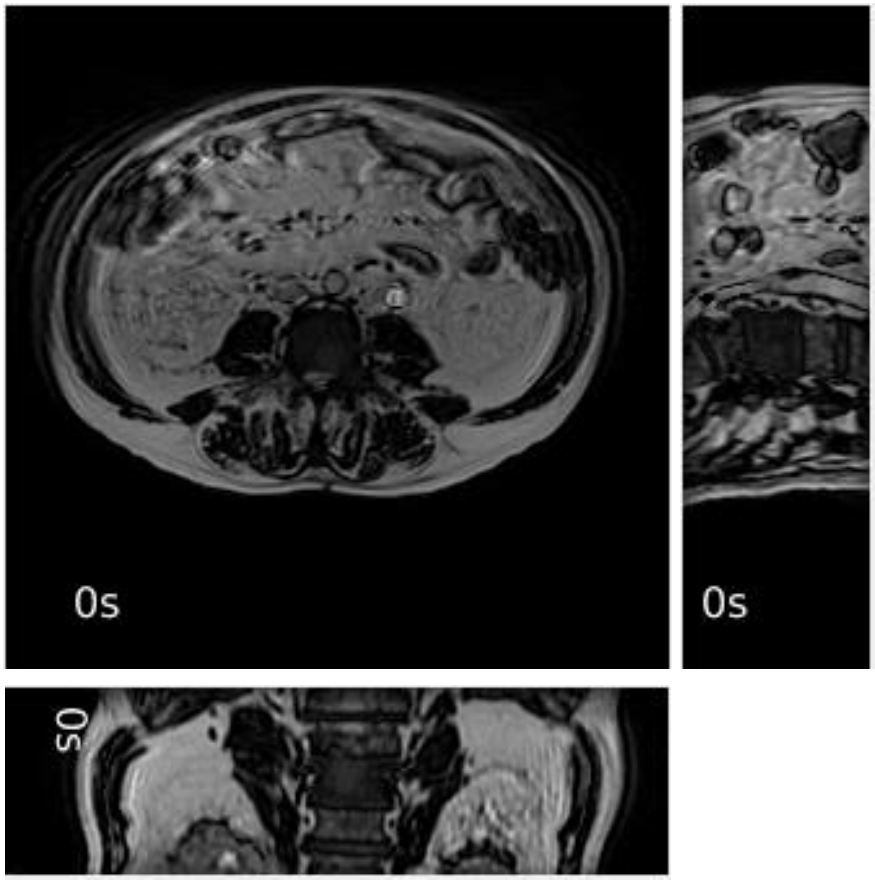




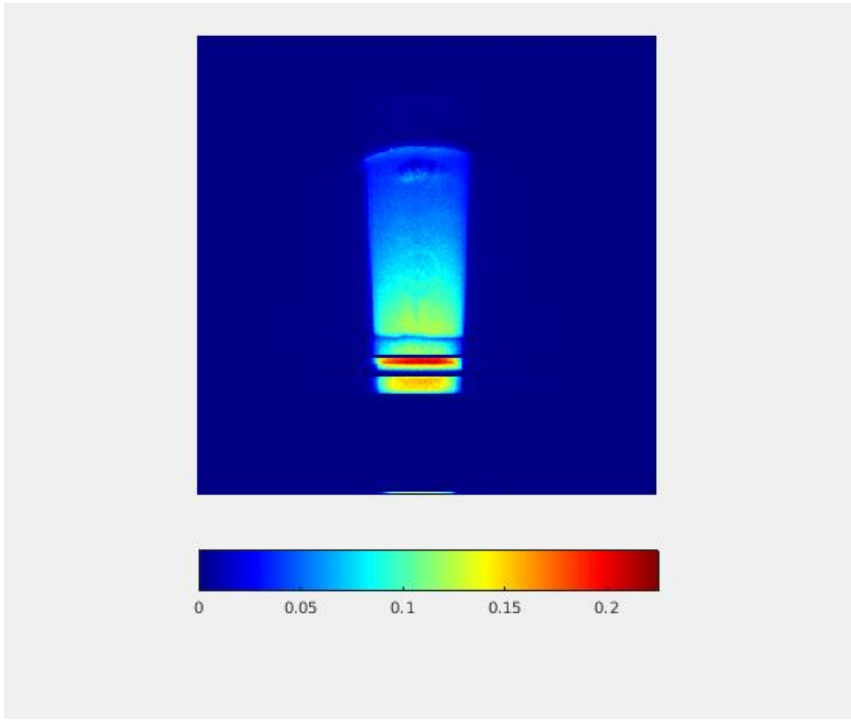


From Stemkes et al. PMB (2016)

Time-resolved (intra-fraction) dose reconstruction by combining time-stamped MRI and linac parameters



1/7 Hz intra-beam 3D MRI during FIM

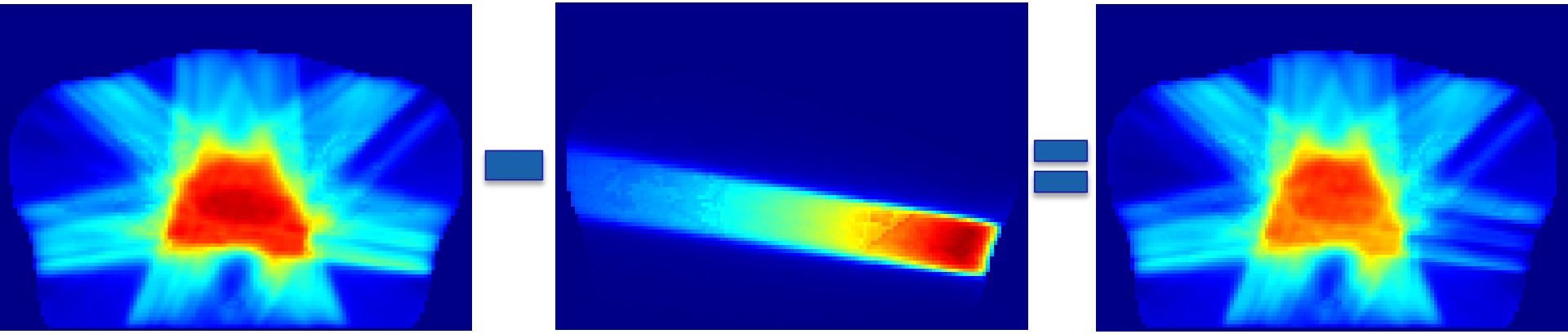


Accumulated/reconstructed dose
(loop not in sync with MRI)

Courtesy Markus Glitzne

MR-linac Treatment Planning (MRLTP)

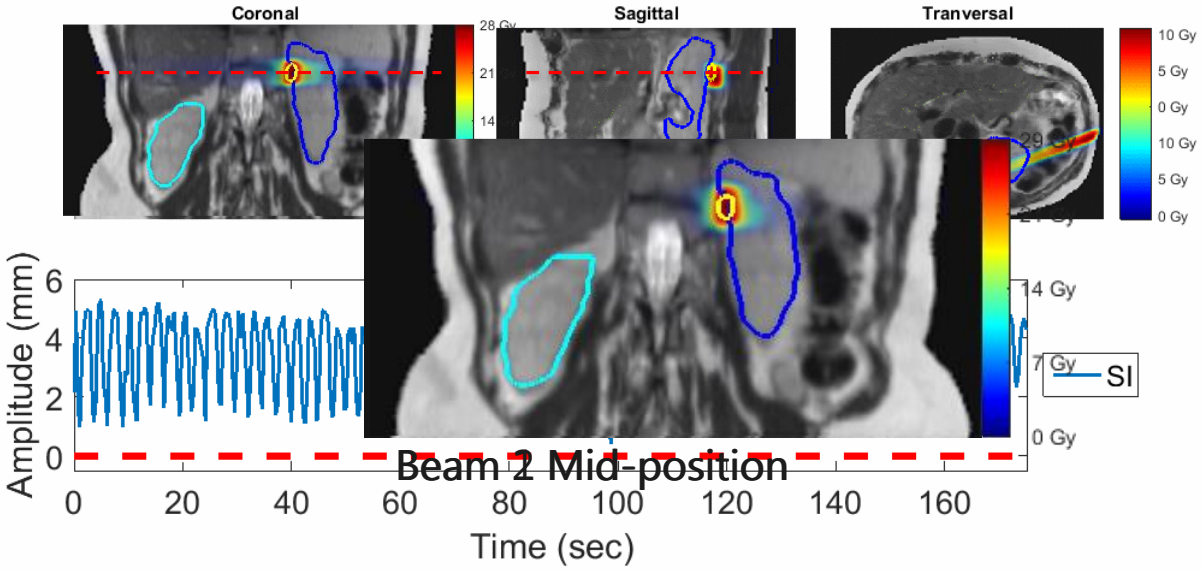
- Integration of online modules
  - Supports anatomy changes
  - Guarantees dose convergence
- Adaptive Sequencer (ASEQ)
- Delivers clinical plans
  - prostate in 90 sec, kidney tumour in 20 sec
  - Validated using regular IMRT QA

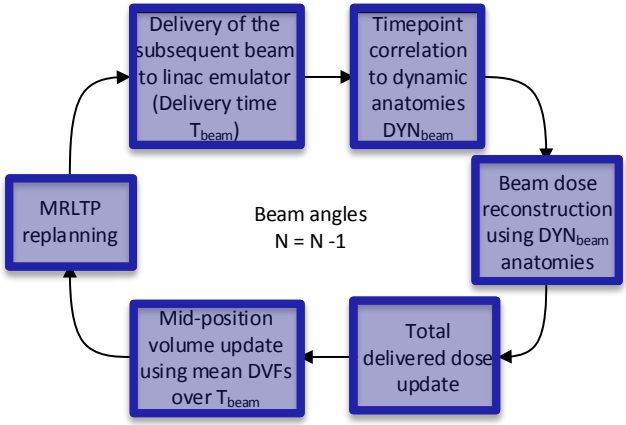


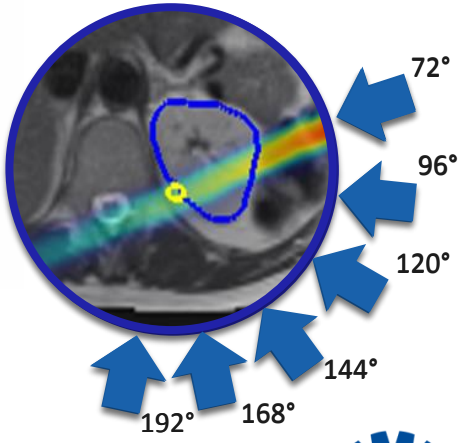
Planned dose **Part of delivered dose** **Updated planned dose**

Kontaxis et al 2015 PMB 60

Inter-beam replanning regime

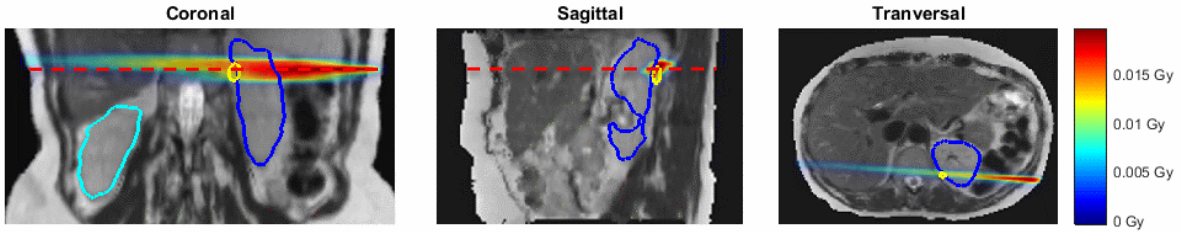


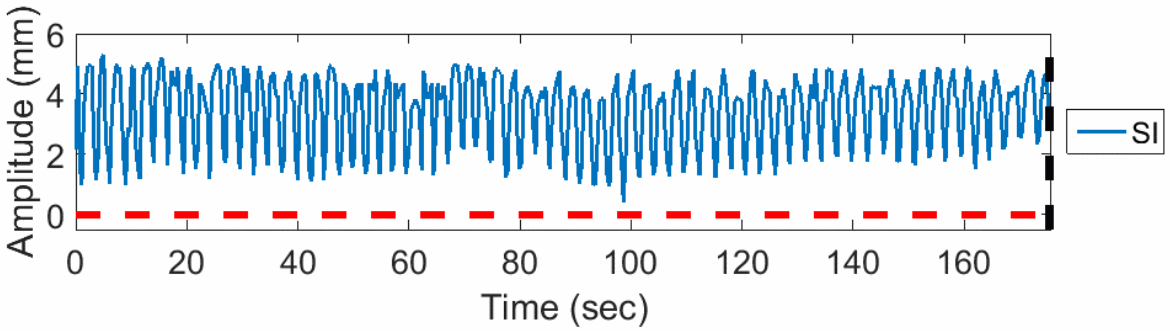


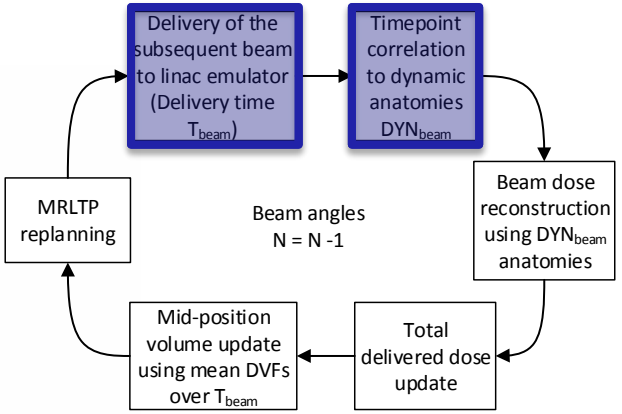


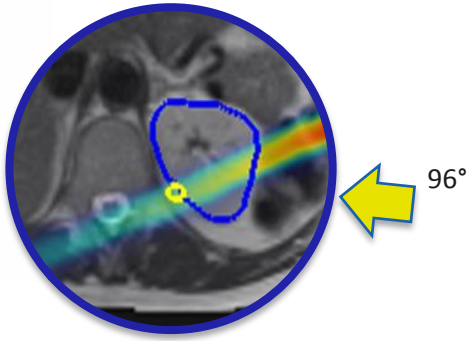
From Kontaxis et al PMB (2017)

Inter-beam replanning regime



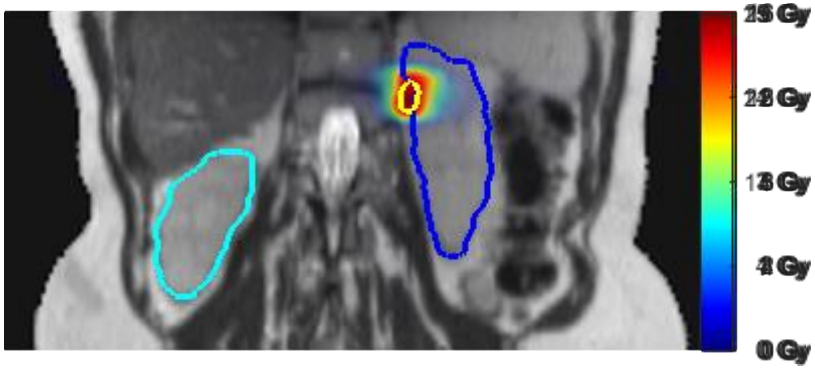


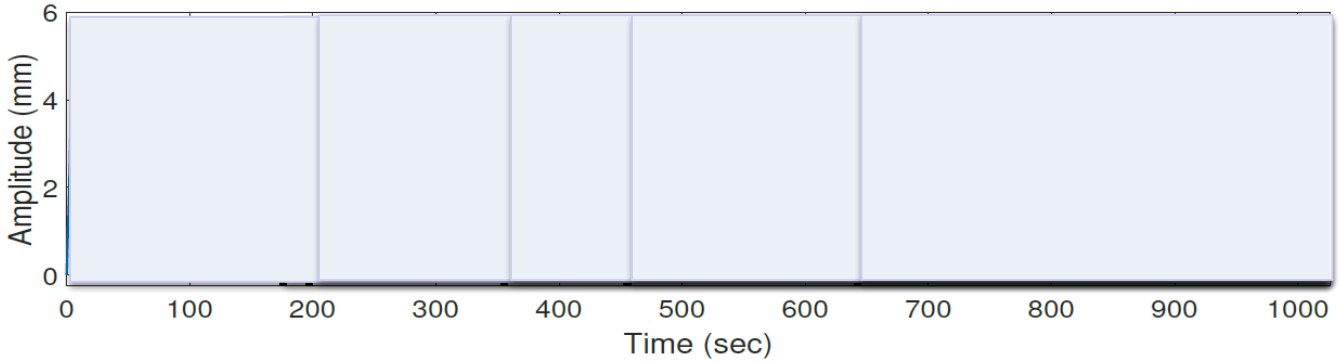


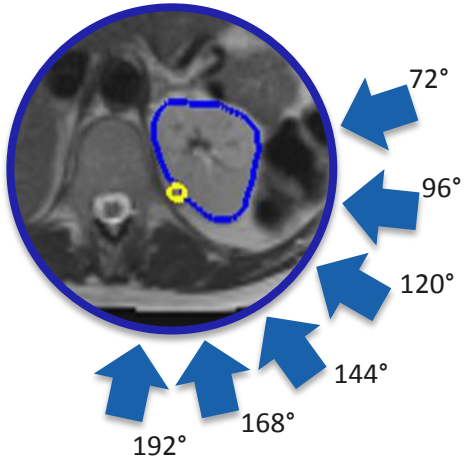


From Kontaxis et al PMB (2017)

Inter-beam replanning regime

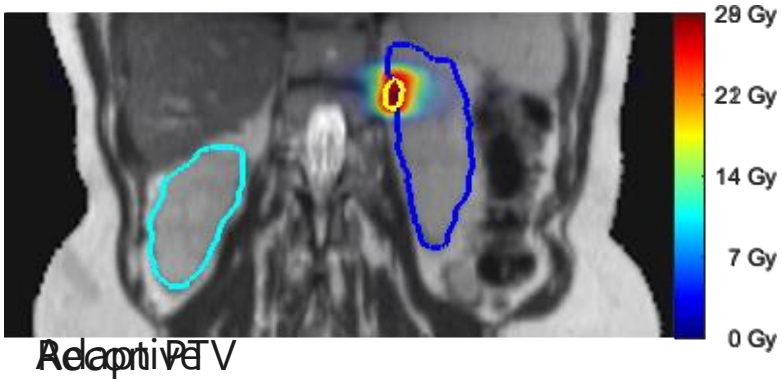






From Kontaxis et al PMB (2017)

Inter-beam replanning vs Conventional



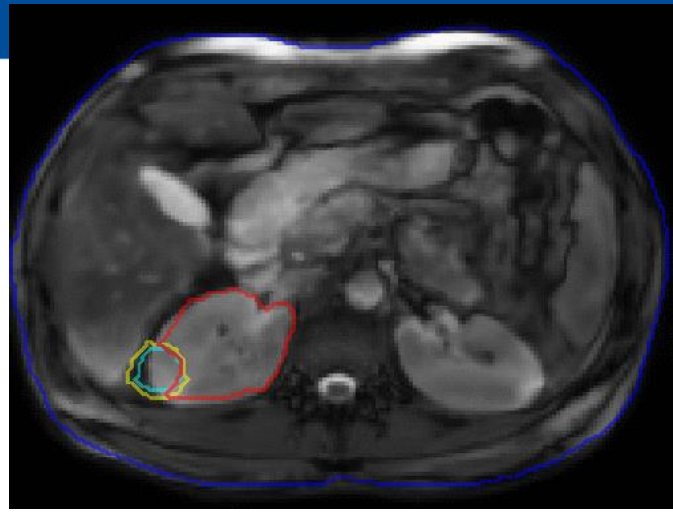
From Kontaxis et al PMB (2017)

Summary

- 1.5 T MRI linac is operational and clinical
- Monte Carlo is required for dose calculations
- Monte Carlo is required for dosimetry calibration

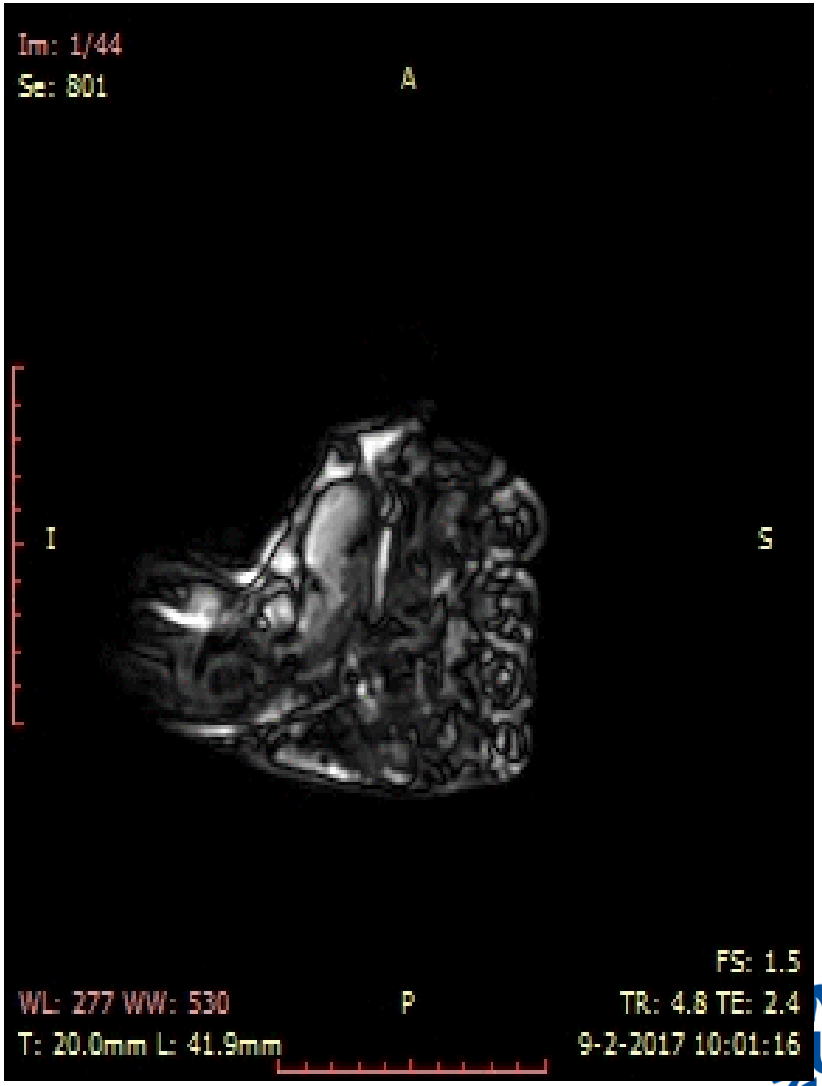
- 1.5 T MRI enables near-real-time 4D anatomical tracking

- This screams for fast Monte Carlo dose engines:
  - Real-time dose accumulation
  - Real-time plan adaptation via re-planning



Real-time plan adaptation while accounting for real-time accumulated dose.
(From Kontaxis et al. PMB, 2015 and 2017)

Thumbs up from and to my co-workers at UMC Utrecht!



First volunteer images on Elekta MRI linac in UMC Utrecht