CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Imaging and image guidance in radiotherapy

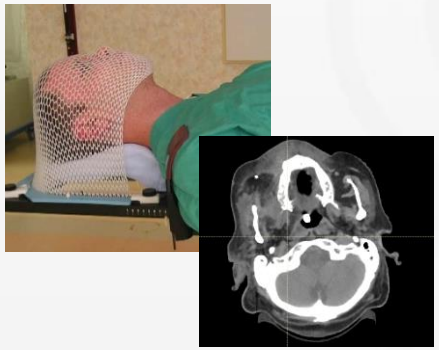
Petra Trnkova

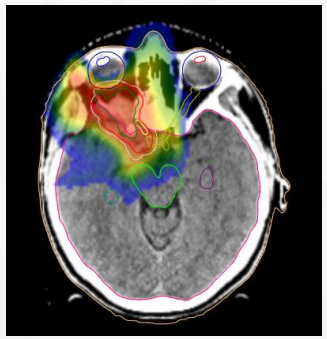
Role of imaging

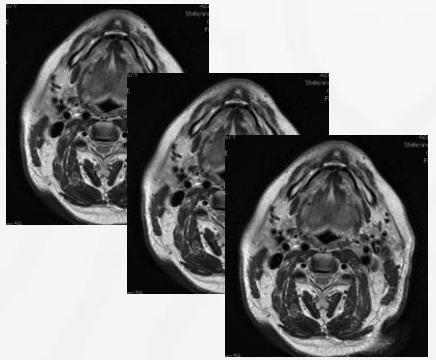
- An essential component of any radiotherapy modality
- Precise tumour localization prior and during the treatment
- Image guidance plays a crucial role in many workflow steps

Standard workflow in radiotherapy

Immobilization and imaging → Treatment planning and verification → Treatment → Follow up

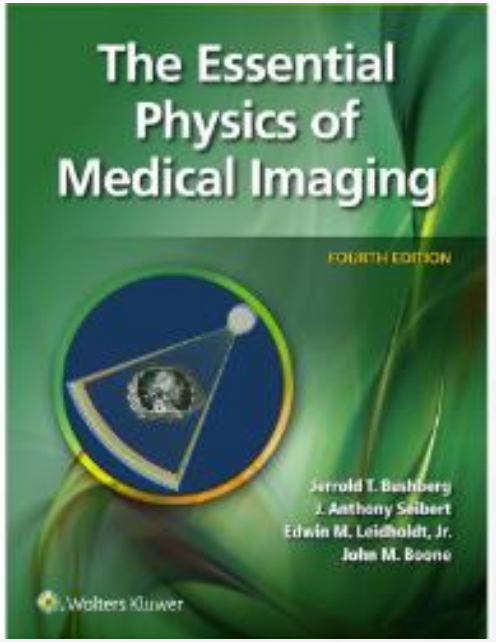






Overview

- Imaging for treatment planning
- Imaging for positioning and verification
- Imaging for monitoring and evaluation
- Imaging for follow-up
- Emerging technologies



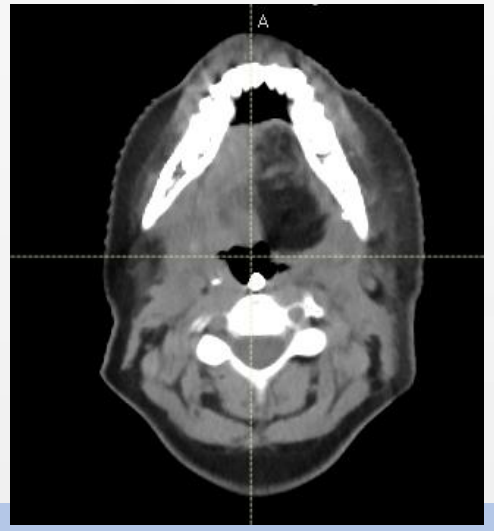
Overview

- Imaging for treatment planning
- Imaging for positioning and verification
- Imaging for monitoring and evaluation
- Imaging for follow-up
- Emerging technologies

Imaging modalities for treatment planning

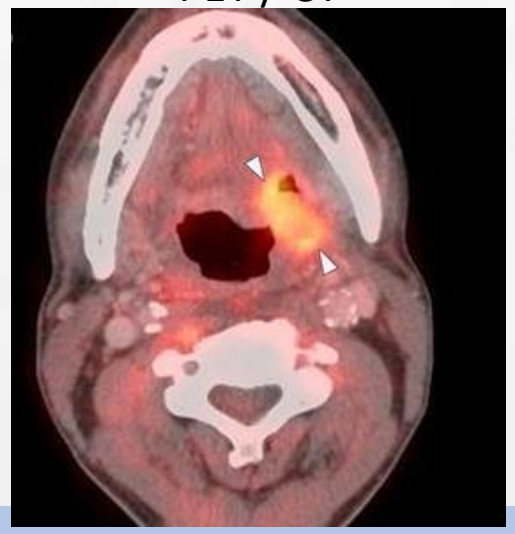
- Computer tomography
- Magnetic resonance imaging
- Positron emission tomography

CT

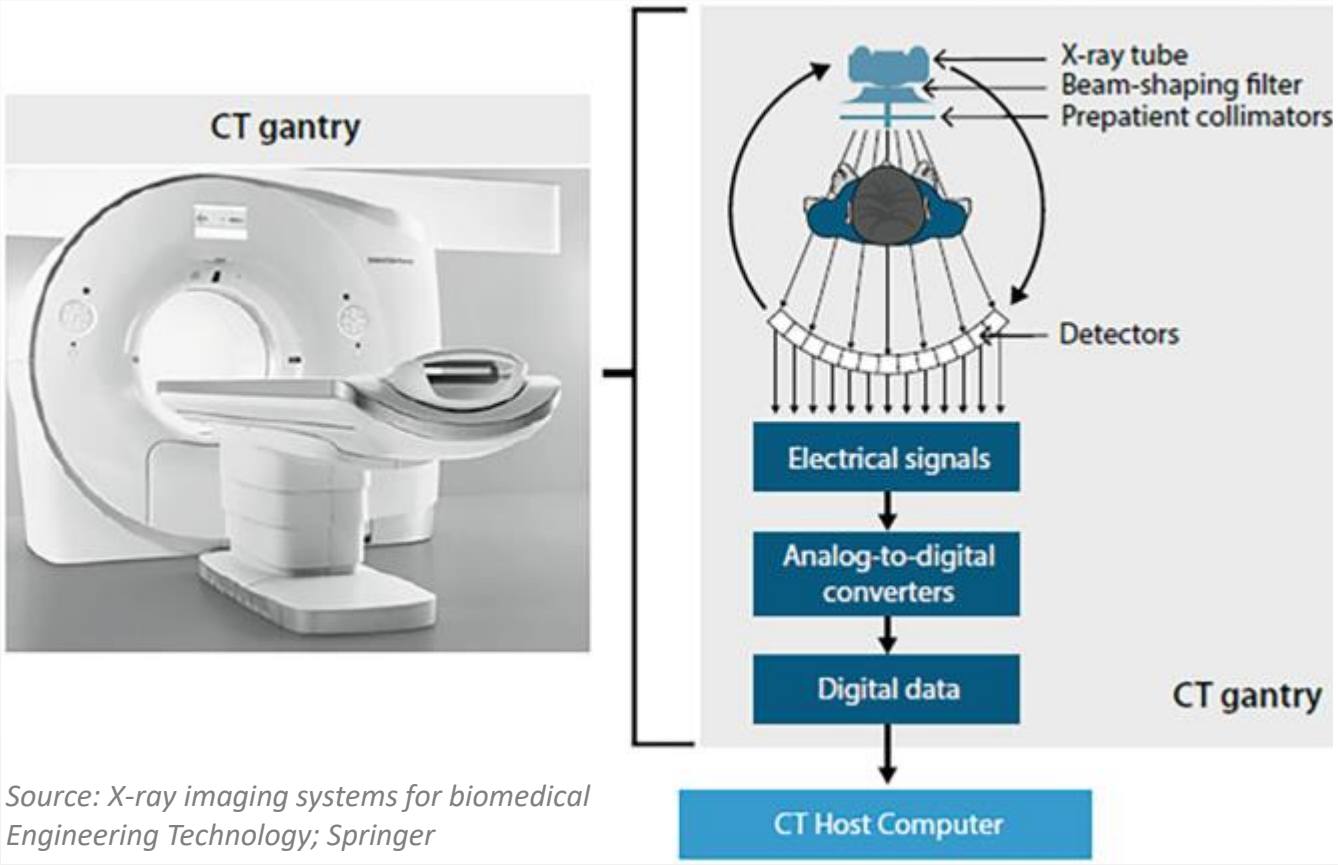


MRI

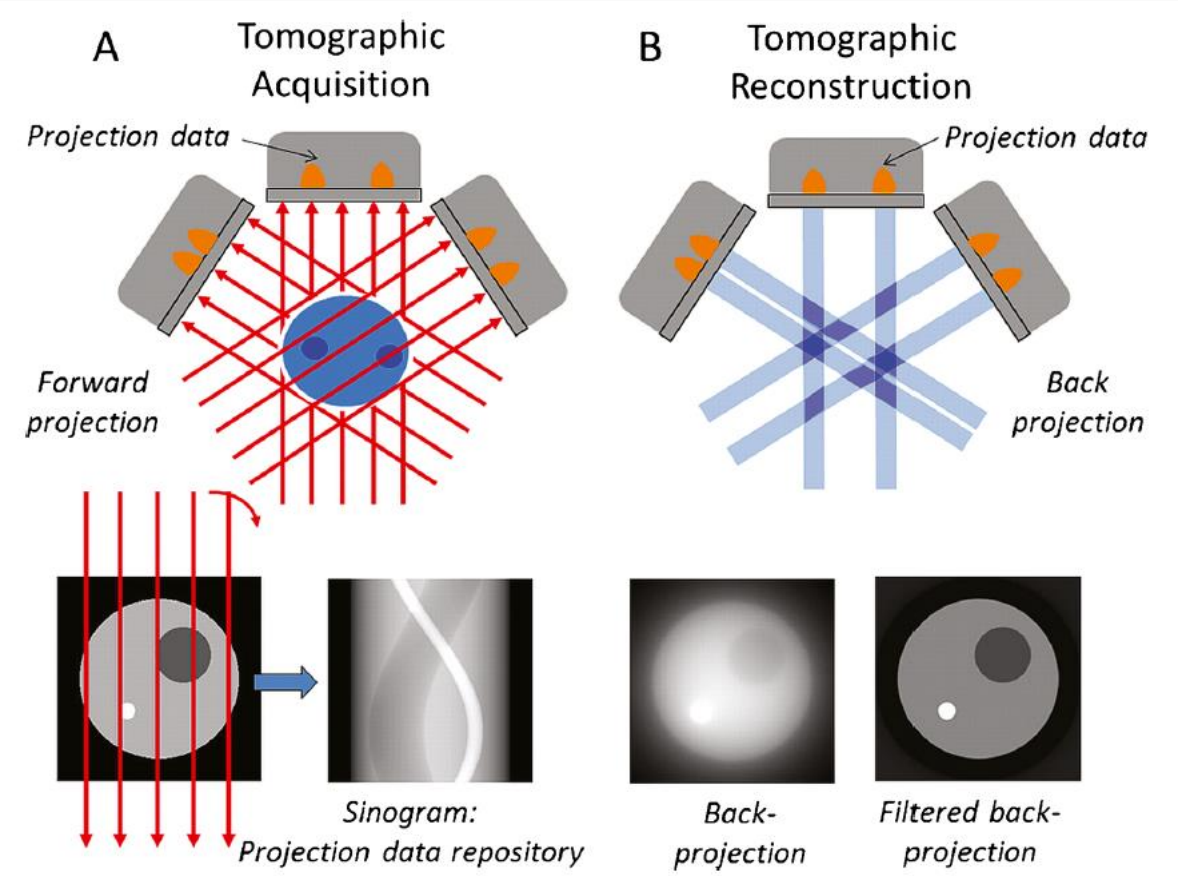
PET / CT



Computer tomography (CT)

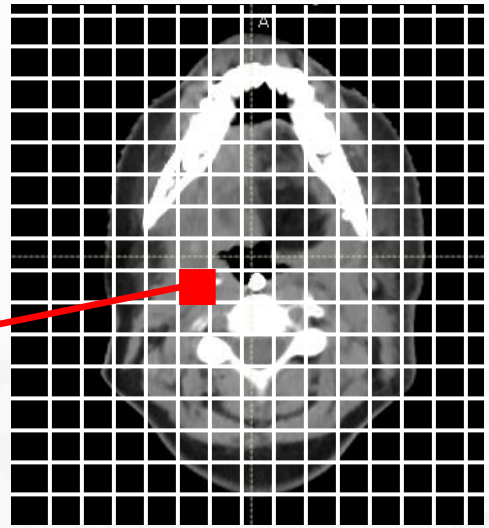


Source: X-ray imaging systems for biomedical Engineering Technology; Springer



Source: Siebert JA: Iterative reconstruction - how it works?; Pediatr Radiol 2014

Hounsfield units



- Definition:

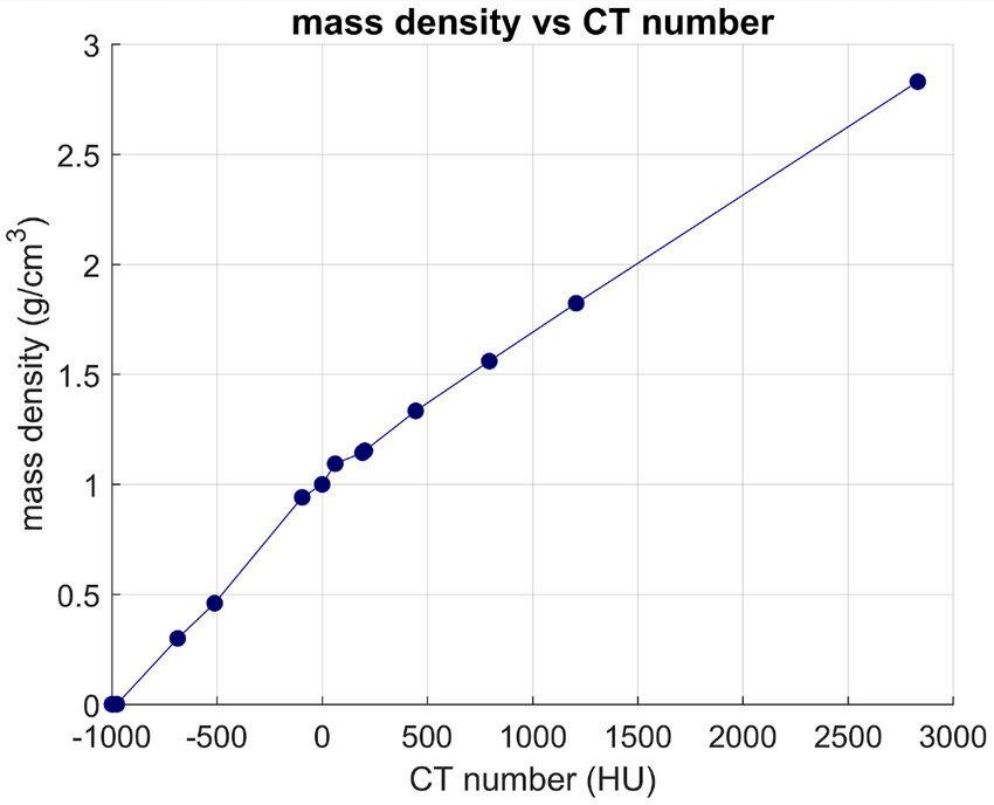
$$Image\ intensity\ [HU] = 1000 * \frac{\mu_{tissue} - \mu_{water}}{\mu_{water}}$$

- Range: −1000 to ~3000
  - Center value: 0 HU -> attenuation of water
  - materials that absorb more x-rays have greater HU values

Cortical bone: ~ 1000 HU
Muscle: ~ 40 HU
Gray matter: ~ 40 HU
White matter: ~ 30 HU

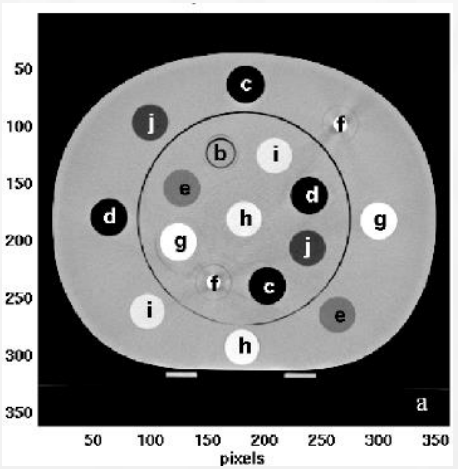
Cerebrospinal fluid: ~ 10 HU
Fat: −60 HU
Air: −1000 HU
Artificial materials: > 1000 HU

Calibration curve

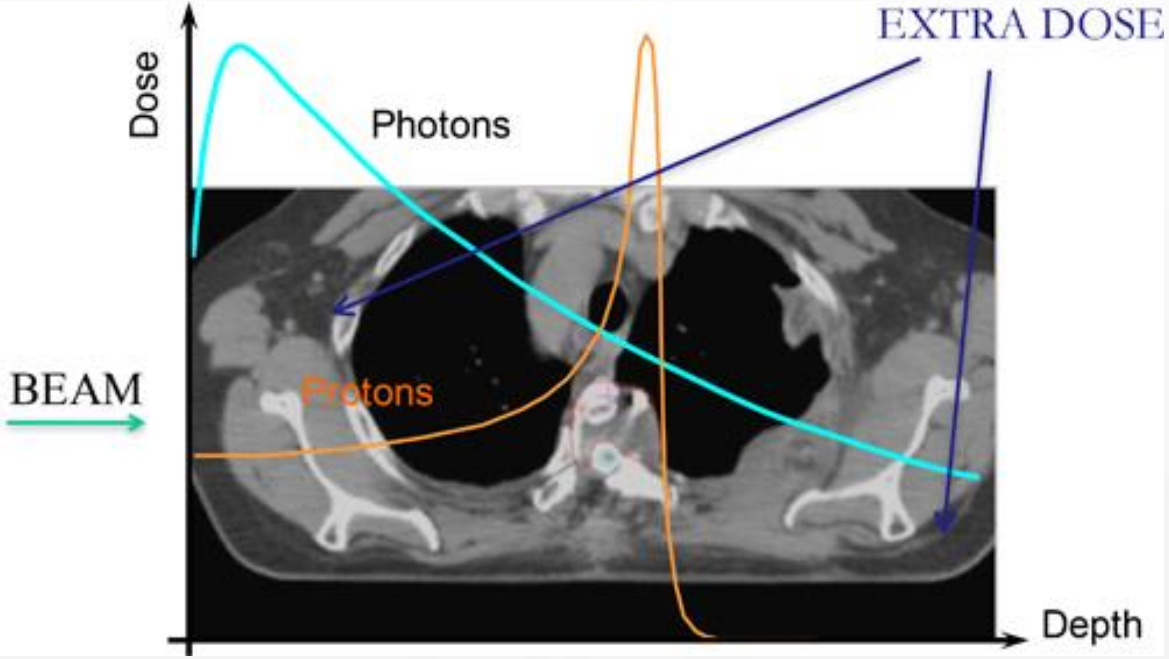


- Measurements with tissue equivalent materials with known mass density

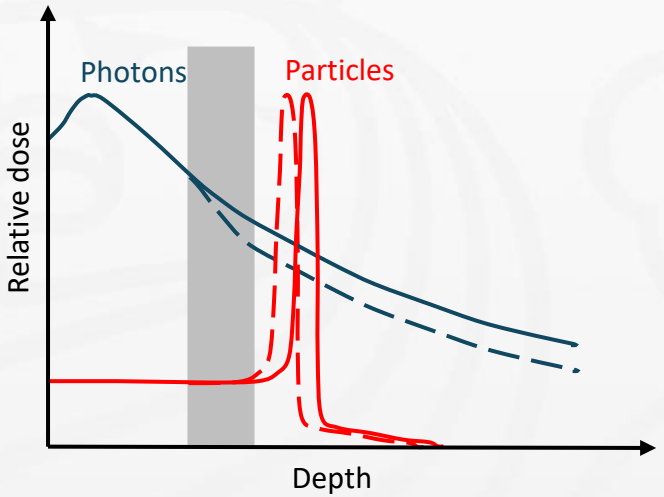
CIRS phantom



Particle therapy



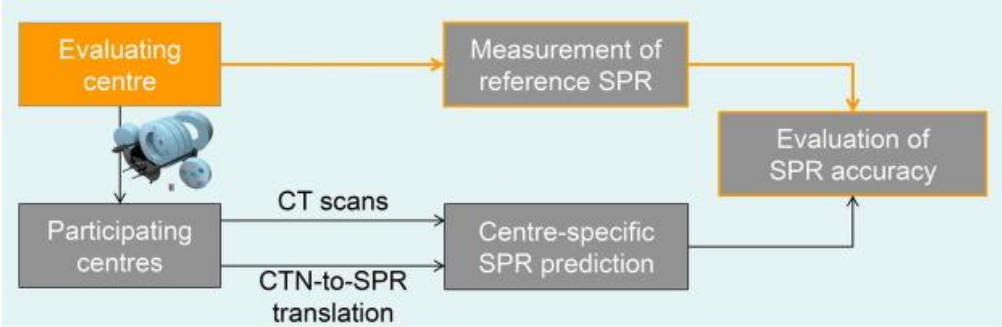
Paganetti, Proton Beam Therapy (Book)



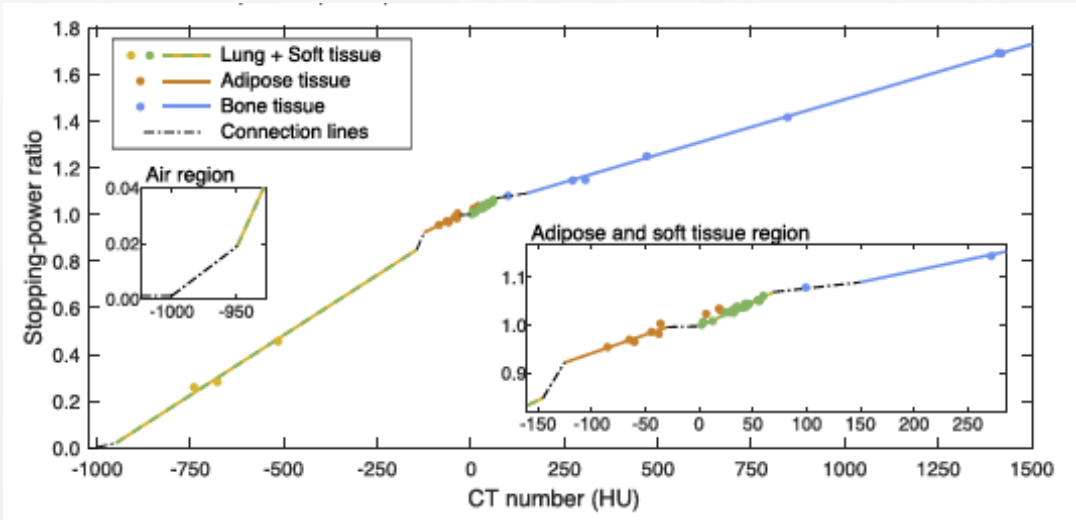
Range estimation ➡ Stopping power ratio

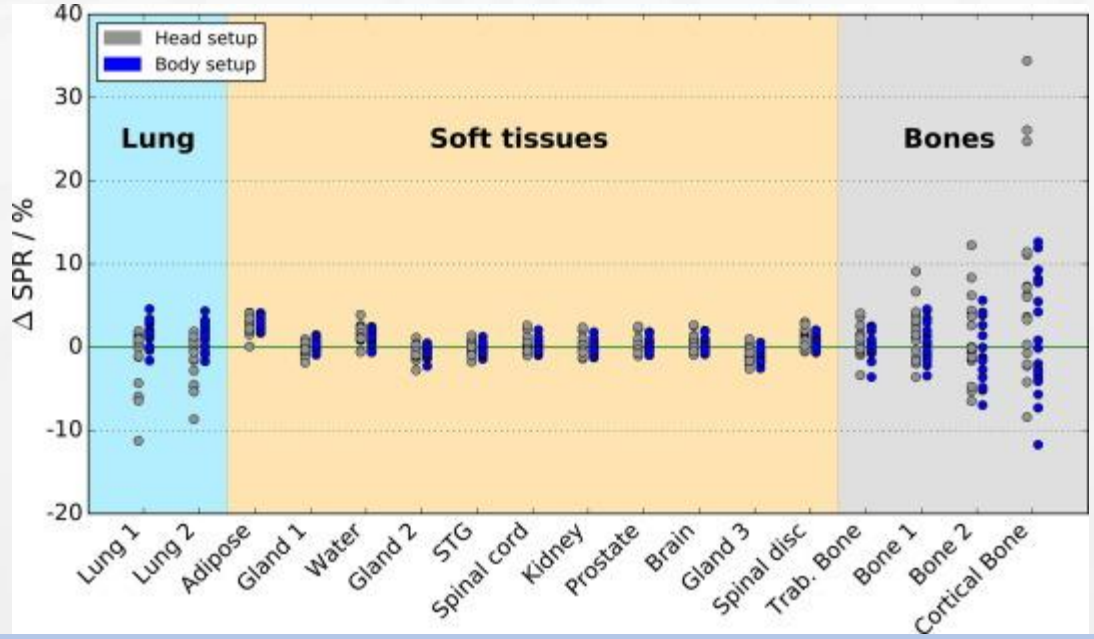
Stopping power ratio

- Experimentally:
  - Measurements of the WET of each insert
- Calculation:
  - Bethe-Bloch equation



Peters, Radiother Oncol, 2021





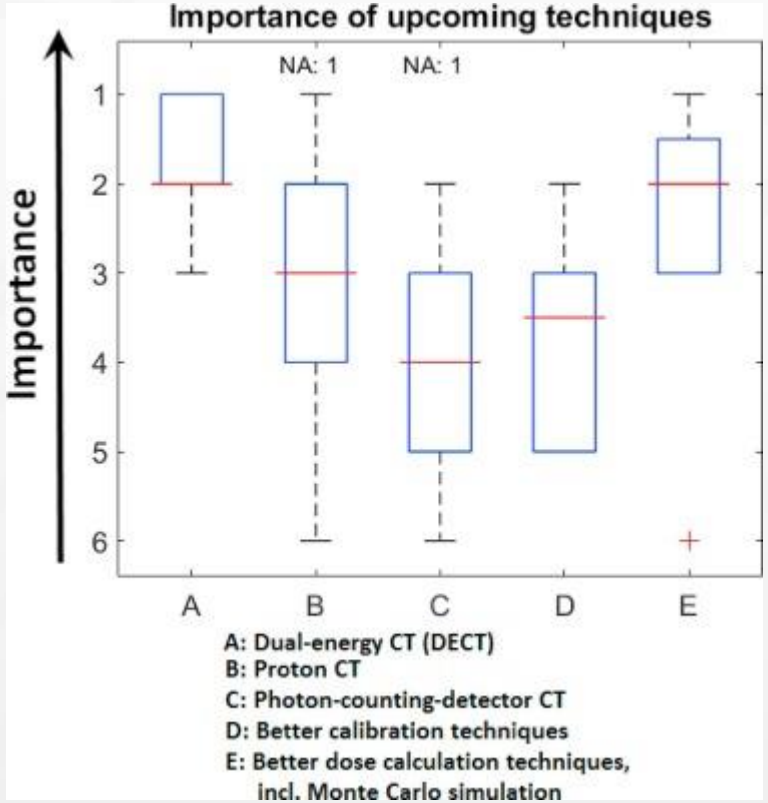
Peters, Radiother Oncol, 2023

Improvement in range estimation

- SECT: software improvements: post-processing algorithms, iterative image reconstruction, artefact reduction
- Dual-energy CT
- Photon counting CT
- Proton CT

- Consensus guide for SPR prediction using a HLUT

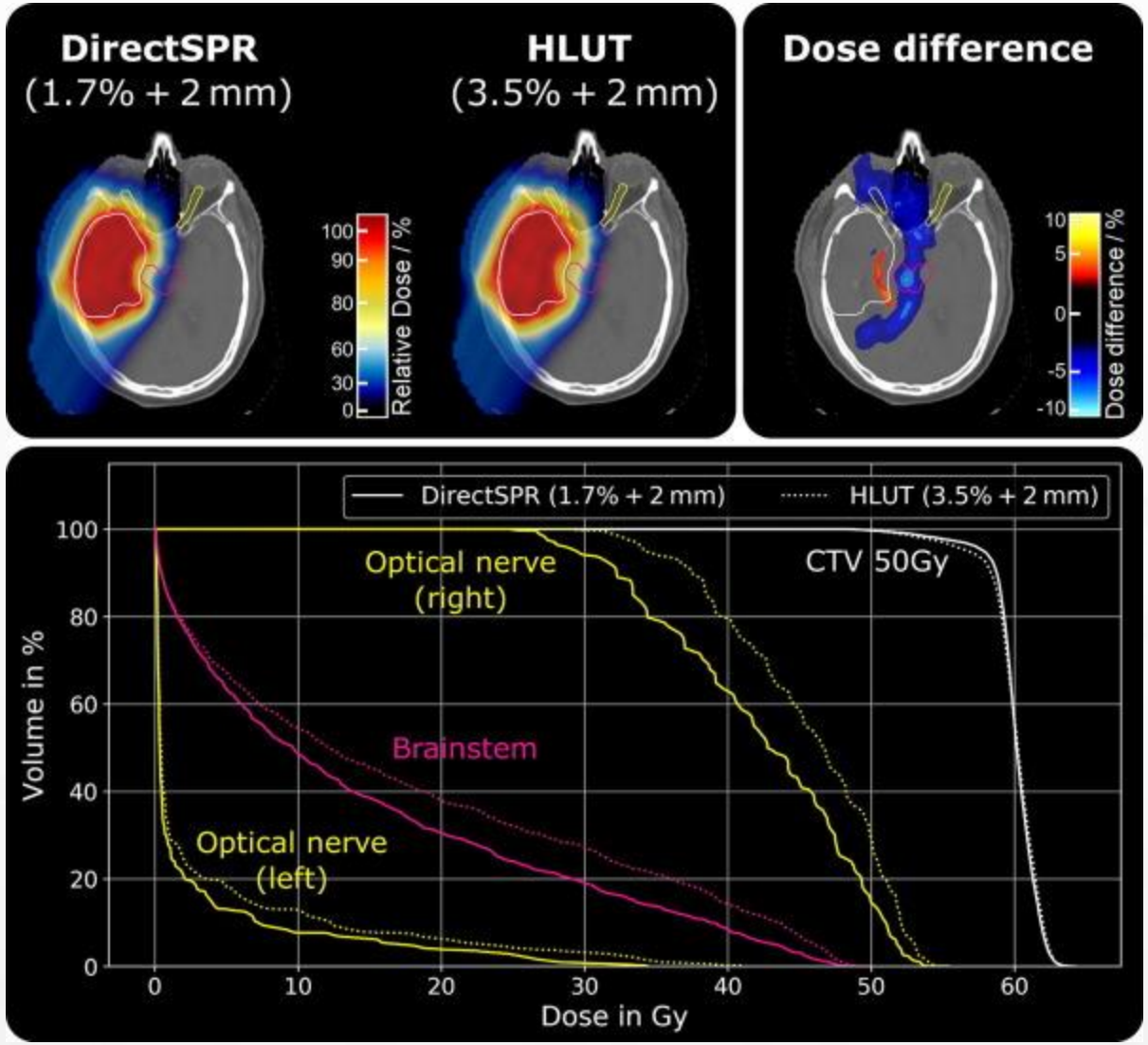
Peters, Radiother Oncol, 2023



Taasti, phiRO, 2018

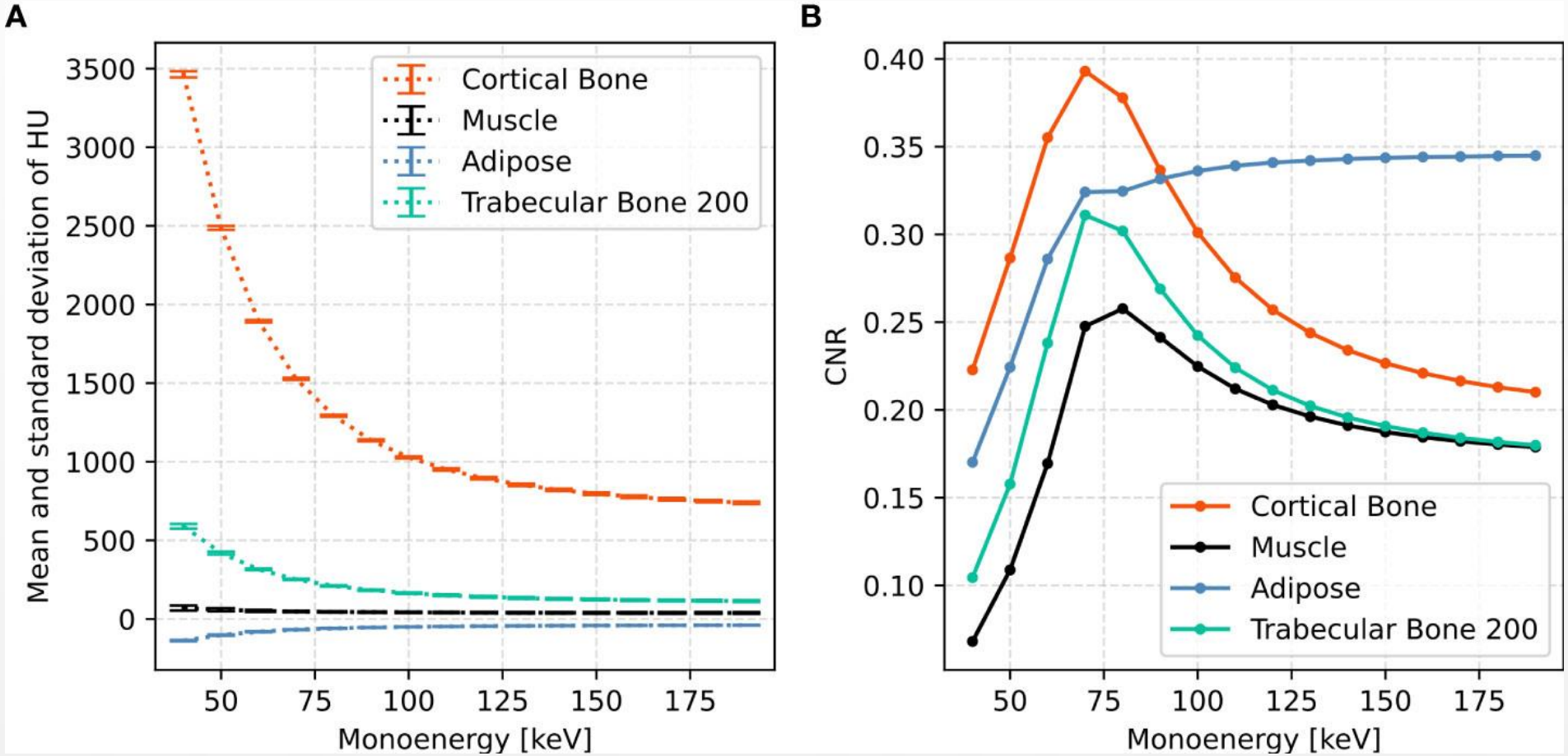
DECT

- Two CT scans with different effective X-ray spectra to gain more information about tissue properties:
  - Relative electron density
  - Mean ionization potential
- <u>Implementation:</u>
  - Pseudo-monoenergetic CT scans with HLUT
  - DirectSPR calculation



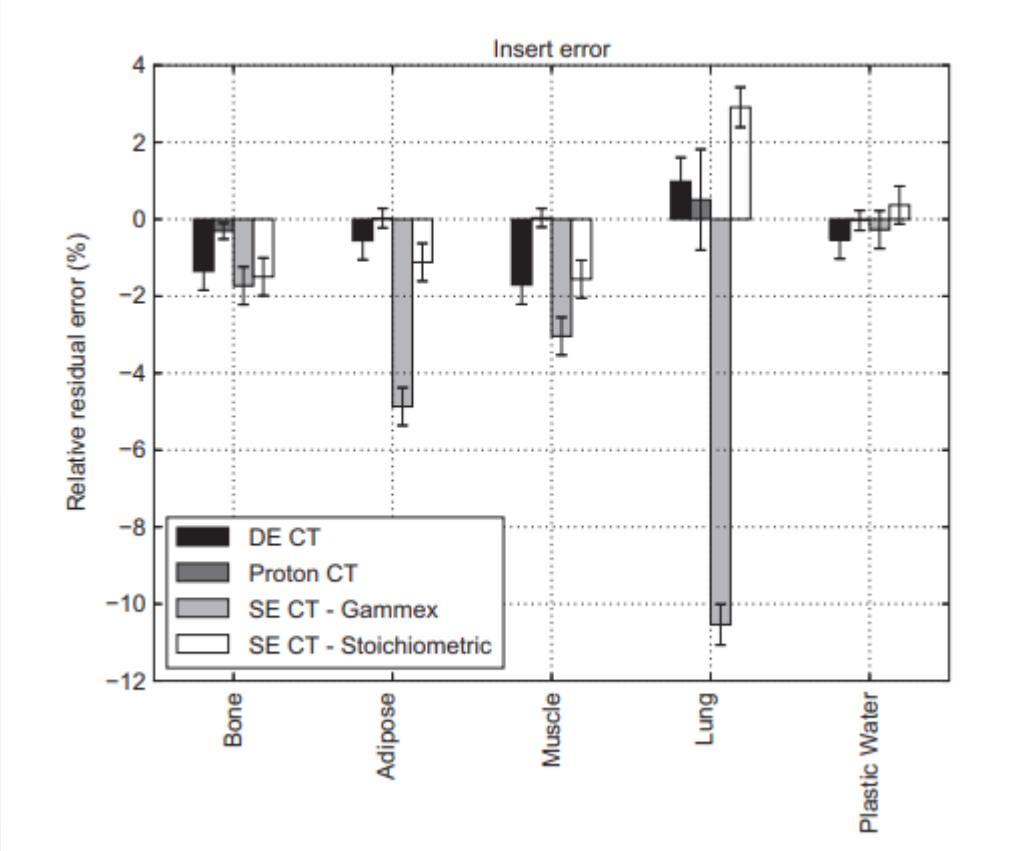
Peters, Radiother Oncol, 2022

Photon counting CT



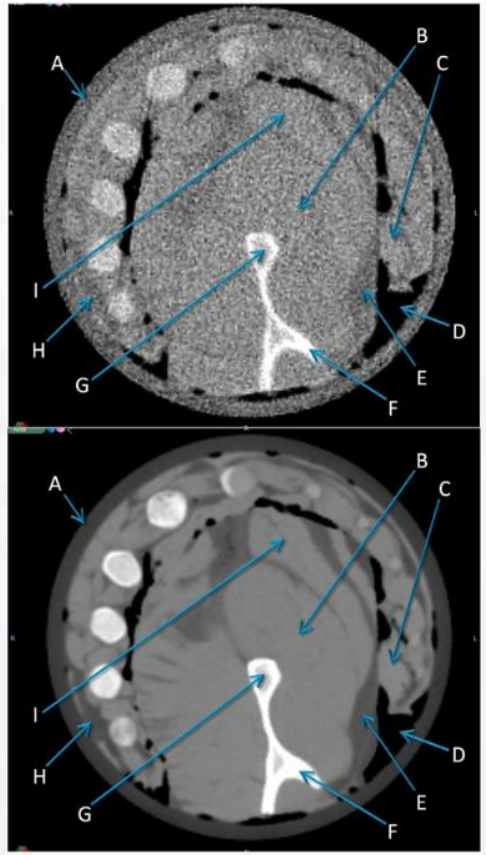
Hu, Front Oncol, 2022

Proton CT



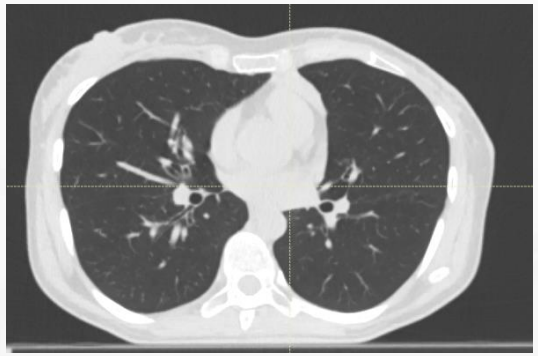
Hansen, Acta Oncol 2015

FIGURE 5 Examples of 1 mm thick CT slices for the porcine pectoral girdle and ribs, showing ROI. Top: pCT. Bottom: x-ray CT. Labels are as follows: A, Blue Wax; B, muscle (shoulder-med); C, muscle (ribs); D, air; E, adipose (shoulder); F, compact bone; G, trabecular bone (shoulder); H, adipose (ribs); I, muscle (shoulder-lat)



DeJongh, MedPhys 2023

CT advantages and disadvantages

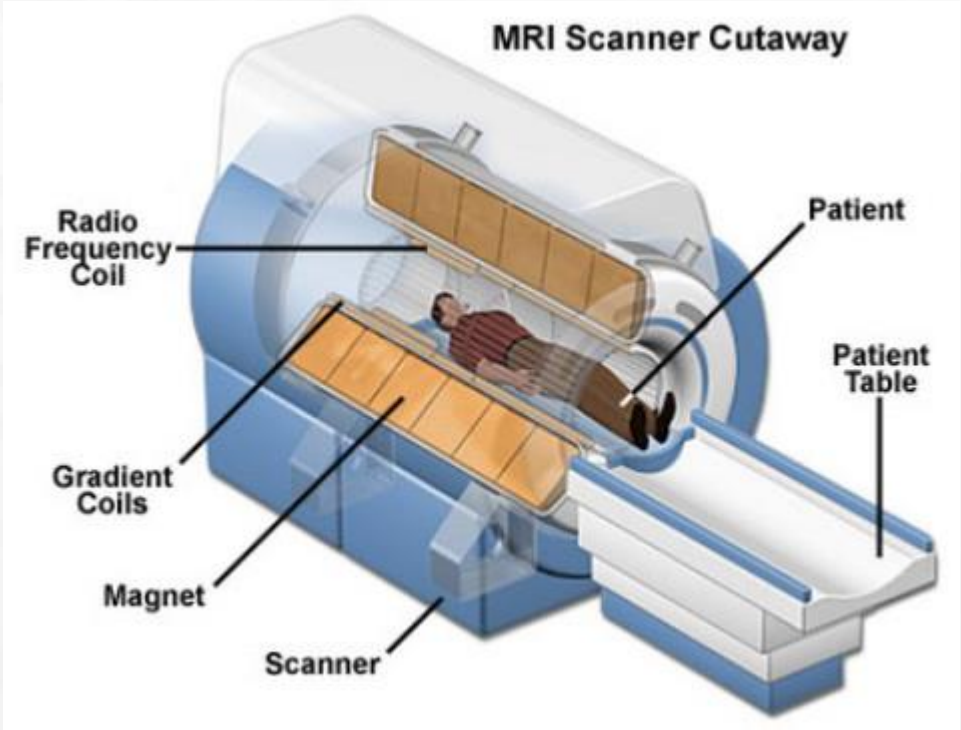




- Advantages:
  - Image intensity: Hounsfiled Units (HU)
  - Direct conversion to electron density or stopping power
- Disadvantages:
  - Low soft tissue contrast

Magnetic resonance imaging (MRI)

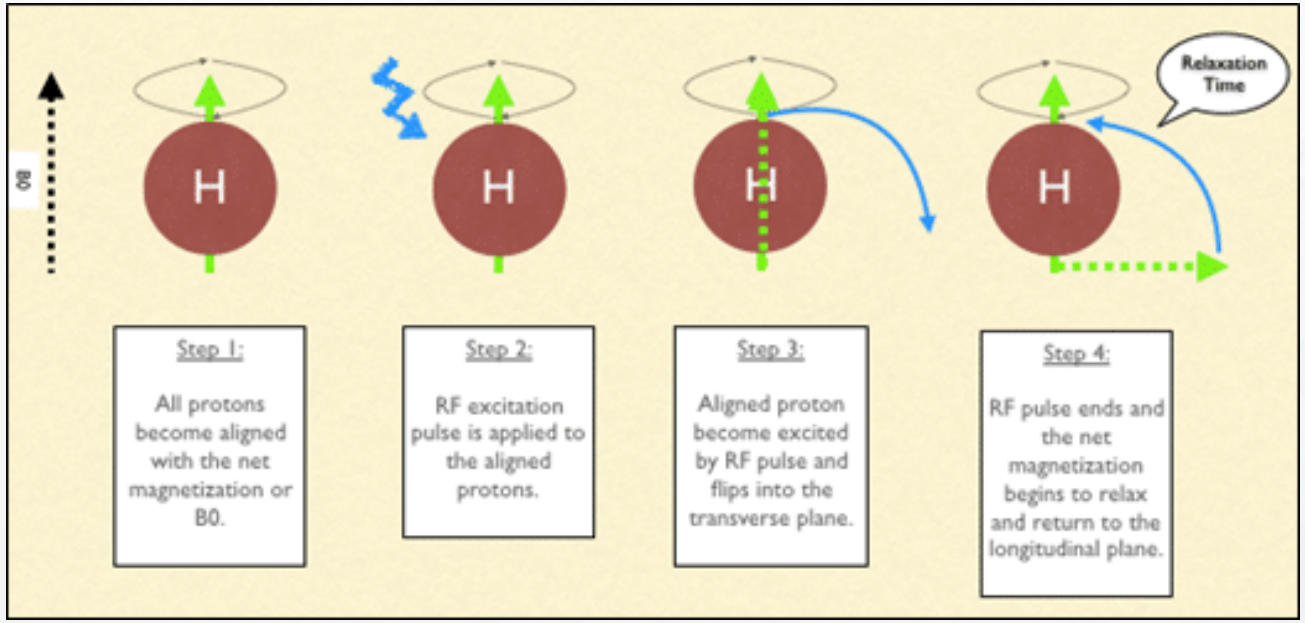
Philips

Philips

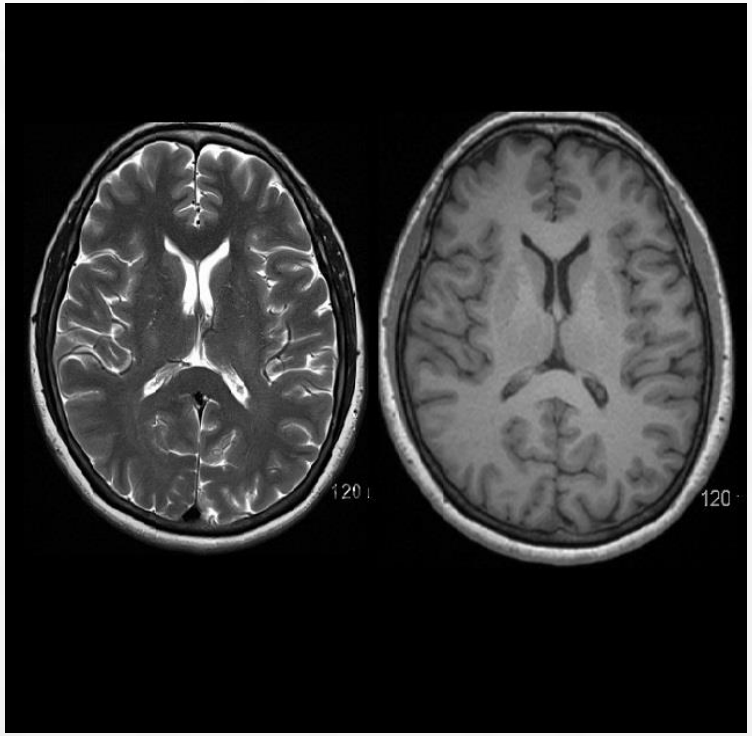


https://www.rpworld.com/

Physics principles

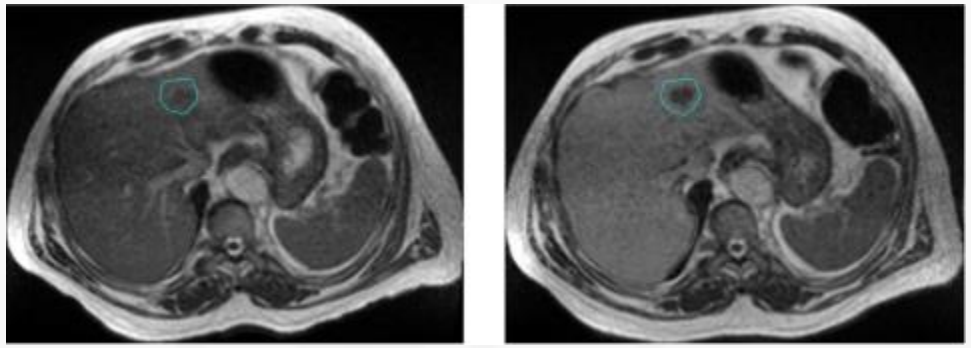


teachmeanatomy.info



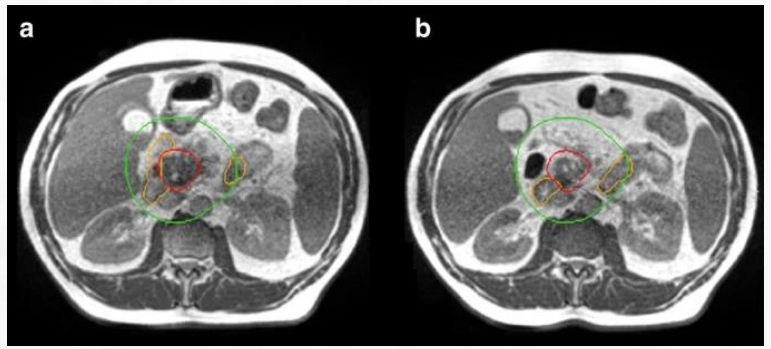
MRI: Magnetic resonance imaging

Liver



Prime et al, Sem Rad Onc 2024

Pancreas



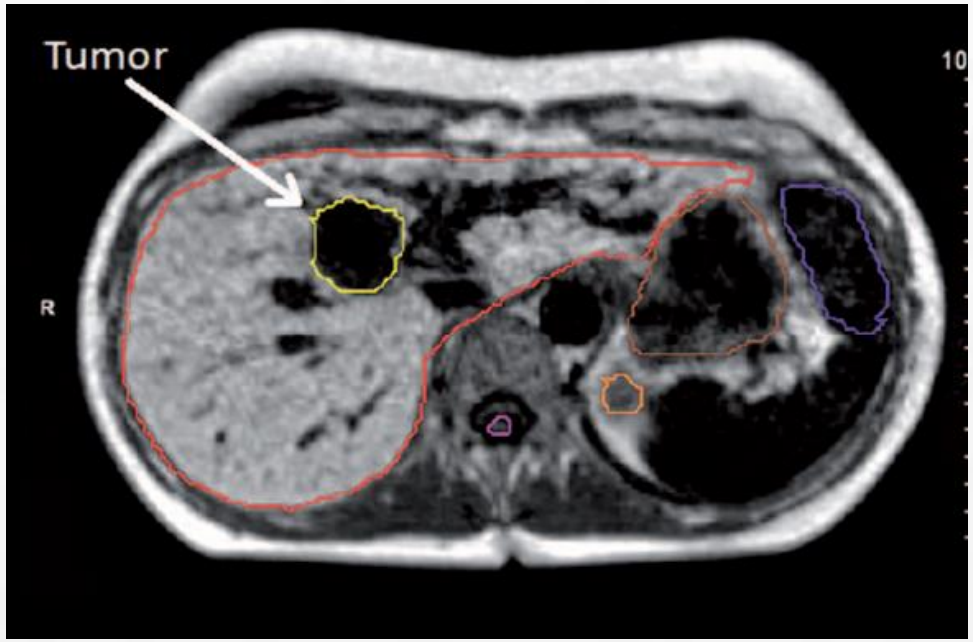
Boldrini et al, Radiation Oncology 2019

- Advantage:
  - High soft tissue contrast
- Disadvantage:
  - Image intensity: magnetic relaxation properties of hydrogen atom
  - No conversation between electron density or stopping power

Comparison MRI and CT

CT

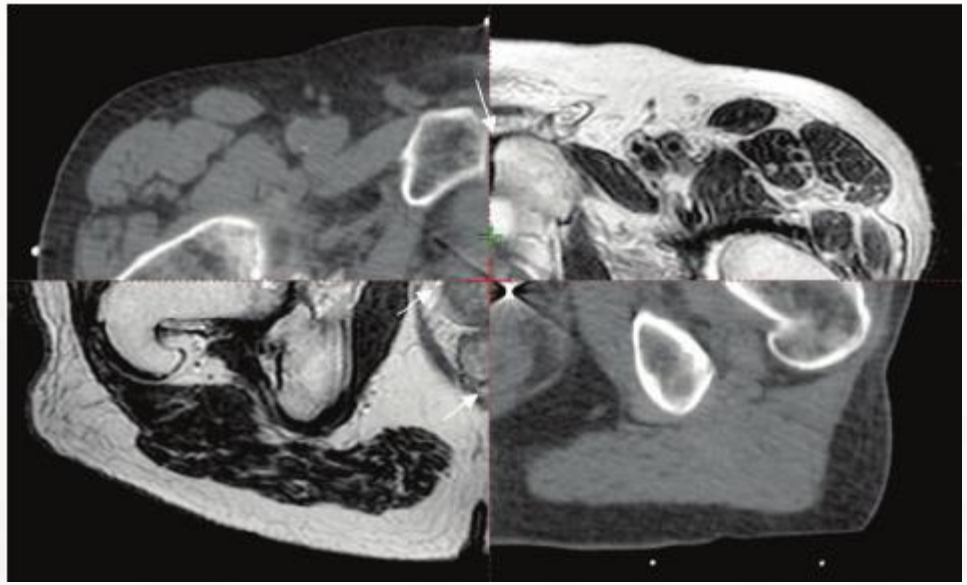
MRI



Registration CT and MRI

- CT: planning
- MRI: segmentation

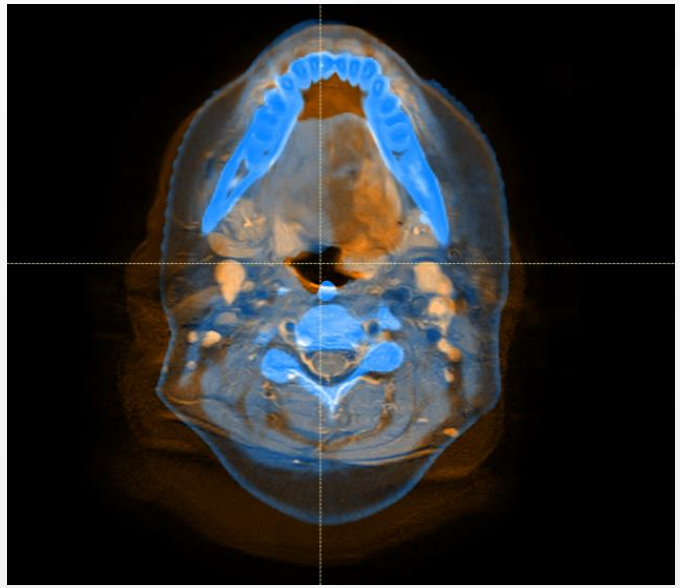
- Disadvantages:
  - Uncertainties in image registration
    - Different position
  - Time requirements
    - More appointments for more imaging modalities

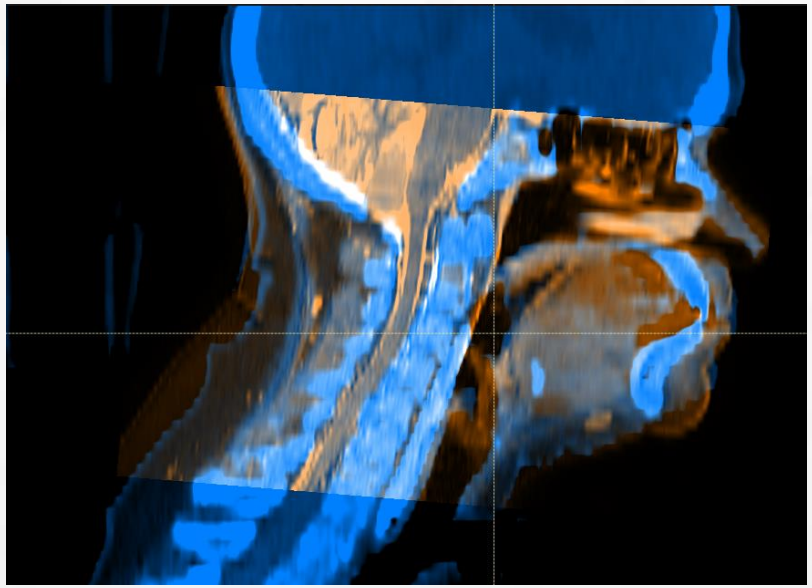


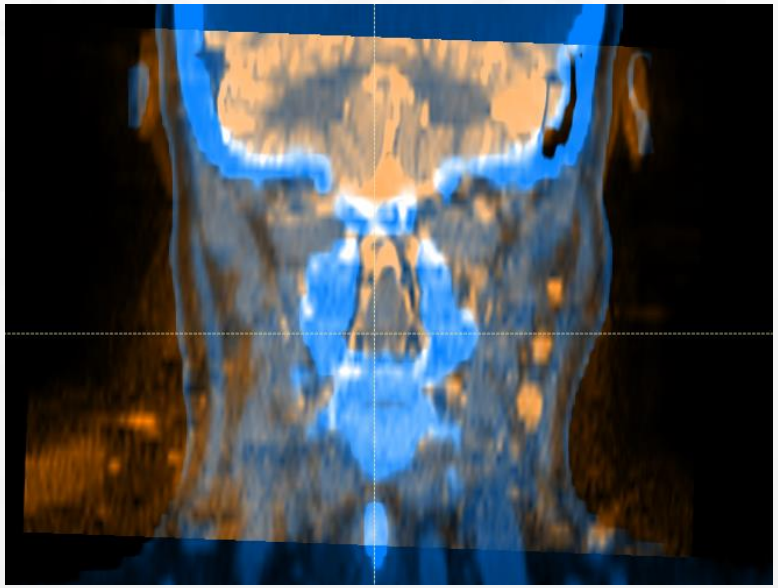
Hanvey et al, Br J Radiol 2012

Image registration

- Geometrical translation and rotation, potentially deformation
- Often difficult -> selection of the focus area

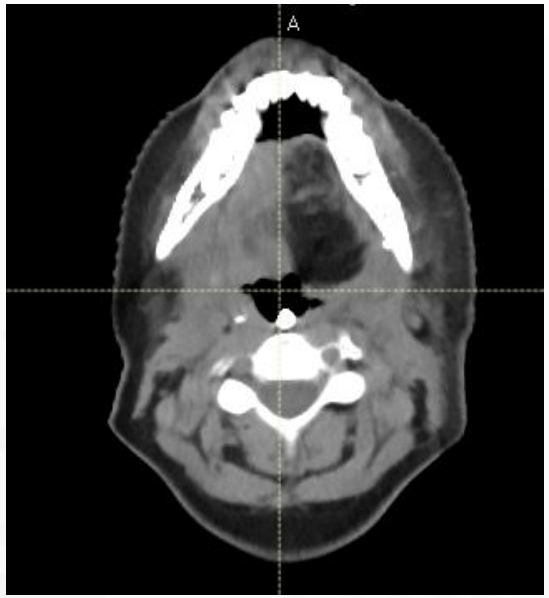






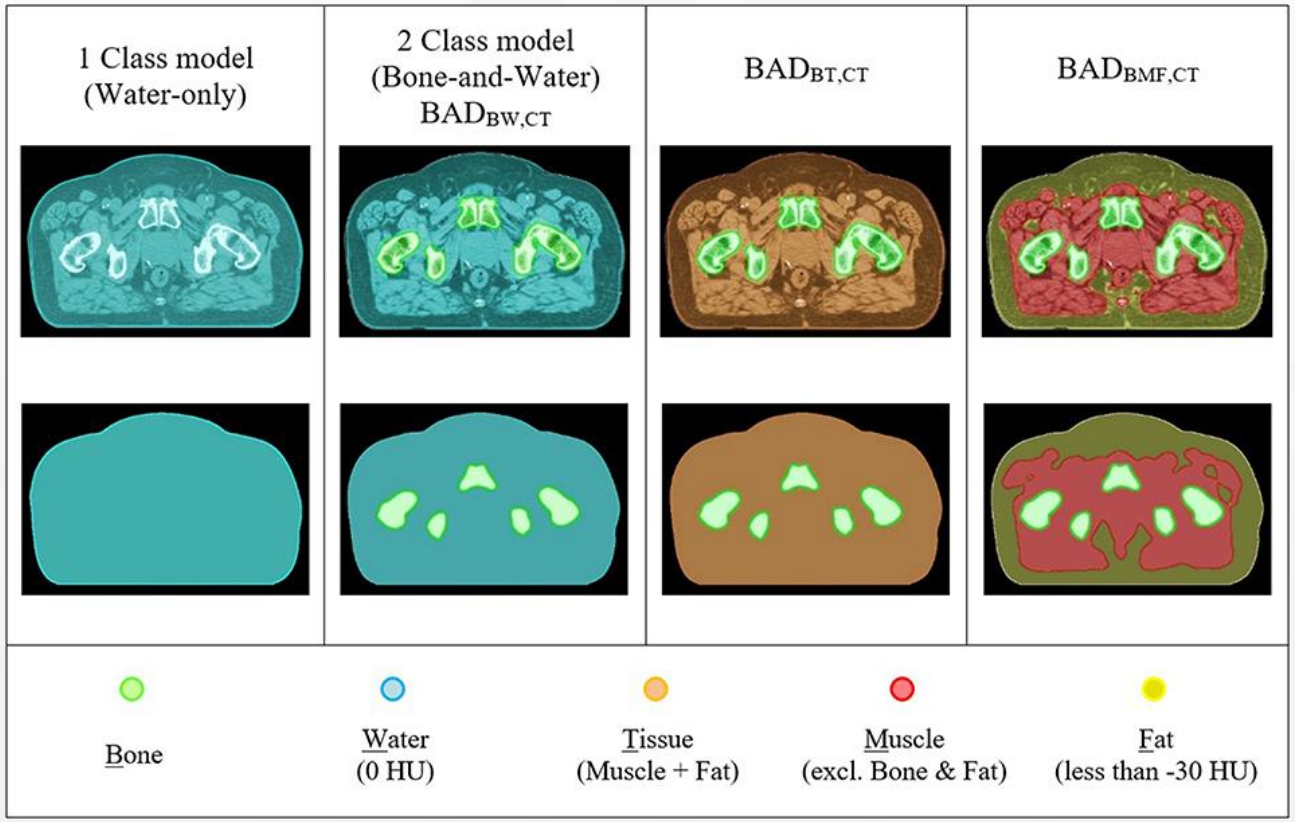
Treatment planning

- Planning CT:
  - Performed in the treatment position
  - No contrast material allowed
  - Correction for artefacts: IMAR
- Additional imaging:
  - MRI, CT with contrast, PET/CT
  - In treatment position if available
  - Diagnostic imaging



MRI-only treatment planning

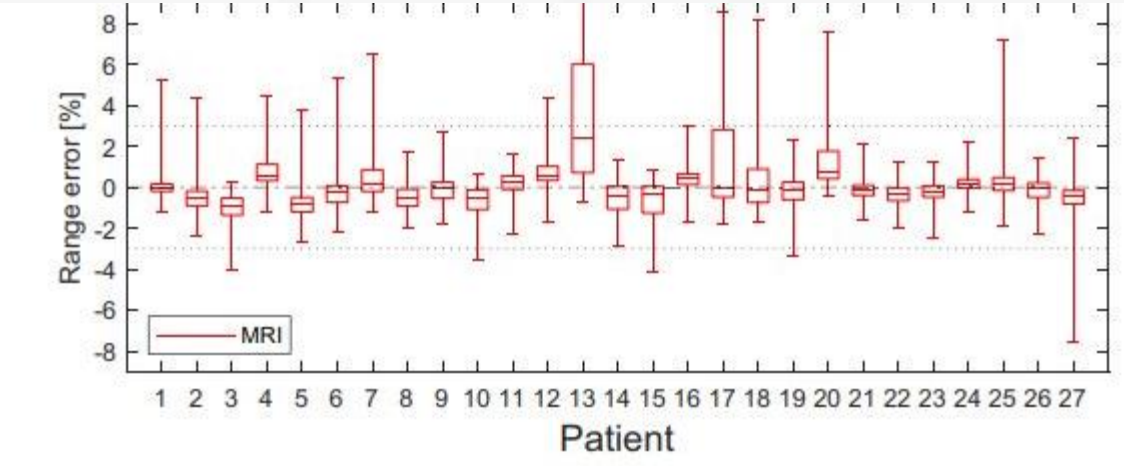
- Bulk density overrides

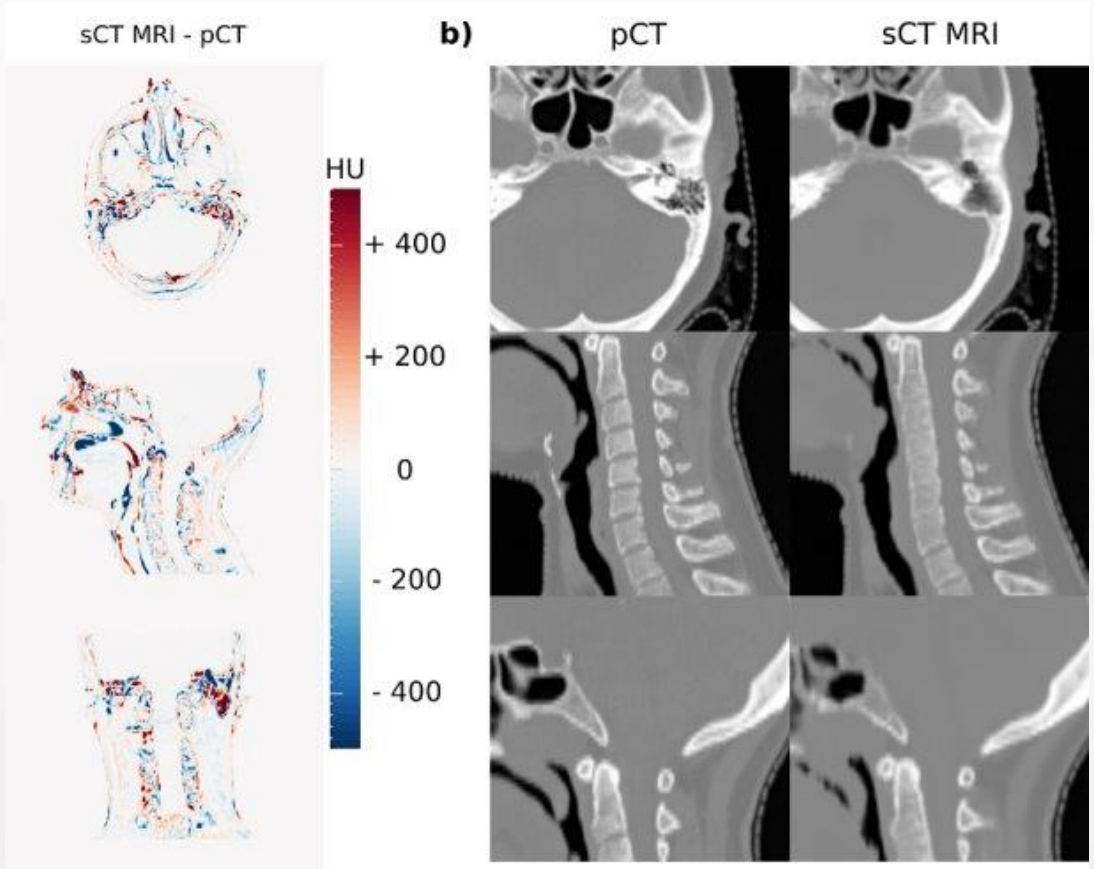


Choi at al, Frontiers 2019

MRI-only treatment planning

- Bulk density overrides
- Synthetic CT generated from MRI images

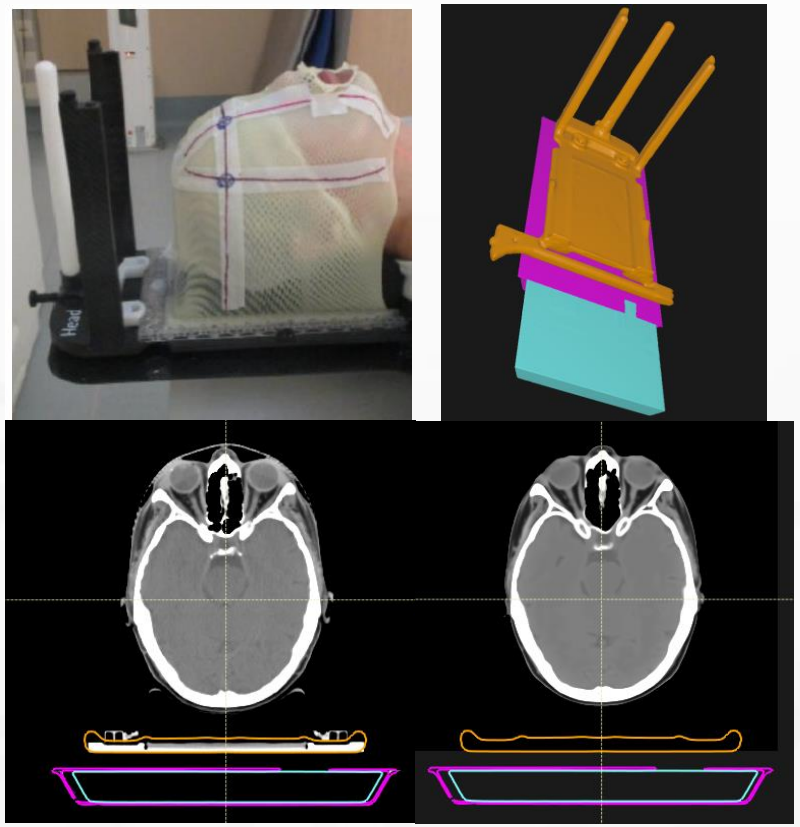




Thummerer at al, PMB 2020

MRI-only radiotherapy

- Photon therapy
  - Clinically implemented
  - Guidelines on commissioning and validation exist
- Particle therapy
  - Work in progress
  - EPTN developing recommendations on clinical implementation



Buschmann et al, ZMP 2025

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journal homepage: www.thegreenjournal.com

Review Article

Challenges and opportunities in the development and clinical implementation of artificial intelligence based synthetic computed tomography for magnetic resonance only radiotherapy

Fernanda Villegas [a,b,1], Riccardo Dal Bello [c,1], Emilie Alvarez-Andres [d,e], Jennifer Dhont [f,g], Tomas Janssen [h], Lisa Milan [i], Charlotte Robert [j,k], Ghizela-Ana-Maria Salagean [l,m], Natalia Tejedor [n], Petra Trnková [o], Marco Fusella [p], Lorenzo Placidi [q,*], Davide Cusumano [r]

Positron emission tomography

Siemens Healthineers

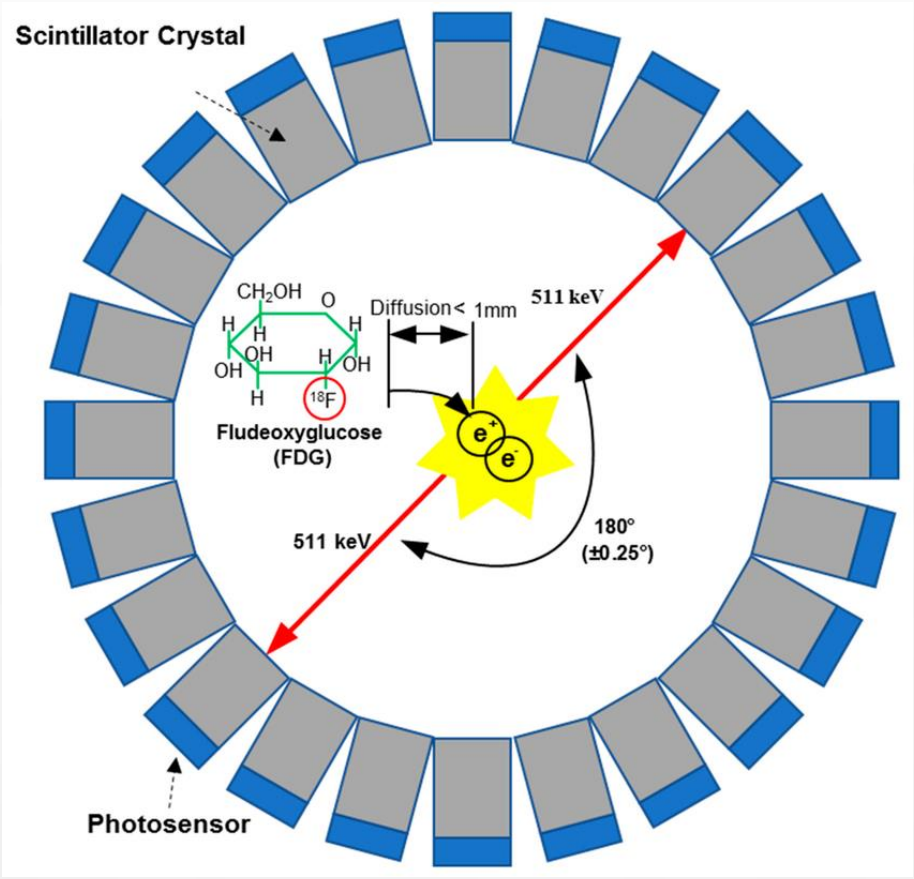
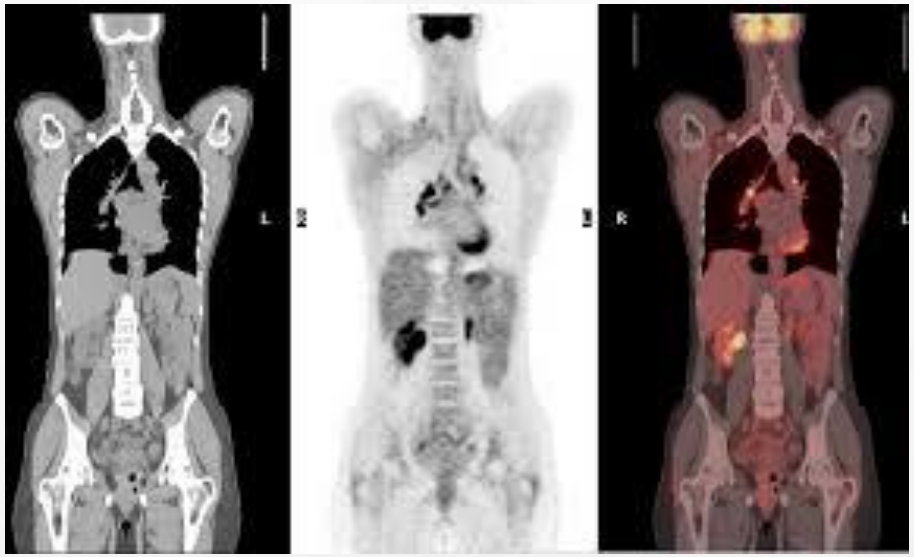
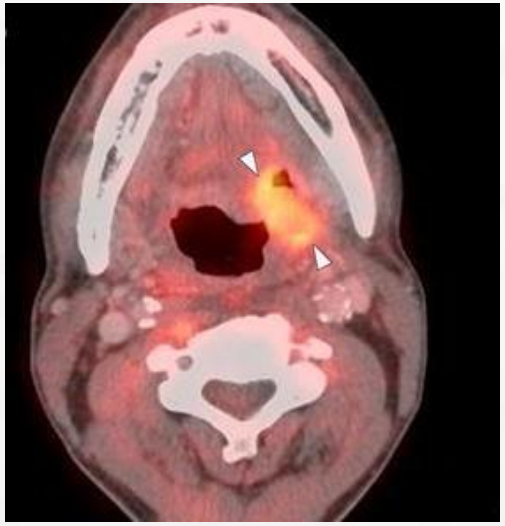


Image examples

CT PET PET/CT

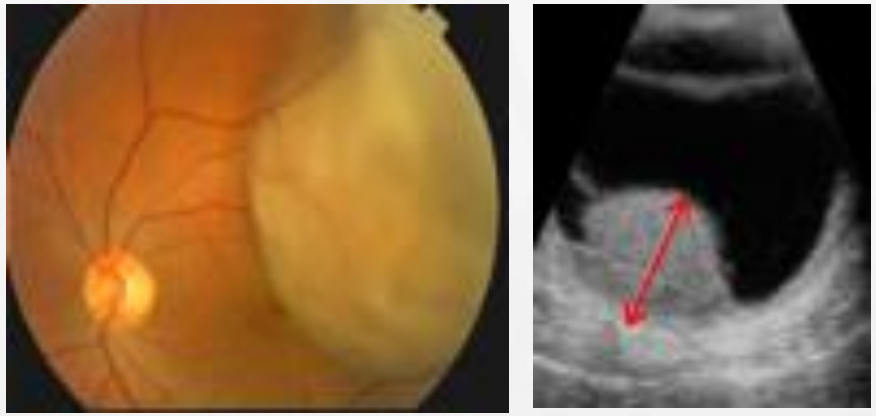




Additional imaging modalities

- Ultrasound
- Fundoscopic imaging

Ocular proton therapy



Prostate brachytherapy

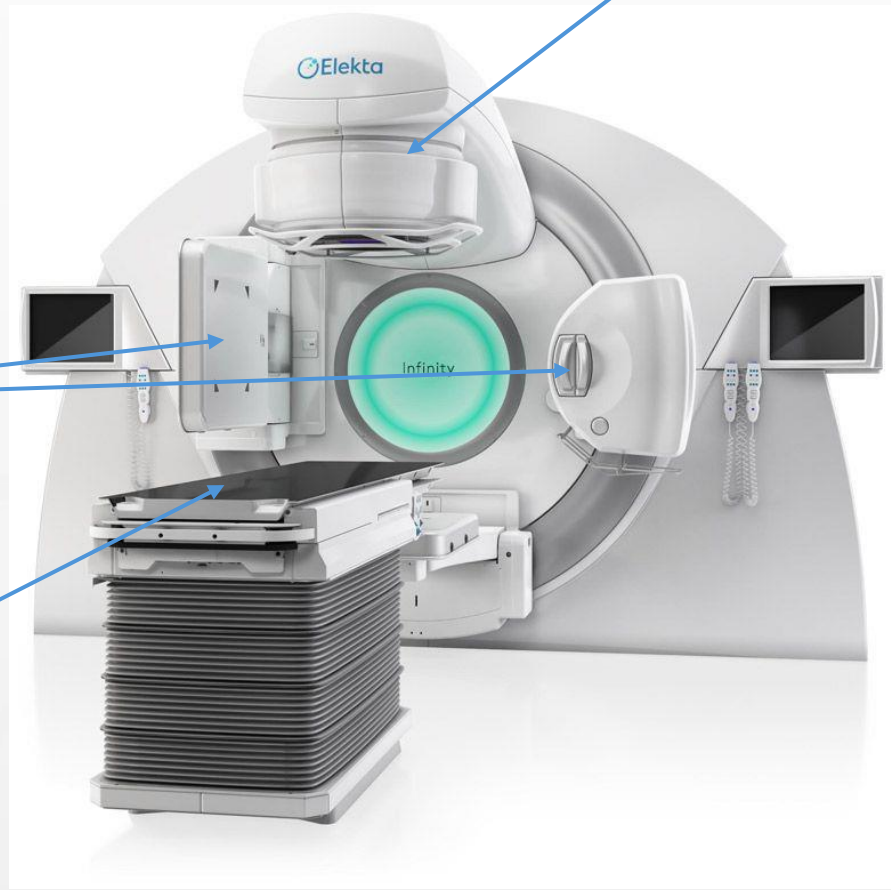
Overview

- Imaging for treatment planning
- Imaging for positioning and verification
- Imaging for monitoring and evaluation
- Imaging for follow-up
- Emerging technologies

In-room imaging

- X-ray based:2D orthogonal images
  - Cone Beam CT
- MRI-based
- Surface scanner

X-ray based: Photon therapy



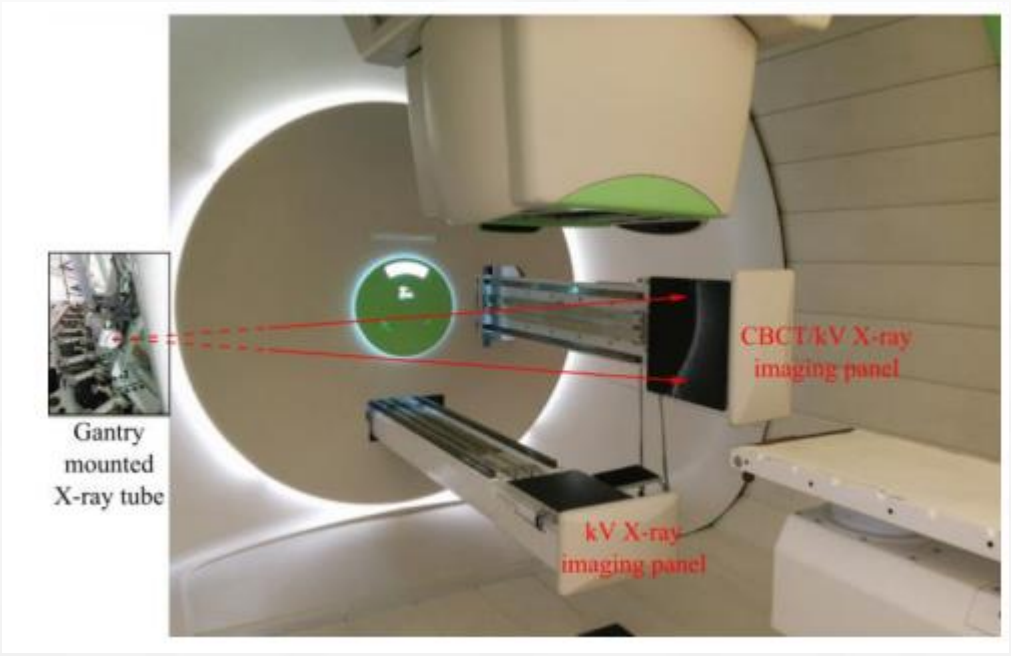
X-ray based: particle therapy

- Gantry-mounted
  - kV, CBCT
- Table mounted
  - imaging ring (kV, CBCT)
- Stand-alone
  - CT on-rails, surface imaging

Landry et al, Med Phys 2018

Gantry-mounted in-room imaging

www.varian.com

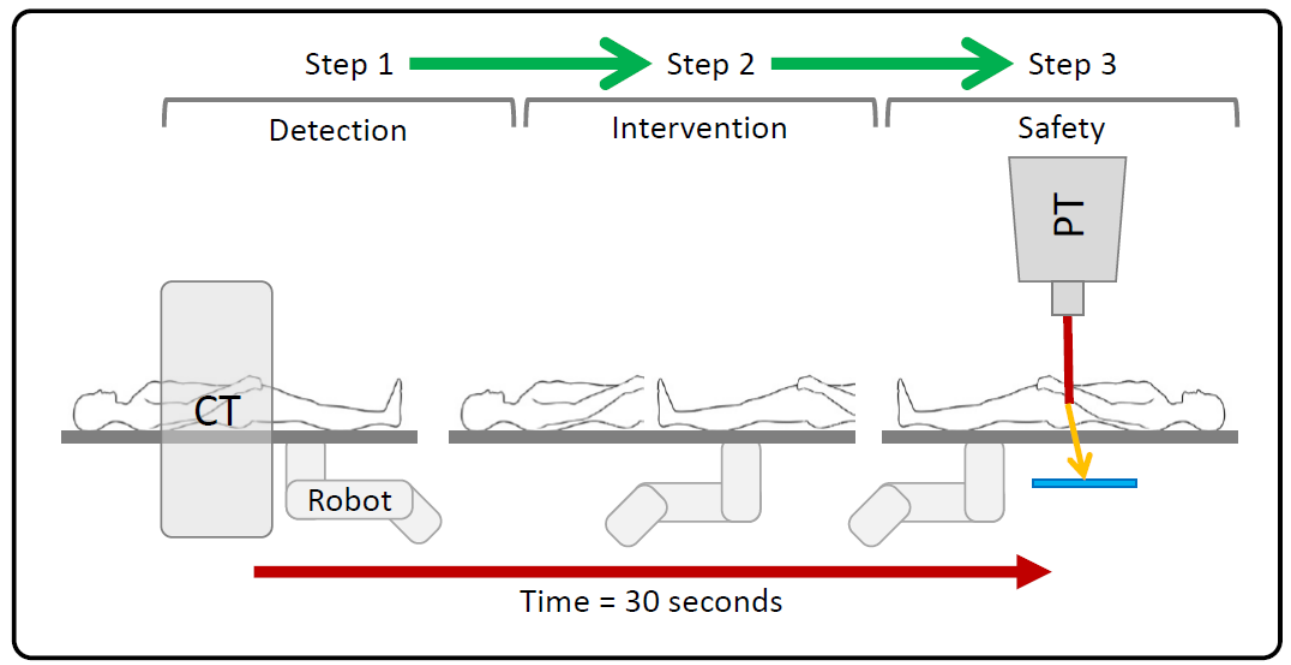


Veiga et al.

Table-mounted in-room imaging

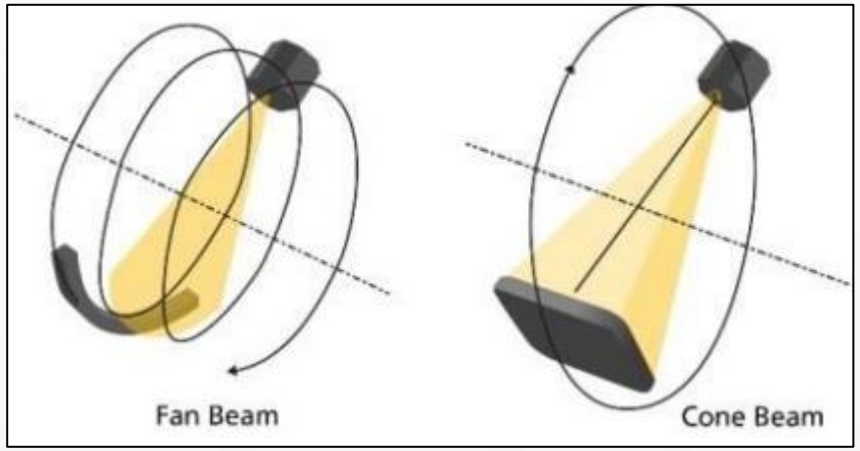
CT on-rails

Albertini Br J Radiol 2020



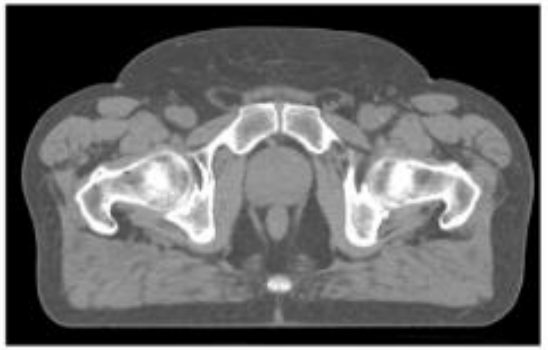
Thyrza Z. Jagt, PhD Thesis, 2020

Cone beam CT



Bojechko C.

Fan Beam CT



CBCT

Leger Appl Sci 2020

- Lower image quality
- Inaccuracy in Hounsfield Units (HU)
- Limited size of reconstruction volume

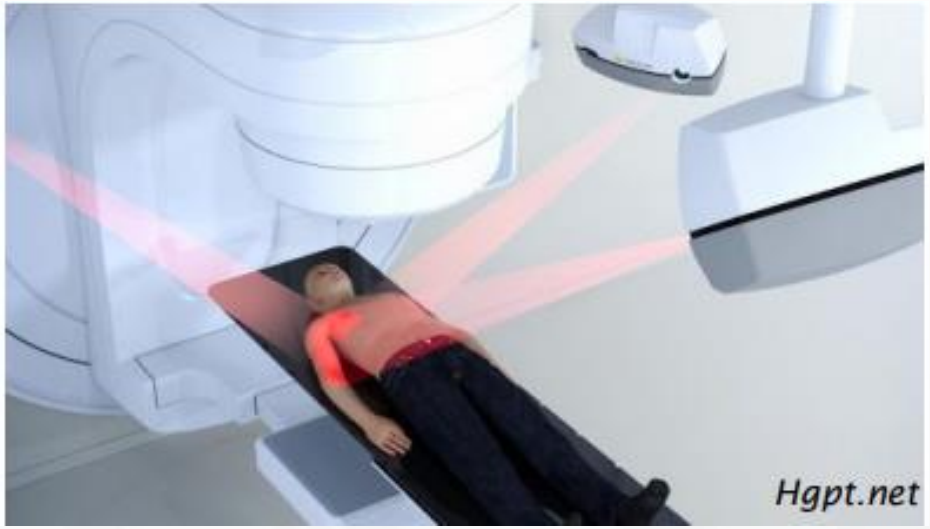
MRI based: photon radiotherapy

- Correction approaches
  - Adapt-to-position
  - Adapt-to-shape
- Impact of the magnetic field
  - Recoil electrons
- Status of implementation
  - Seminars in radiation oncology 2024, Issue 1

Electa Unity

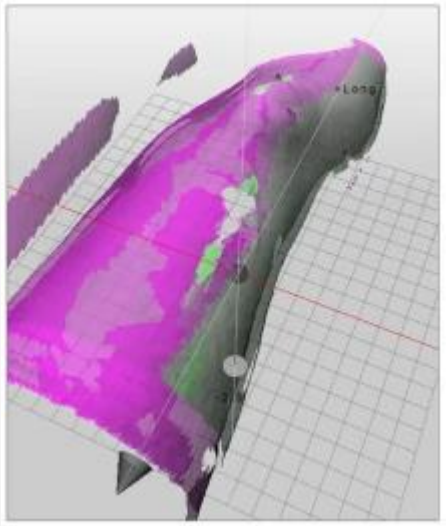
Surface imaging

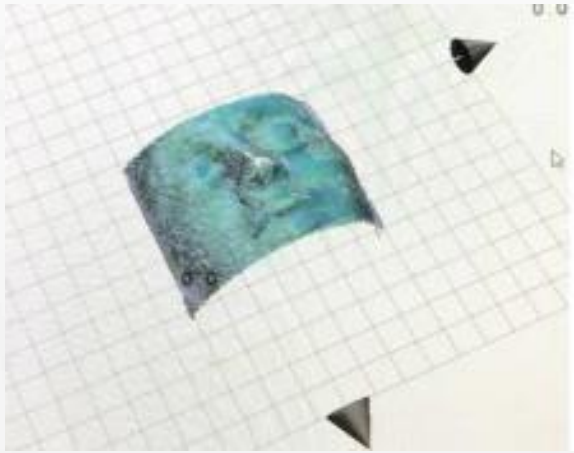
- Optical surface scanning
- A projector and one / several camera units to register a real-time 3D surface of the patients
- Application: patient positioning, intra-fraction motion monitoring and respiratory gating
- Advantages:
  - online in-room information
  - More accurate positioning for superficial tumours
  - Reduced positioning time for deeper tumours
  - No radiation

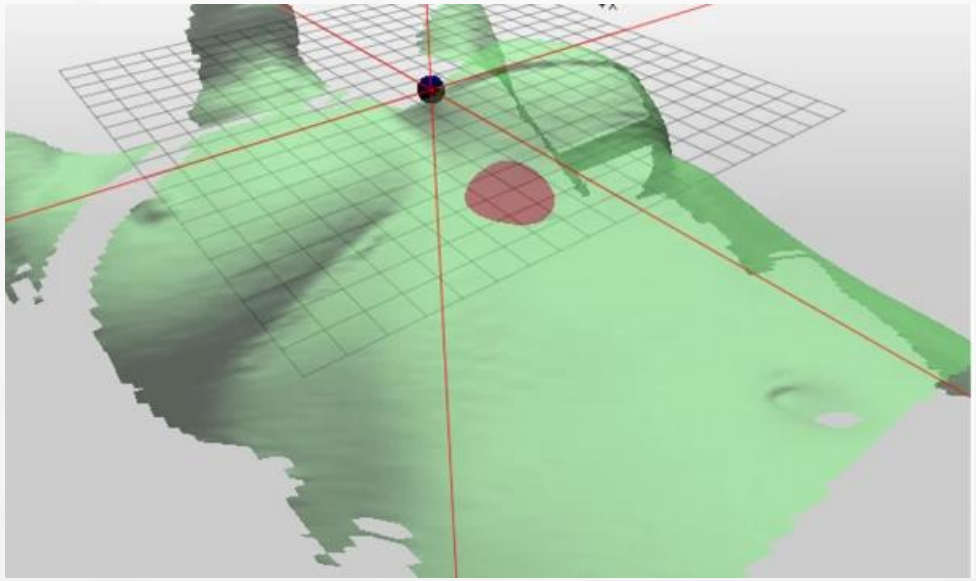


Sorgato et al. TIPSRO 2022

Surface scanner







Freislederer, Radiation Oncology 2020

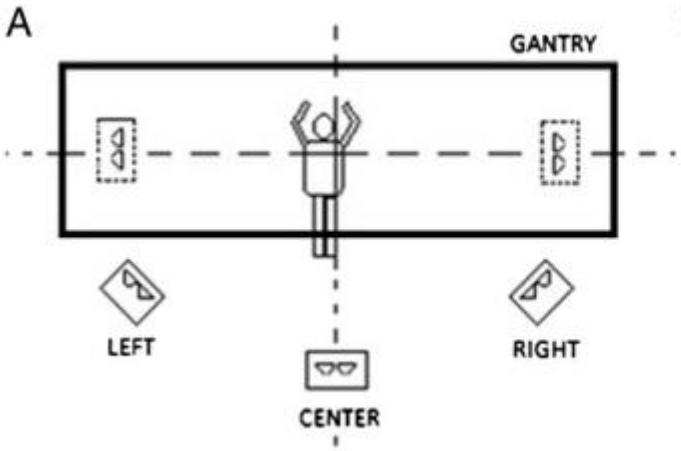
SGRT implementation

- SGRT (photons): AAPM TGR-302 (2021)
- Challenges in proton therapy:
  - Location and stability of surface cameras' mounting
  - Different distances compared to Linac: different camera lenses and camera settings

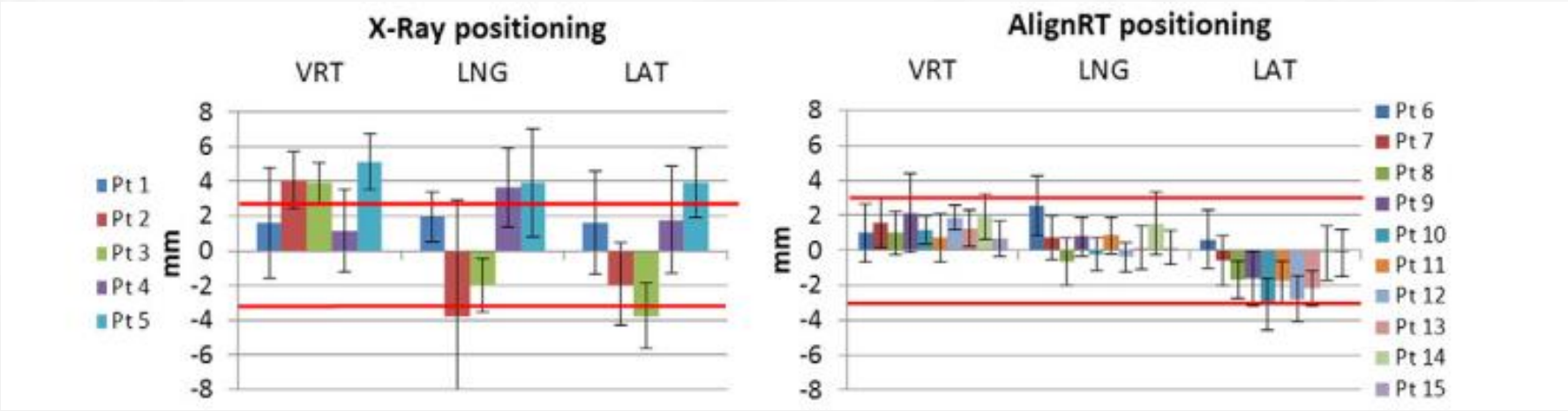
SGRT implementation

- SGRT (photons): AAPM TGR-302 (2021)
- Challenges in proton therapy:
  - Location and stability of surface cameras' mounting
  - Different distances compared to Linac: different camera lenses and camera settings
  - Half gantries, fixed beam lines with non-in-line imaging
  - Change of surface relative to bony anatomy: larger dosimetric impact
  - Complex movements of robotic tables

Clinical example of SGRT implementation

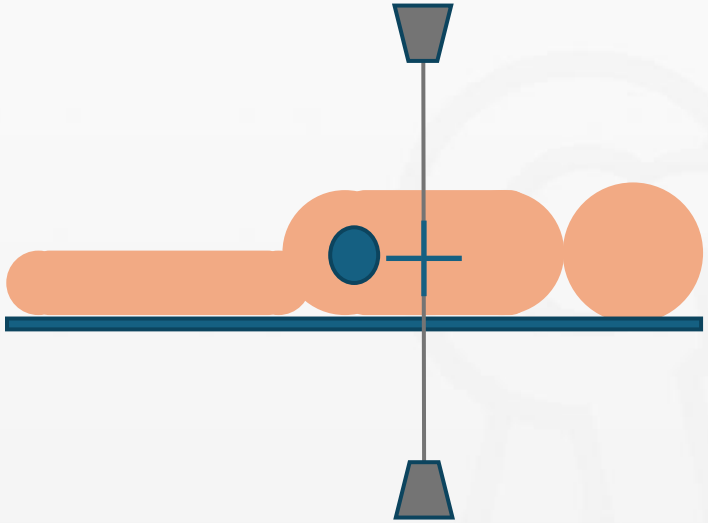


Batin, Pract Rad Onc 2016

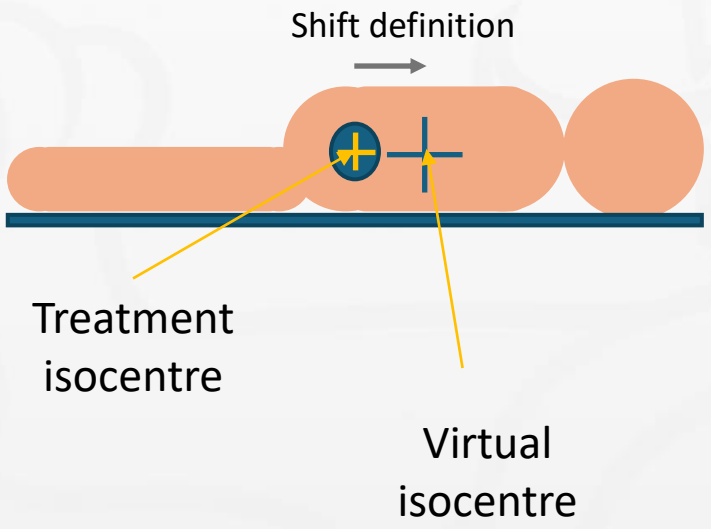


Patient positioning

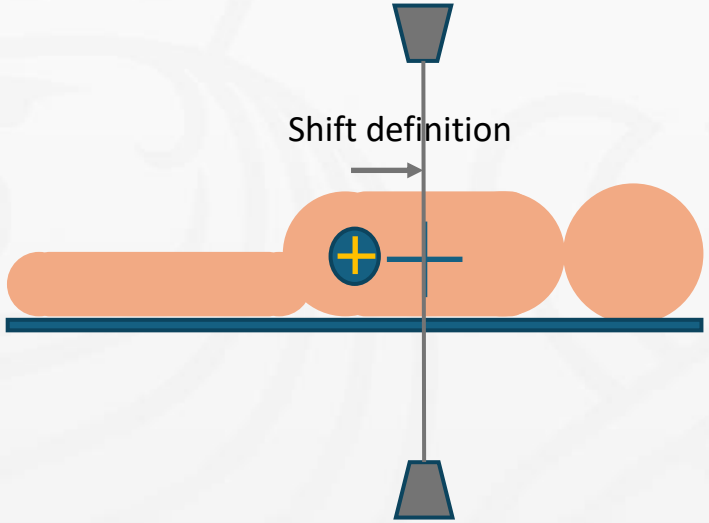
Planning CT acquisition



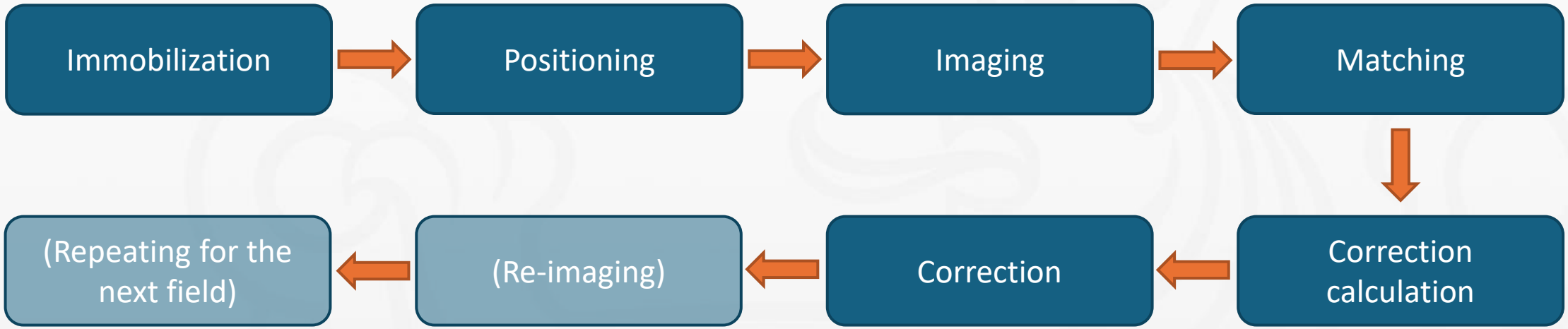
Treatment planning



Positioning for treatment



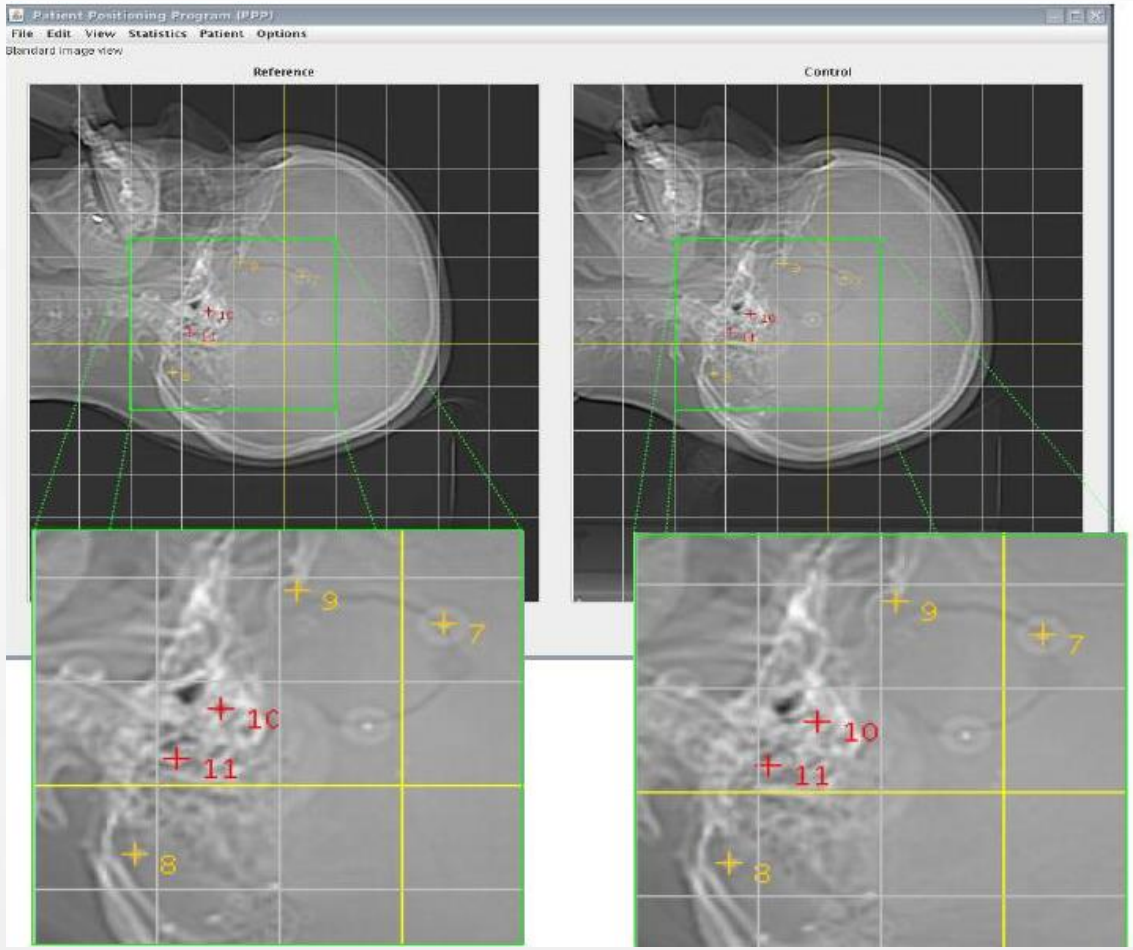
Patient positioning workflow



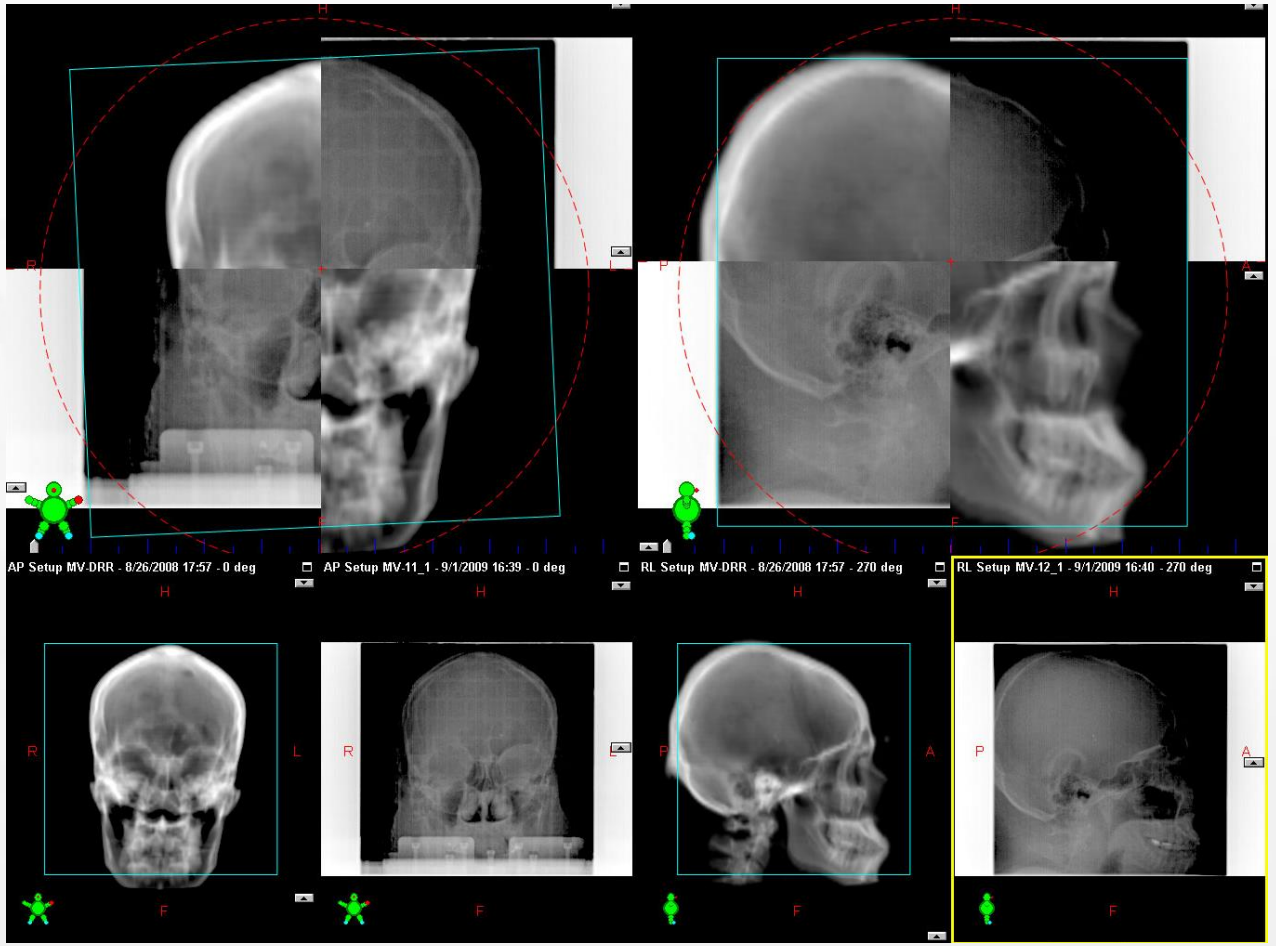
Position verification

- Comparison of the reference image with control image:
  - Reference image: CT, DRR
  - Control image: CBCT, kV
- Matching between the images:
  - 2D-2D
  - 2D-3D
  - 3D-3D
- Calculation of correction:
  - Translation
  - Rotation

2D – 2D matching



3D - 3D matching



Overview

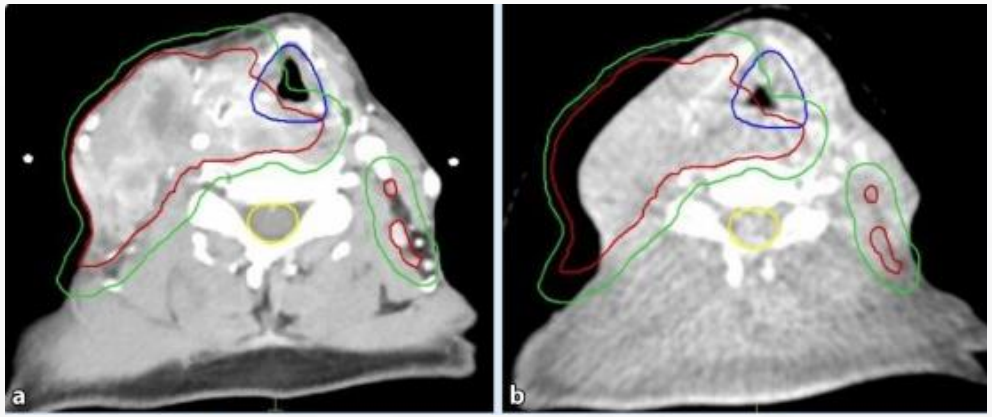
- Imaging for treatment planning
- Imaging for positioning and verification
- Imaging for monitoring and evaluation
- Imaging for follow-up
- Emerging technologies

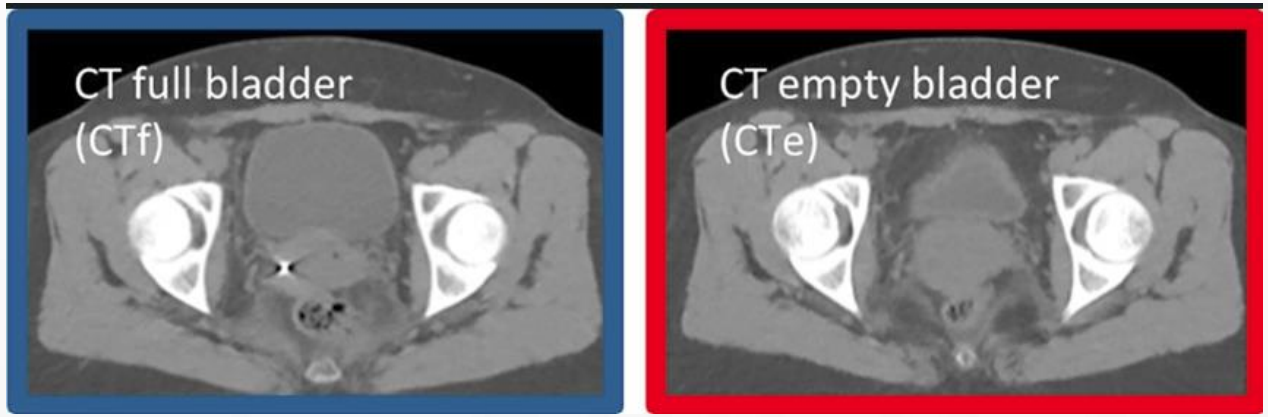
Monitoring of changes

- Interfraction motion – adaptive radiotherapy
- Intrafractional motion – real-time tumour motion monitoring

- Range changes – in-vivo range verification

Adaptive radiotherapy

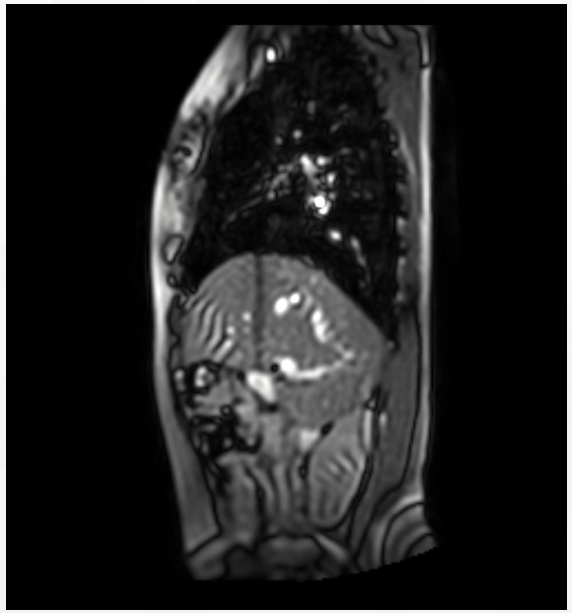




- Mitigation of inter-fractional changes:
  - Tumor shrinkage, weight-loss, organ size and shape changes
- More than one treatment plan per target per treatment course
  - Mitigating the detrimental effect of anatomical changes
  - Improving target coverage and OAR sparing

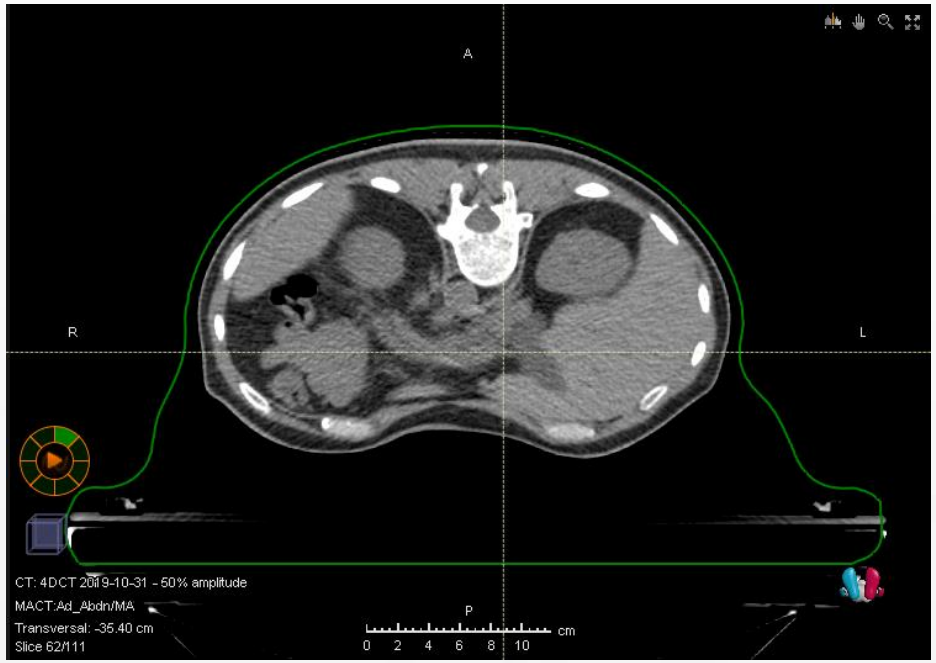
Intra-fractional motion

- Source of motion:
  - Breathing
  - Peristaltic
  - cardiac motion

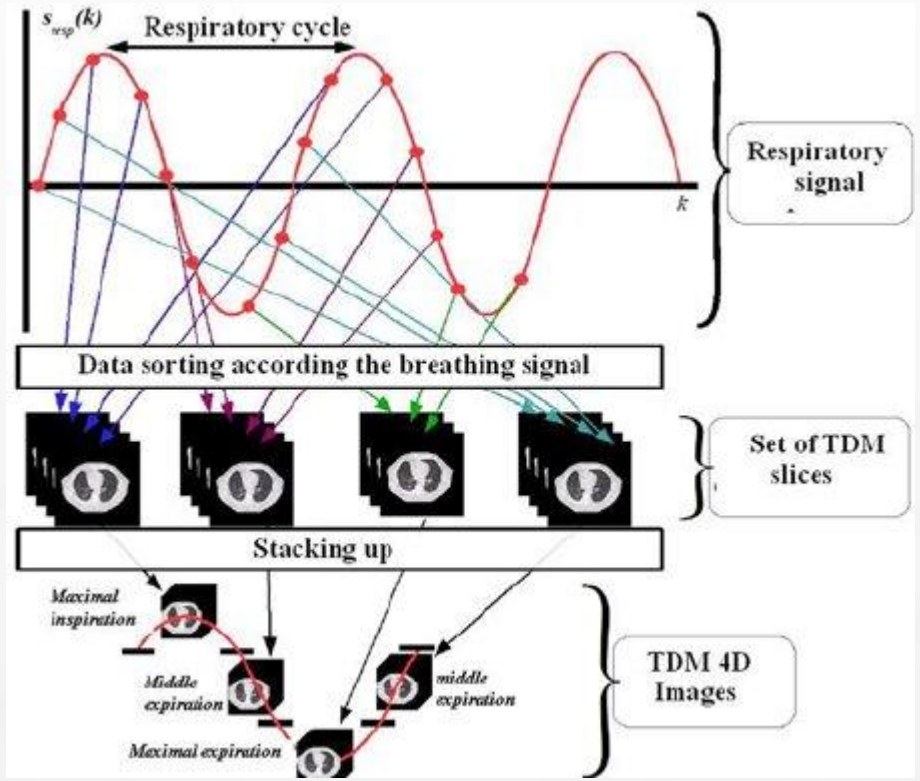


Courtesy of Aswin Hoffmann (OncoRay)

4D imaging for treatment planning



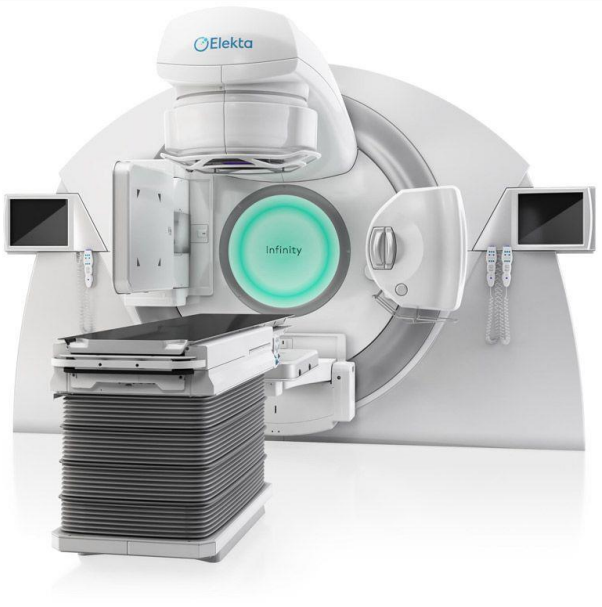
Courtesy of Franciska Lebbink(OncoRay)

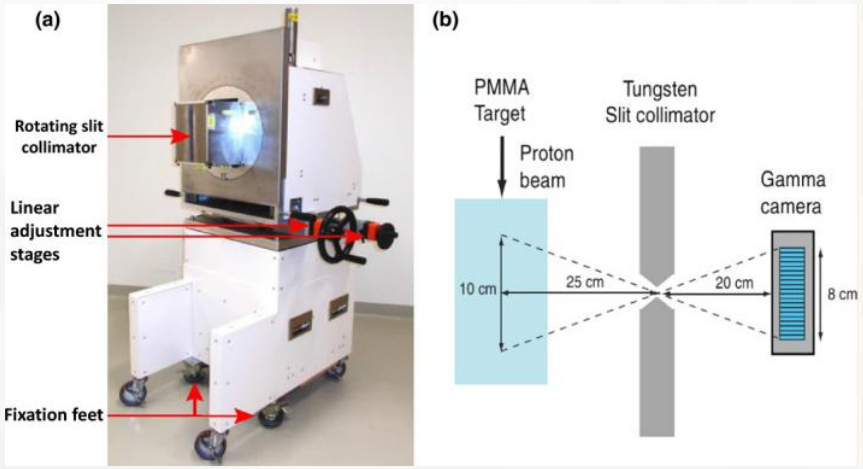


Laurent, Acta Polytecnica 2010

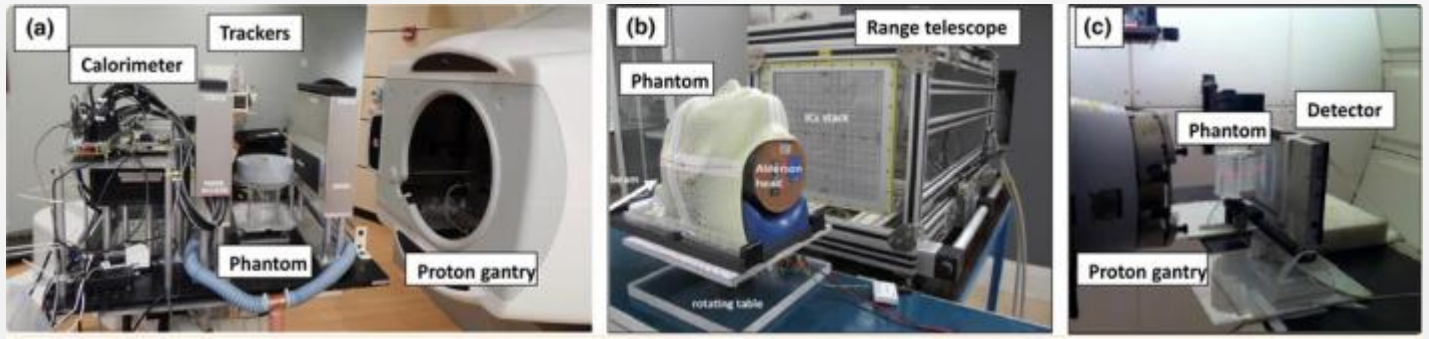
In-vivo verification

- Photon radiotherapy:
  - Portal dosimetry
- Proton therapy:
  - Range probing
  - PET
  - Prompt gamma





Parodi, Med Phys 2018



Overview

- Imaging for treatment planning
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Imaging for follow up

- To evaluate the treatment outcome
- To monitor the side effects
- Longitudinal data
- Diagnostic imaging:
  - CT, MRI, PET/CT, …

Overview

- Imaging for treatment planning
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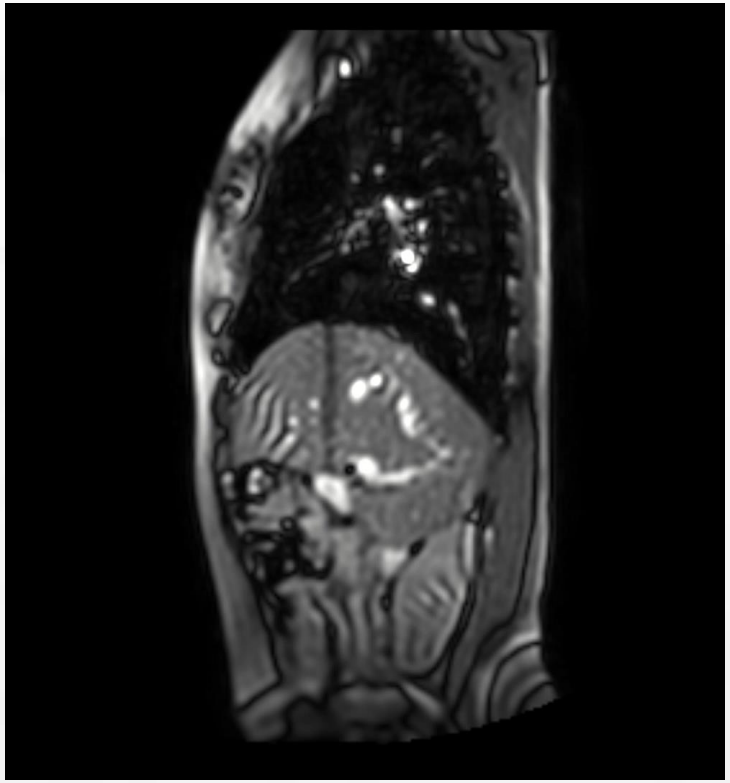
Emerging technologies

- MRI-integrated proton therapy
- Upright proton therapy
- Biological optimization

MRI-integrated proton therapy

- Advantages MRI:
  - Superior soft tissue contrast
  - Absence of ionizing radiation
  - Possibility of real-time imaging
  - Functional imaging

- MRI-guided proton therapy
  - Combination of great soft-tissue of MRI contrast with high conformity of proton therapy
  - Plan adaptation on daily images
  - Synchronization of proton beam with tumour motion



Courtesy of Aswin Hoffmann (OncoRay)

Future of MRI-integrated proton therapy

Med Phys. 2017 Aug;44(8):e77-e90. doi: 10.1002/mp.12371. Epub 2017 Jul 4.

Future of medical physics: Real-time MRI-guided proton therapy

Bradley M Oborn [1 2], Stephen Dowdell [3], Peter E Metcalfe [2 4], Stuart Crozier [5], Radhe Mohan
Paul J Keall [4 7]

Review. Phys Med Biol. 2021 Feb 26;66(5):10.1088/1361-6560/abcd16.
doi: 10.1088/1361-6560/abcd16.

Roadmap: proton therapy physics and biology

Harald Paganetti [1 2], Chris Beltran [3], Stefan Both [4], Lei Dong [5], Jacob Flanz [1 2], Keith Furutani [3], Clemens Grassberger [1 2], David R Grosshans [6], Antje-Christin Knopf [4], Johannes A Langendijk [4], Hakan Nystrom [7 8], Katia Parodi [9], Bas W Raaymakers [10], Christian Richter [11 12 13], el O Sawakuchi [14], Marco Schippers [15], Simona F Shaitelman [6], B K Kevin Teo [5], nkelbach [16], Patrick Wohlfahrt [1], Tony Lomax [15]

Review. Semin Radiat Oncol. 2024 Jan;34(1):135-144. doi: 10.1016/j.semradonc.2023.10.015.

The Future of MR-Guided Radiation Therapy

Matthias Guckenberger [1], Nicolaus Andratschke [2], Caroline Chung [3], Dave Fuller [3], Stephanie Tanadini-Lang [2], David A Jaffray [3]

Interaction of electromagnetic field with proton beams

- Impacting magnets in the beamline, control system and beam monitoring systems
- Acoustic and magnetic interactions of ionization chambers

SHIELDING

- Impacting the proton beam path

DOSE CALCULATION

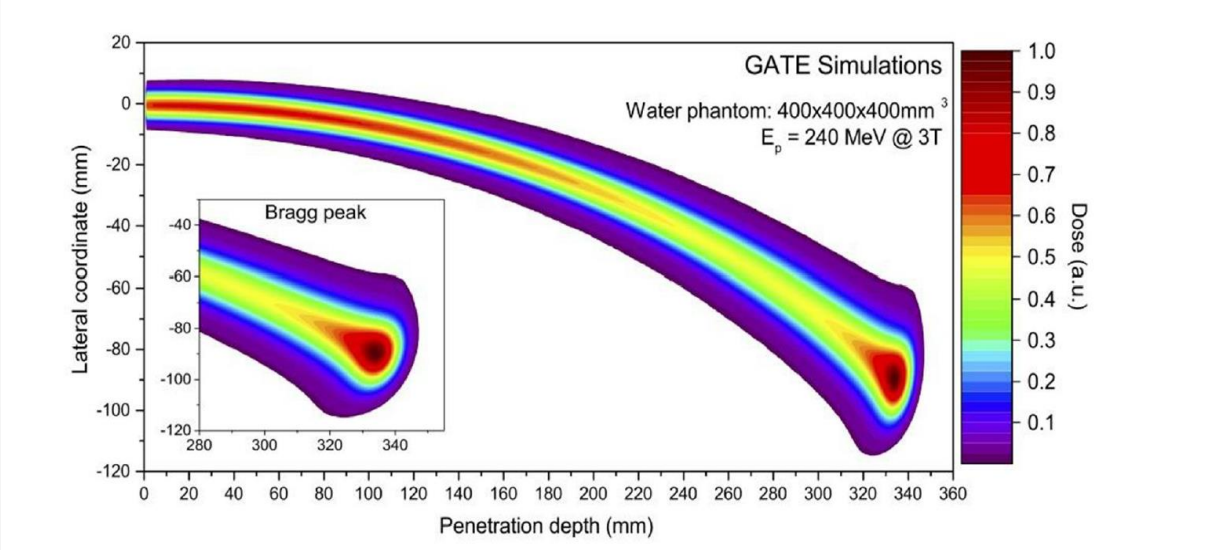
REVIEW Open Access

MR-guided proton therapy: a review and a preview

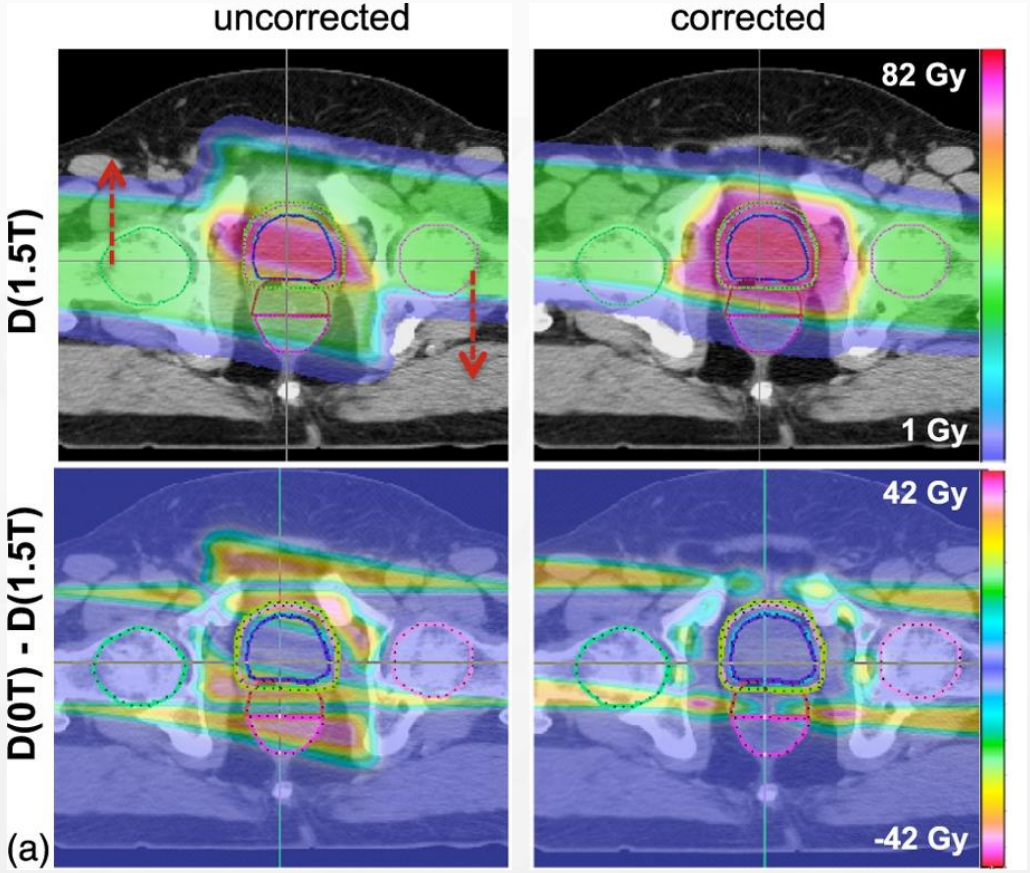
Check for updates

Aswin Hoffmann[1,2,3], Bradley Oborn[4,5], Maryam Moteabbed[6], Susu Yan[6], Thomas Bortfeld[6], Antje Knopf[7], Herman Fuchs[8,9], Dietmar Georg[8,9], Joao Seco[10,11], Maria Francesca Spadea[10,12], Oliver Jäkel[13], Christopher Kurz[14,15] and Katia Parodi[15*]

Dose calculation

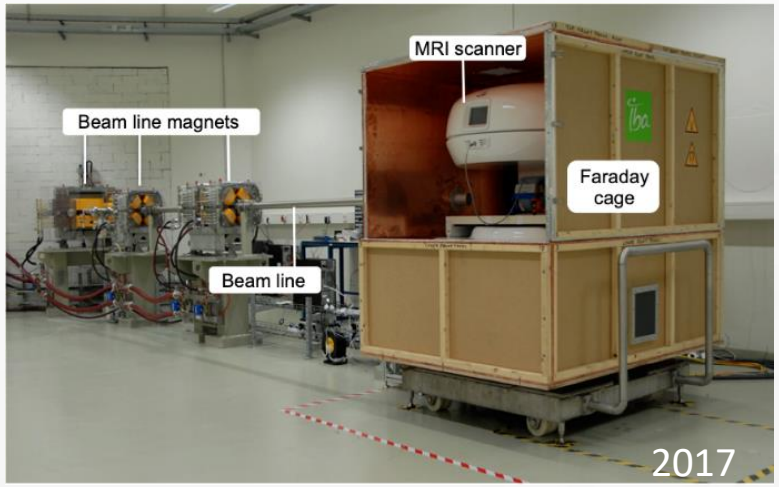


F. Padilla-Cabal PhD thesis 2020



Moteabbed et al, Med Phys 2016

Research at OncoRay



0.22 T in-beam MRI at static beamline:

- Successful **proof-of-concept**
- Good image quality during beam delivery

Schellhammer *et al*. *Phys Med Biol* 2018
Gantz *et al*. *Phys Med Biol* 2020

0.32 T in-beam MRI at PBS beamline:

- **Extremity** MR scanner
- Preparations for **first-in-human** treatment ongoing

Gebauer *et al*. *Med Phys* 2023

0.5 T in-beam MRI at PBS beamline:

- **Whole-body** MR scanner
- Allowing **upright** treatment
- **Real-time imaging**

Courtesy of Aswin Hoffmann

Research at OncoRay

Back side of RF shielding attached to PBS Beamline

Front side of RF shielding

Courtesy of Aswin Hoffmann

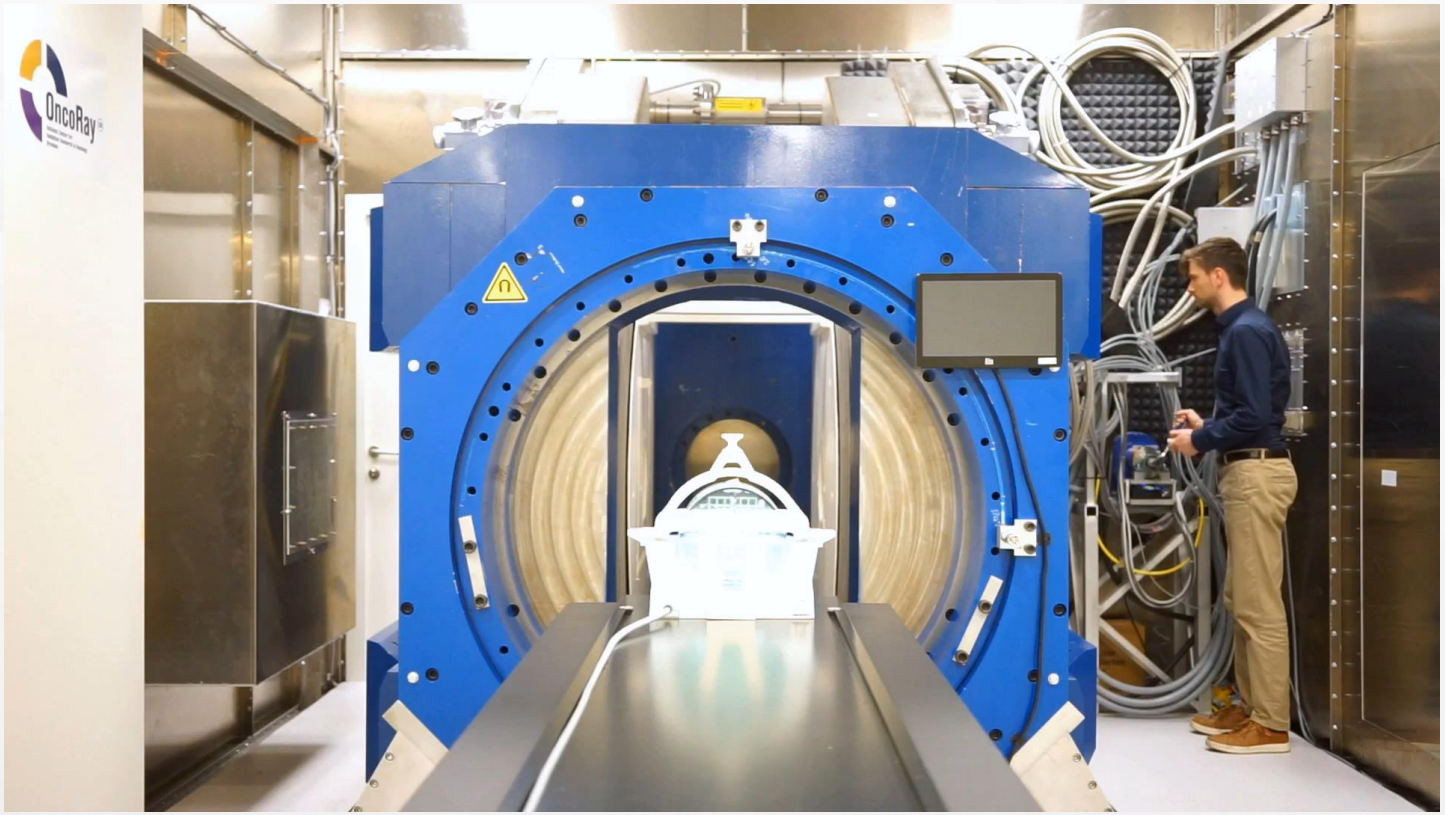
Research at OncoRay

Magnet and patient couch sections

Magnet at vertical position

Courtesy of Aswin Hoffmann

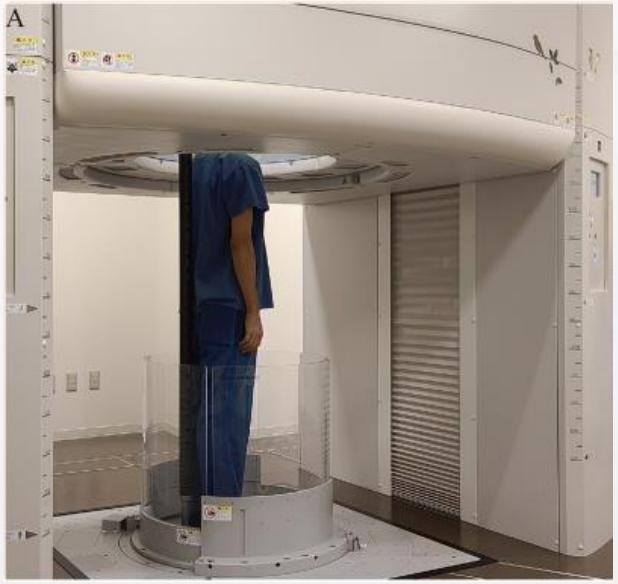
Research at OncoRay



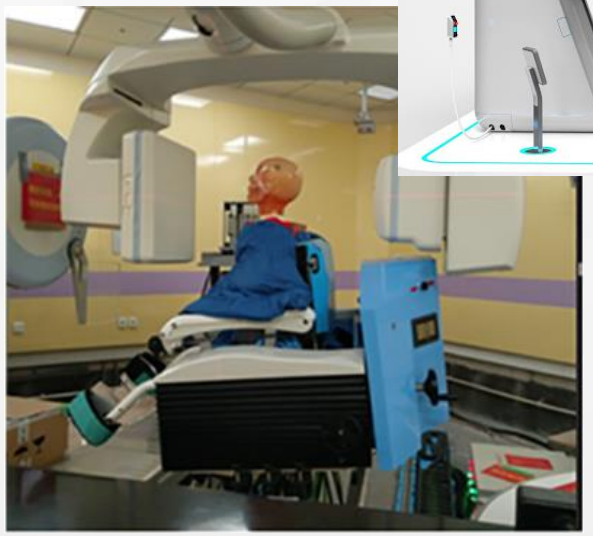
Courtesy of Aswin Hoffmann

Upright imaging

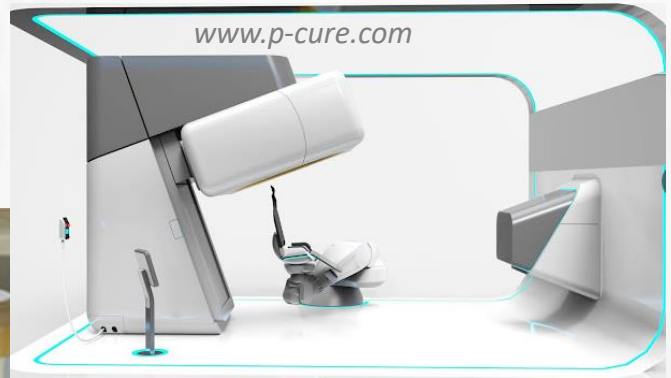
- Imaging and image guidance



Fukuoka, Eur Radiol, 2023



Zhang, Med Phys 2020

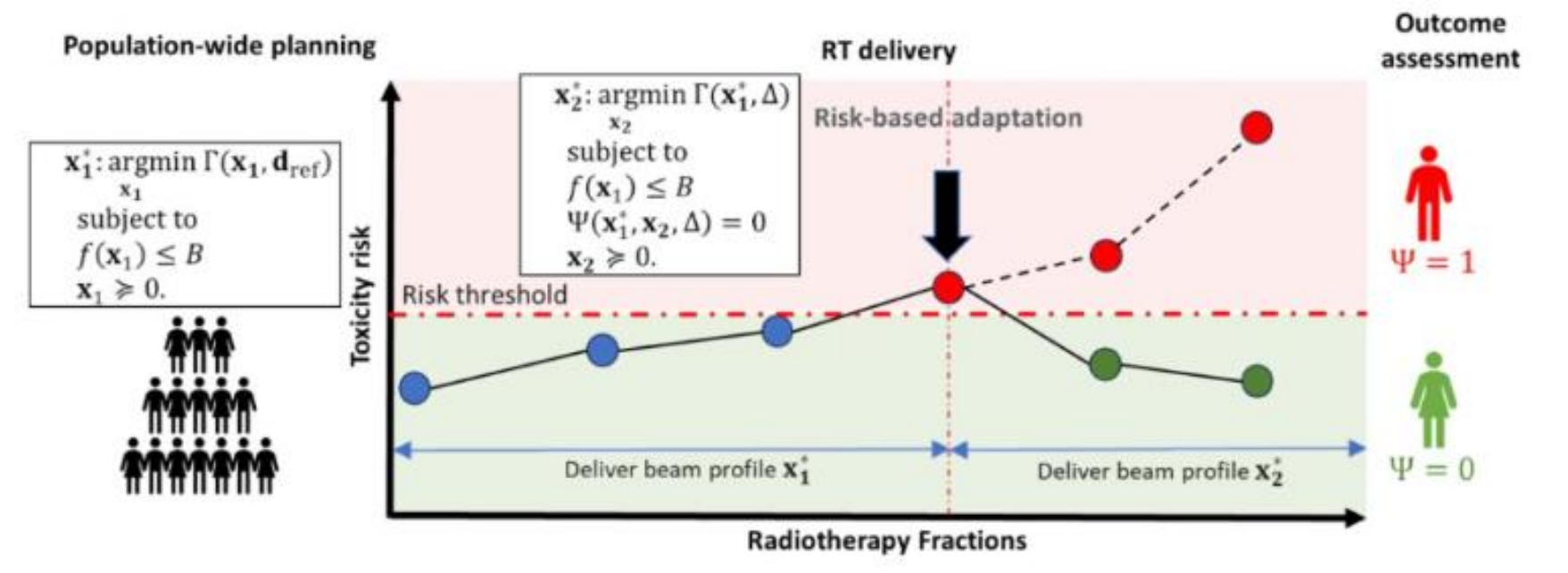


www.leocancercare.com

Biological imaging

- Monitoring of imaging biomarkers
- Monitoring tumour response
- Functional imaging
  - Functional MRI
  - PET imaging

Biological optimization



Ajdari, ESTRO 2024, Abstract 3444

Take-home message

- Imaging is an essential component of radiotherapy
- Image guidance plays a crucial role in many workflow steps
- Main imaging modalities for planning and follow-up are CT, MRI and PET/CT
- For in-room imaging X-ray based, MRI based and surface scanners
- In-room imaging monitors inter- and intra-fractional changes
- MRgPT, Upright RT and biological imaging for optimization are new emerging technologies

Thank you for your attention!