MR only planning

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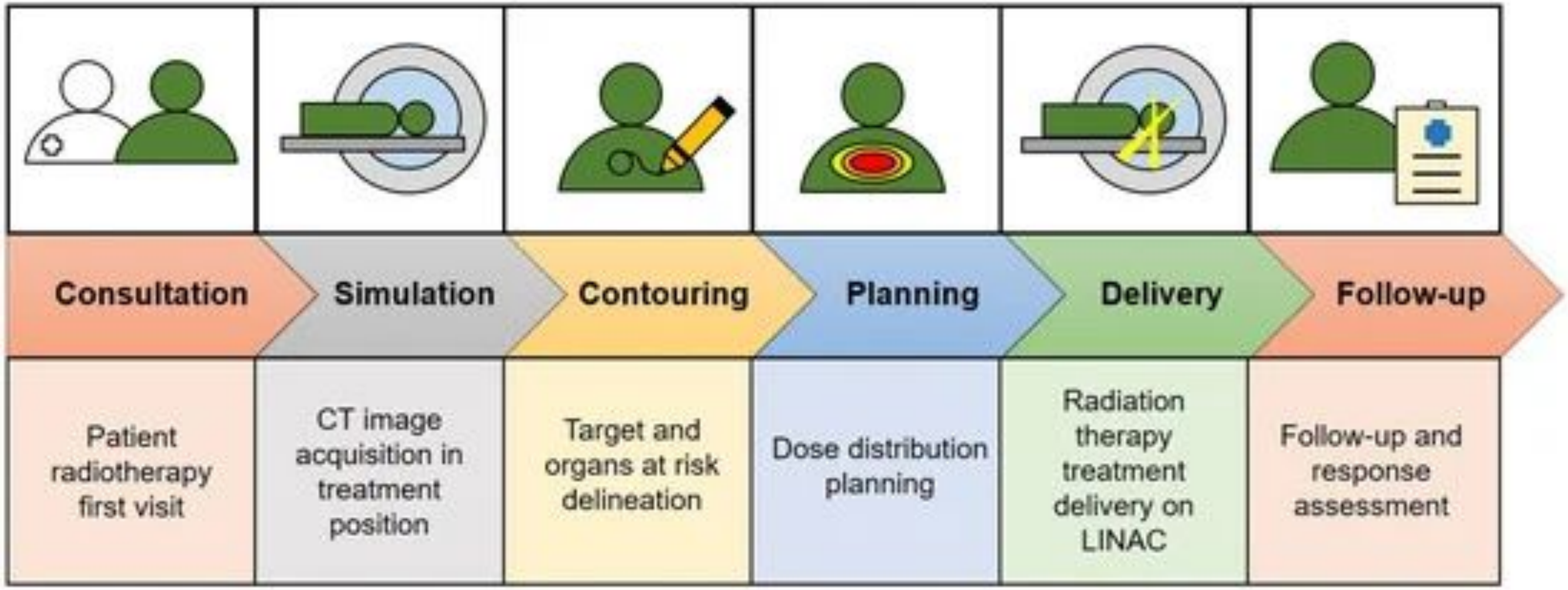
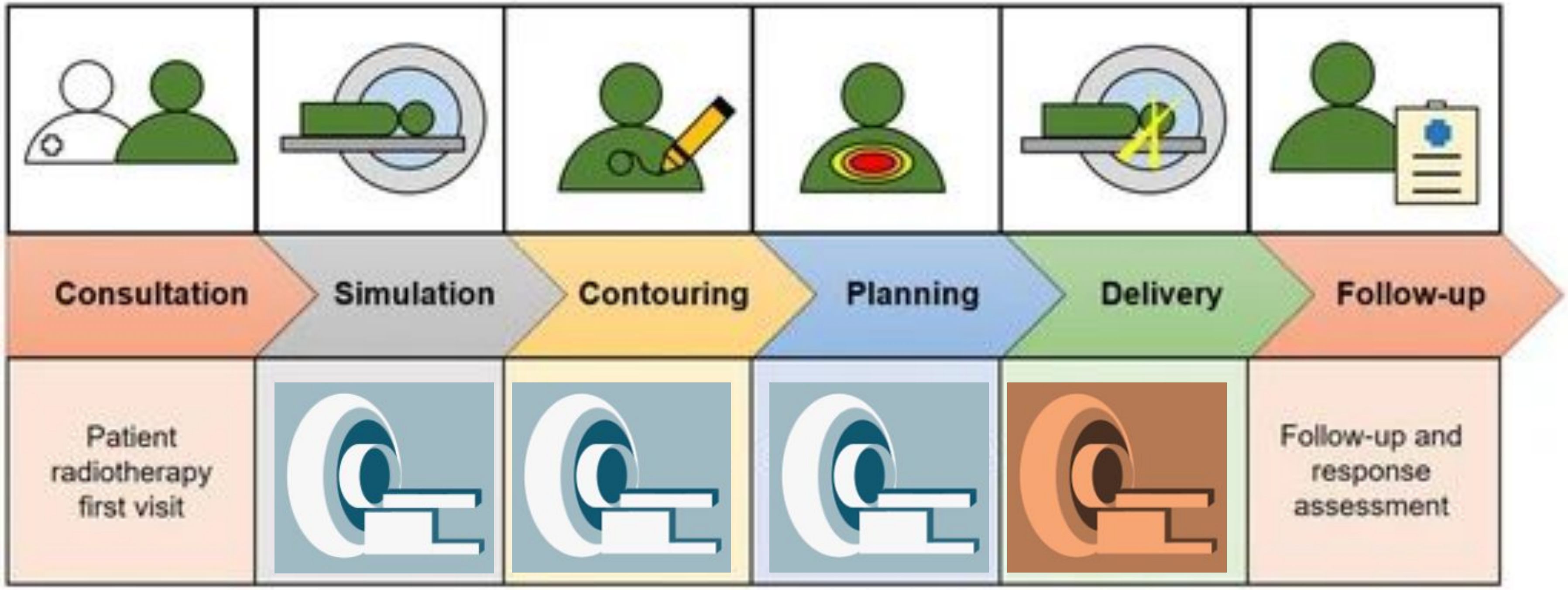
Radiotherapy process



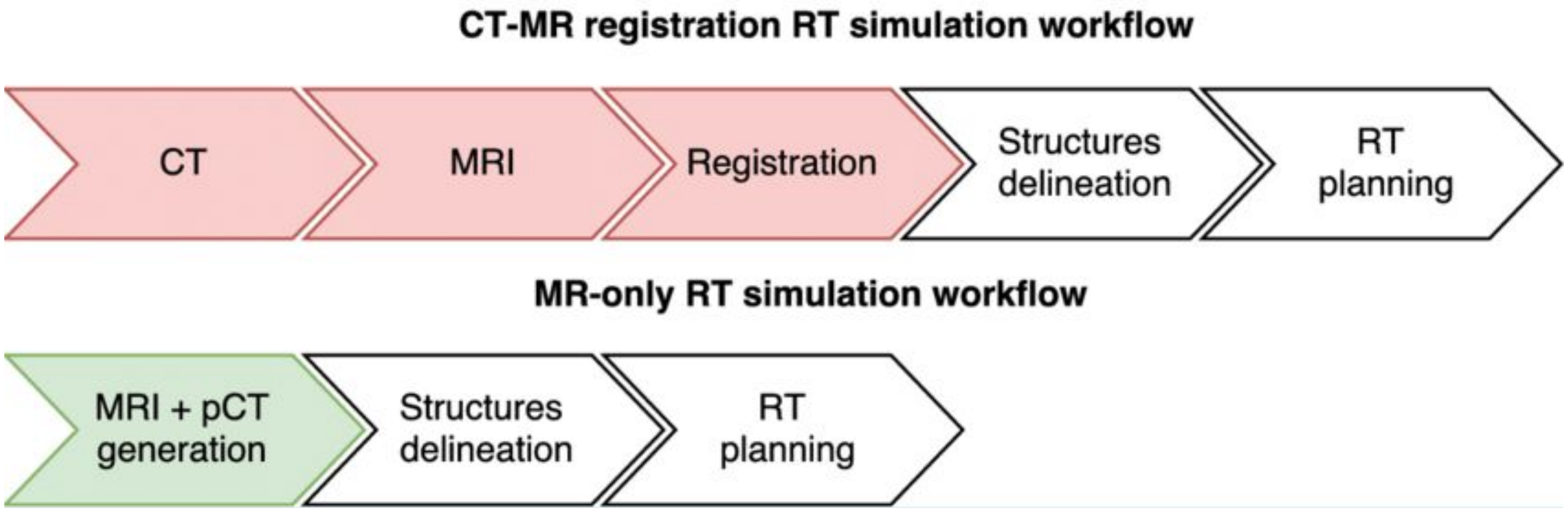
G. Marvaso et al. Appl. Sci. 2022

Radiotherapy process



G. Marvaso et al. Appl. Sci. 2022

MR only planning

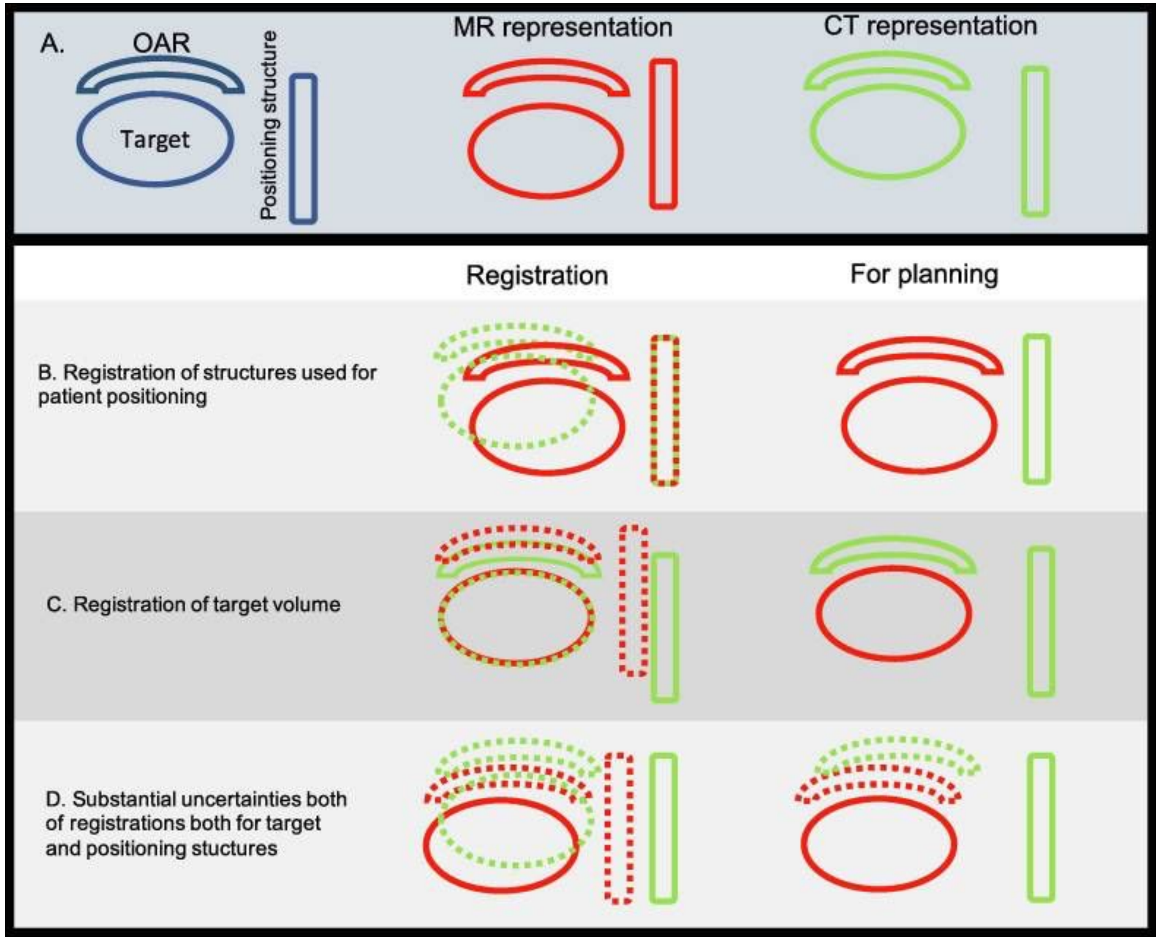


MR only planning

Advantages	Challenges
Gets rid of registration uncertainties	Need of the generation of a synthetic CT for dose calculation (ACCURACY??)
Reduction X-ray exposure for patients	No consensus on evaluation metrics/acceptance criteria for image quality and dose calculation
More convenient for patients	Patient immobilization
Avoids issues on timining between CT and MRI imaging (change bladder/rectal filling)	Staff training
Cost and efficiency	MR artifacts

MR only planning

Registration uncertainties



J. Jonsson et al. ctRO 2019

Differences in position between a certain landmark within the patient in two sets of images:

Registration uncertainty

Anatomic movement between two sets of images

MR only planning
Registration uncertainties

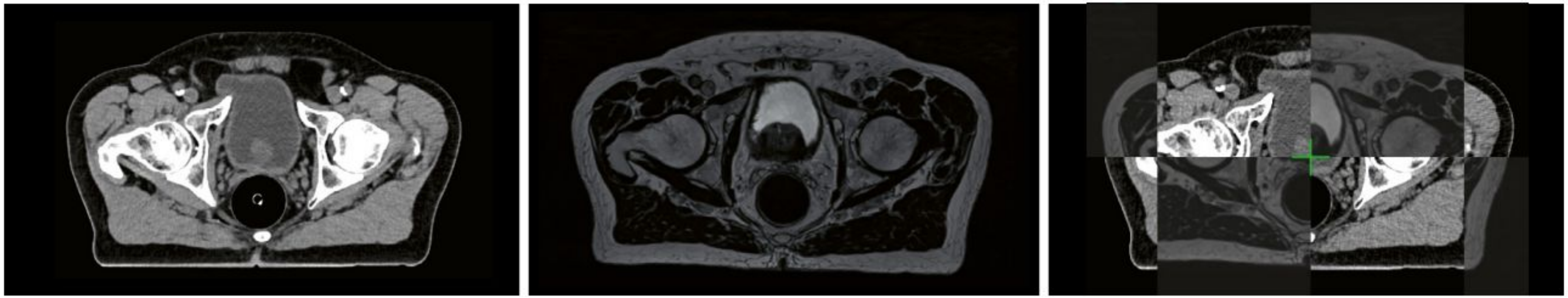
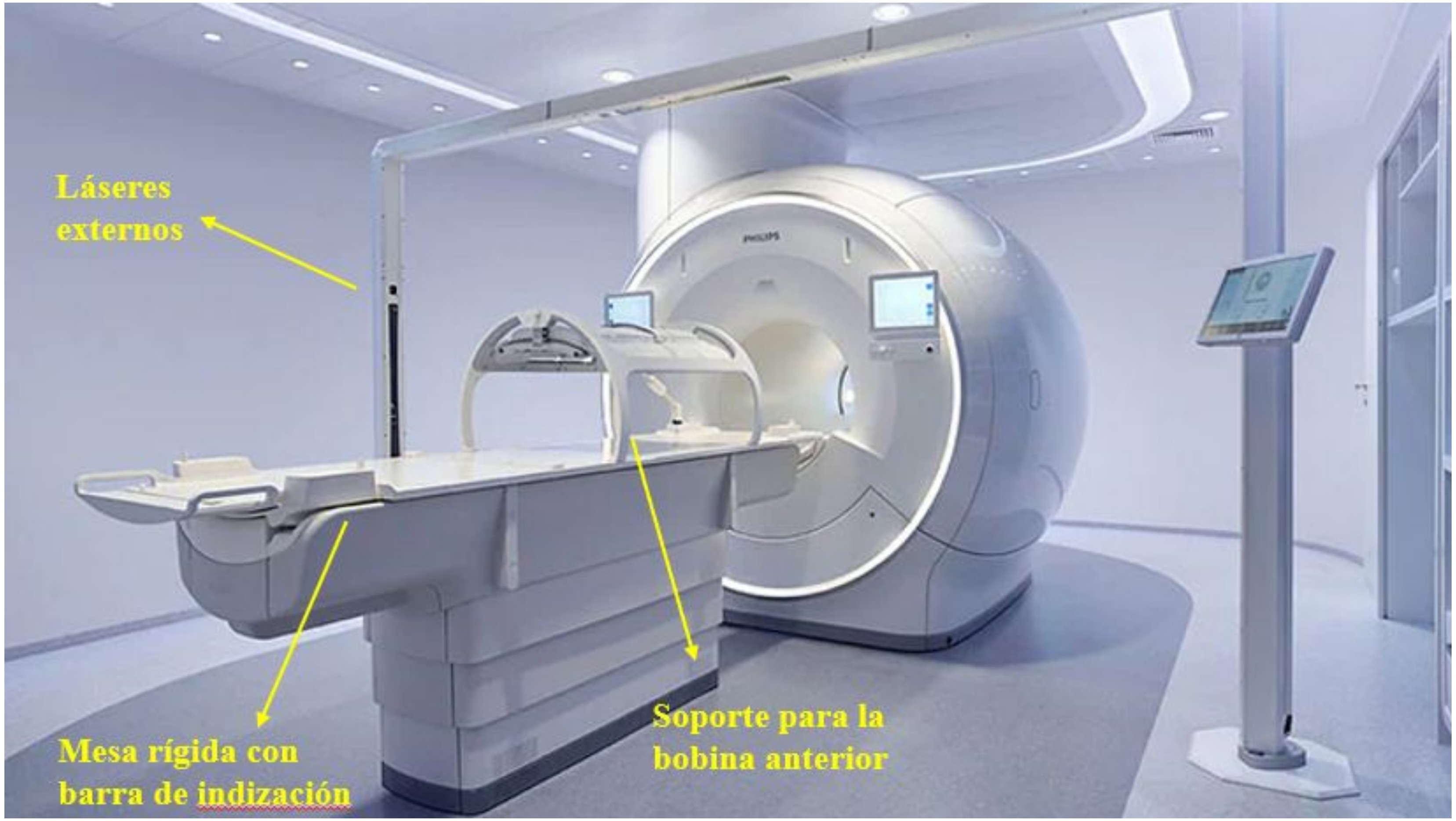


Figure 2: Left image: Planning CT, center image: T2w MRI, right image: registration visualized with the checkerboard tool[1].
Registration errors may persist and registration can be cumbersome.
Courtesy of Universitätsklinikum Erlangen, Germany.

MR only planning
Immobilization systems

- MR-safe immobilization systems
- Flat couch tops, indexing positions
- Localization lasers
- Big MR bores
- MRI receiver coils placed on a bridge to avoid contact with the surface of the patients
- Fast MR imaging sequences
- Fiducials markers: vitamin A

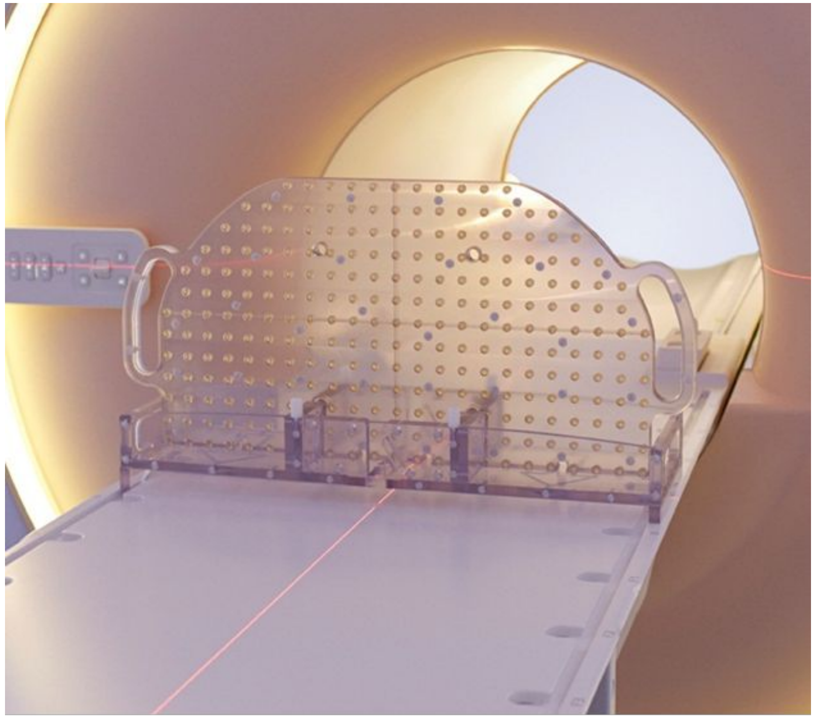
MR only planning
Immobilization systems



MR only planning

MRI acquisition

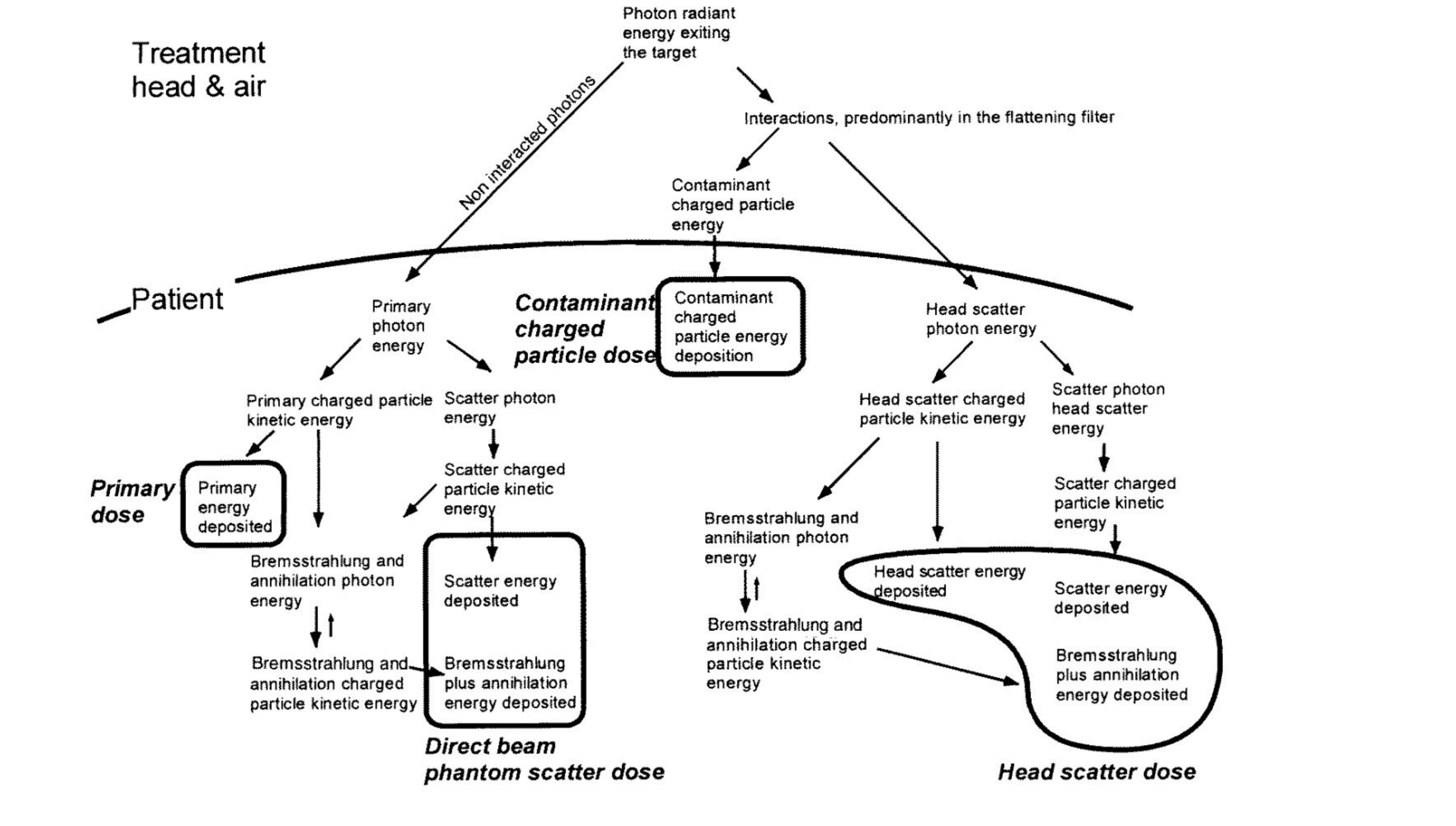
- Accelerate acquisition time
- Check for geometrical distortion
  - Non linearity in the gradients system (corrected through a map of non-linearities)
  - Use large FoV phantoms
  - Attention to patient specific distortions
    - Chemical field artifacts and susceptibility
    - Metal artifacts (implants that are MRI safe)



Geometric QA phantom and rack

Patient model

Radiation transport and absorbed dose calculation



A Ahnesjo and M M Aspradakis Phys Med Biol 1999

Each voxel assumed to have single atomic composition and density

To correct for non-water media or for direct simulation of radiation we need:

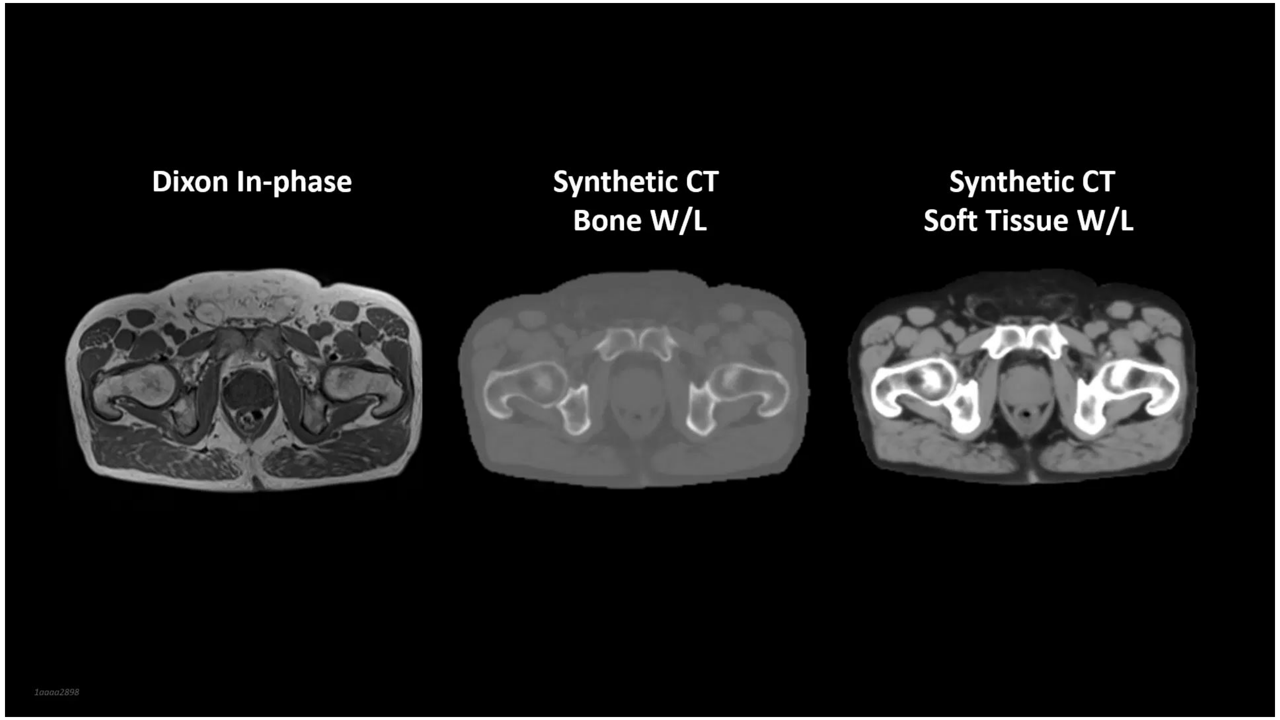
- Electron Density
- Mass Density
- (Chemical composition)

Patient model

Radiation transport and absorbed dose calculation

- MRI signal depends on the proton density as well as tissue relaxation properties.
  - Can not be used directly for dose calculation

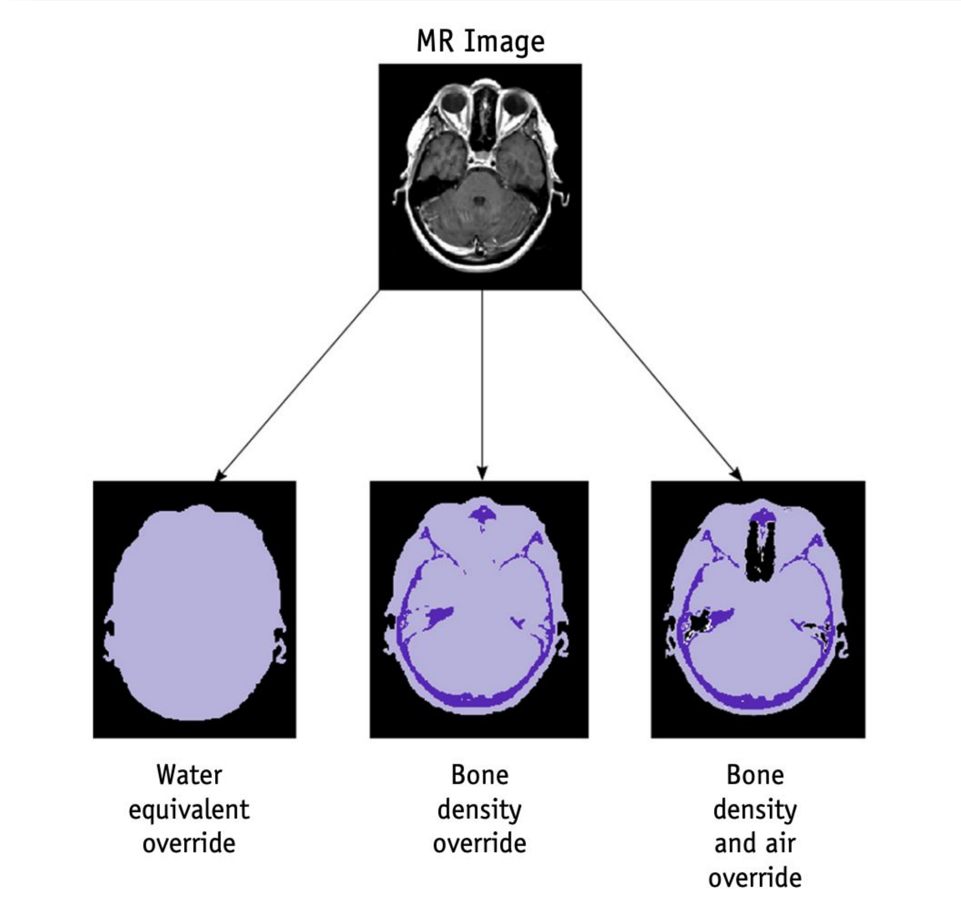
Synthetic CT: **sCT**



White paper: MR-based Synthetic CT reimaged Siemens healthineers.com

Patient model

Generation of sCT from MR images : bulk density assigment

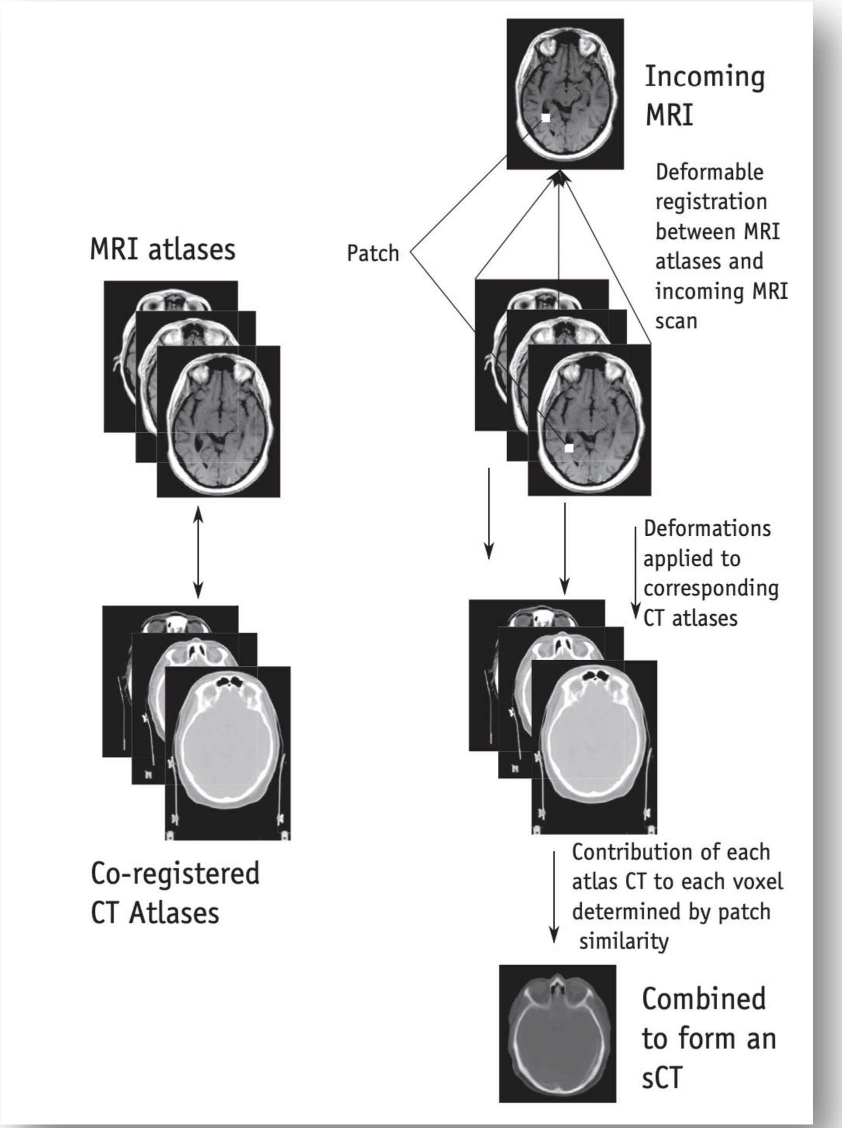


Johnstone et al. Int. Journ. Radiat. Oncol. Biol. 2018

- Bulk density assignment (3-5 different tissue classes)
  - Soft tissue, bone and air
  - For prostate and brain dose differences < 2% when bone is segmented
  - In MR is difficult to distinguish bone from cortical bone

Patient model

sCT generation:Atlas based technique



Johnstone et al. Int. Journ. Radiat. Oncol. Biol. 2018

- Only one single, standard MRI sequence.
- It uses atlas created by pairs of co-registered MRI and CT scans from a patient data-base

Patient model

sCT generation:Voxel based technique

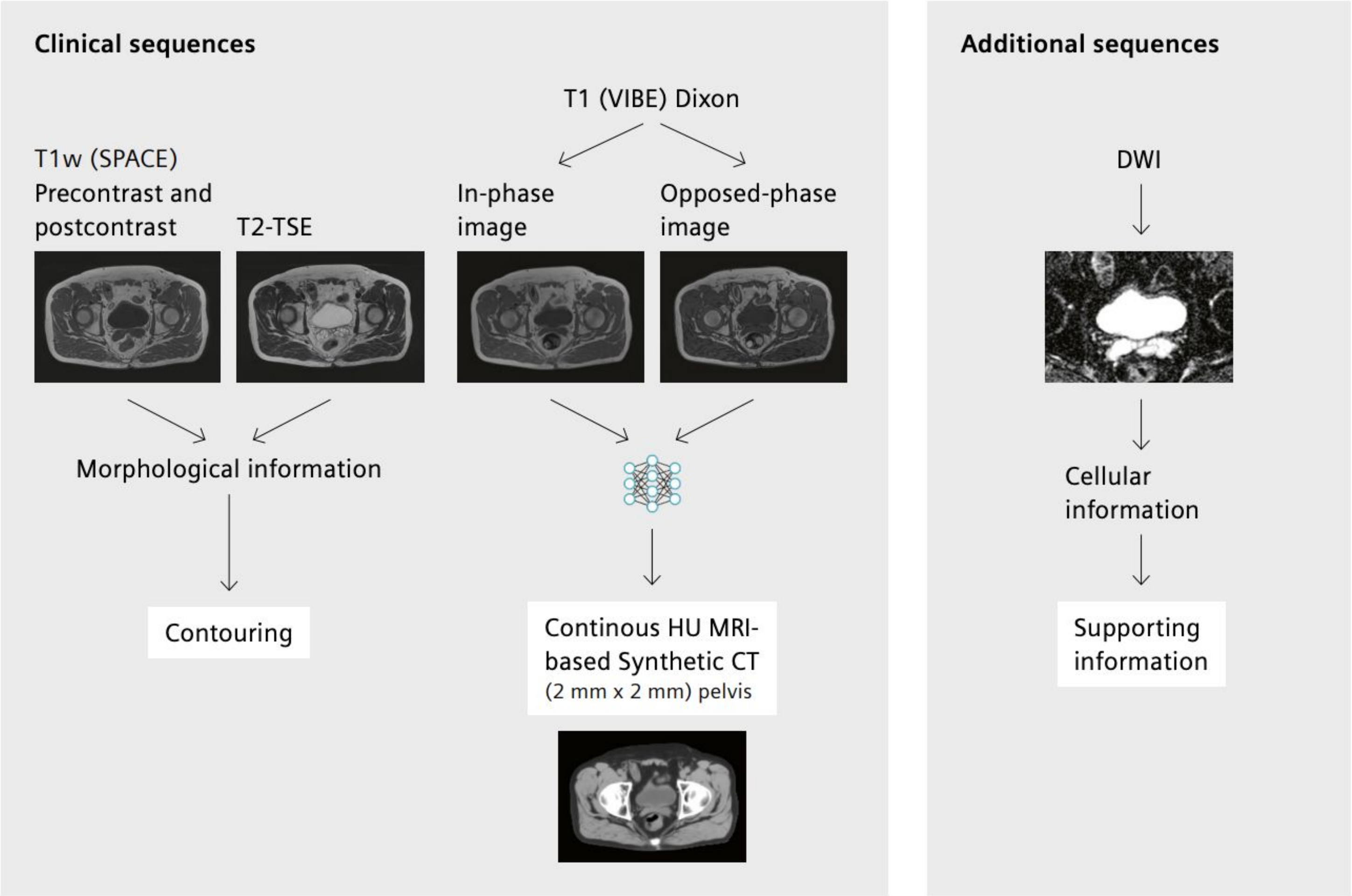


Figure 3: Example of a scanning protocol for a prostate MR-only workflow.
Courtesy of Universitätsklinikum Erlangen, Germany

Synthetic CT: **sCT**

White paper: MR-based Synthetic CT reimaged Siemens healthineers.com

Patient model

sCT generation:Voxel based technique

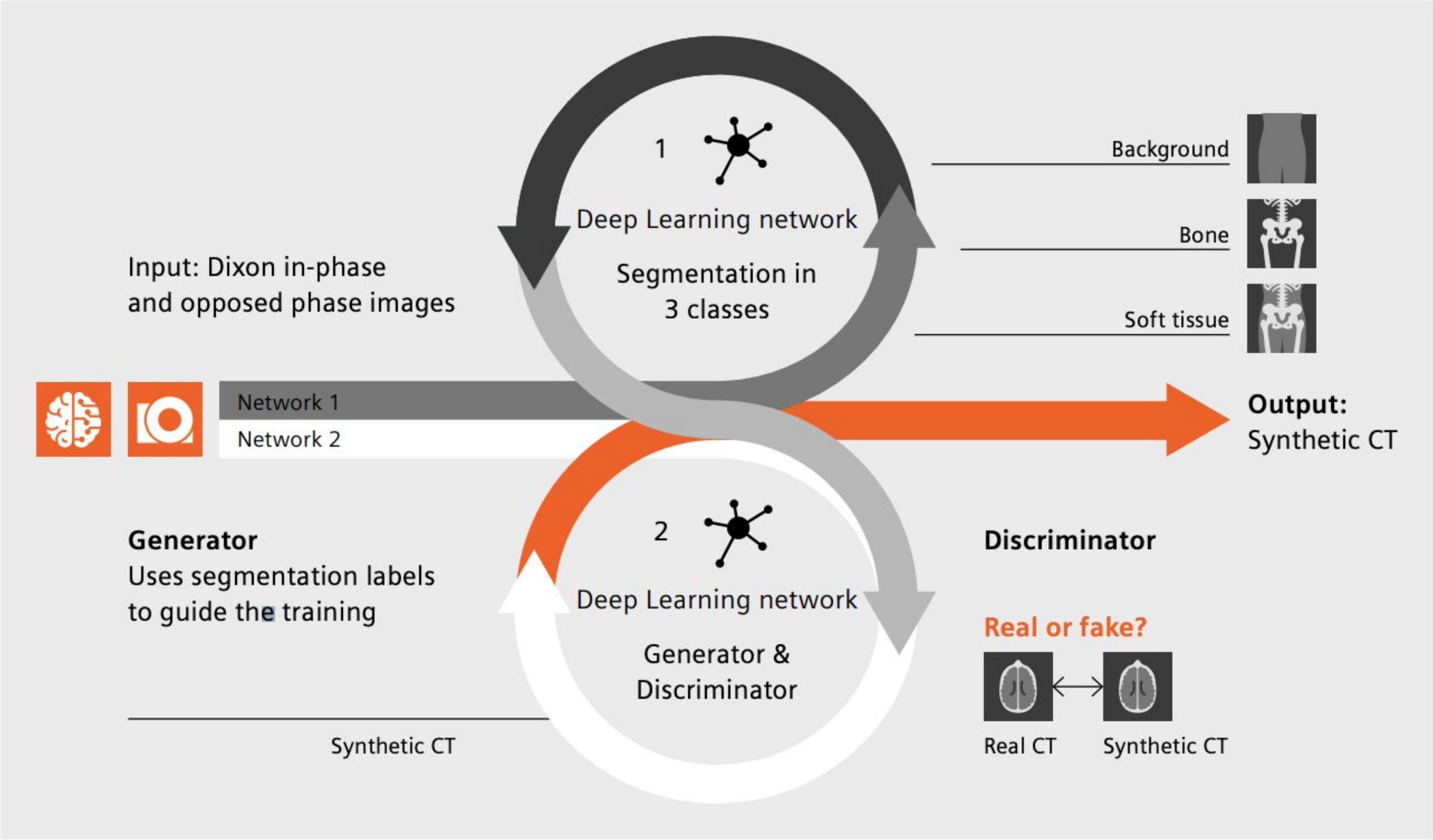


Figure 4: The cGAN (conditional generative adversarial network) training scheme.

Synthetic CT: **sCT**

White paper: MR-based Synthetic CT reimaged Siemens healthineers.com

Patient model

Radiation transport and absorbed dose calculation

Synthetic CT: **sCT**

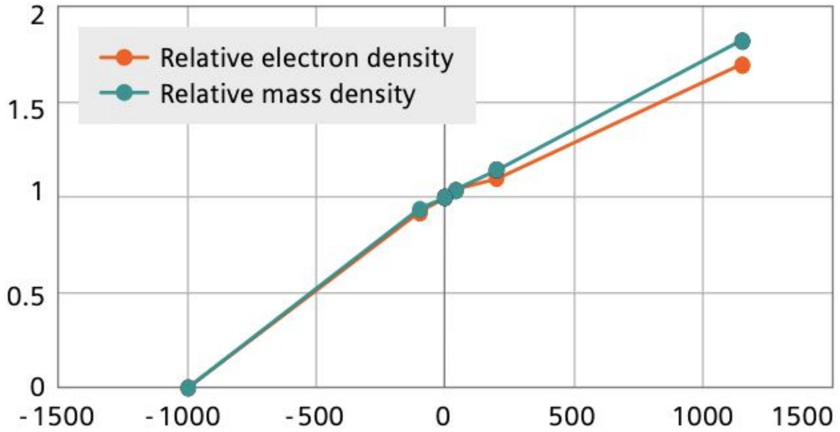


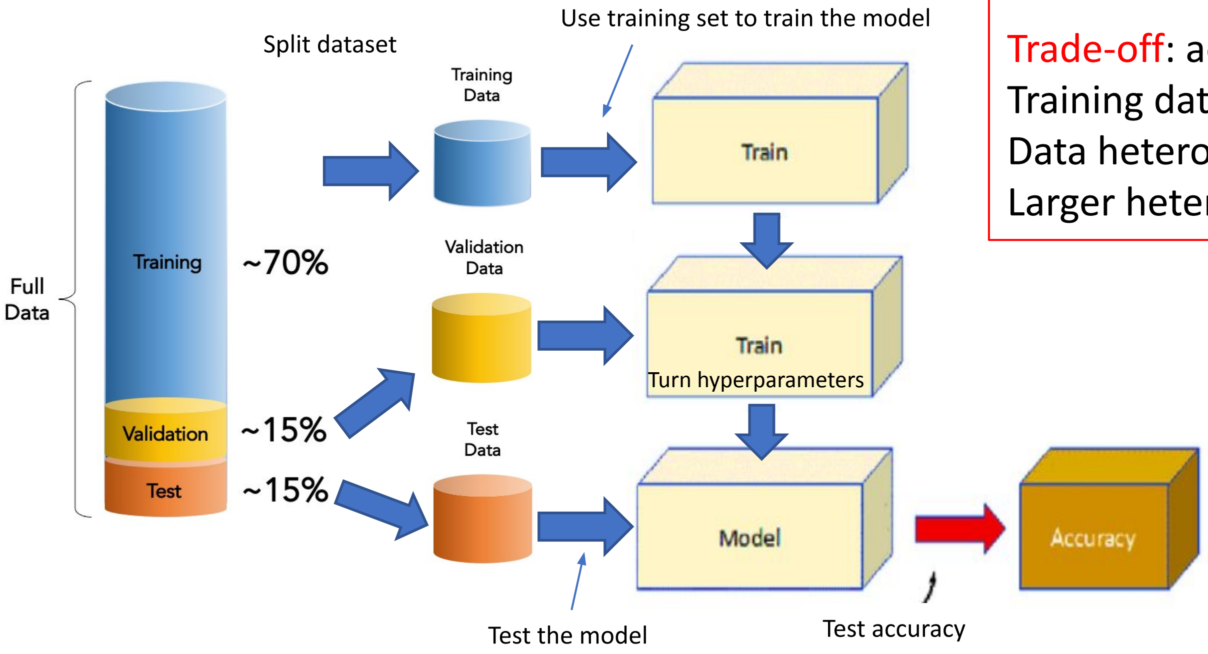
Figure 6: Synthetic CT calibration curve

Tissue class	HU value	Relative electron density	Relative mass density
Air	- 1000	0	0
Fat	- 100	0.924	0.941
Liquid	0	1	1
Brain/Muscle	40	1.04	1.04
Spongeous Bone	200	1.096	1.143
Cortical Bone	1150	1.695	1.823

White paper: MR-based Synthetic CT reimaged Siemens healthineers.com

Patient model

DL-based sCT: Technical development



Curation of training data:

Trade-off: accurate site and machine specific sCT model versus generalizability
Training data should represent the clinical cohort for which the model will be used
Data heterogeneity to ensure model robustness
Larger heterogeneity, larger training set

Data pre-processing and training process:

Bias field correction, spatial resampling, geometric fidelity corrections, image registration if paired data are required and histogram equalization

Patient model

DL-based sCT: Technical development

Hardware requirements

Need of computational resources capable of very high throughput parallel computing

Network selection:

Generator-only models:
Translation of MR to CT image domain
minimizing an intensity-based voxel-wise loss function
Requires accurate spatially registered CT/MRI data pairs for training

GAN (2014):
Two models trained at the same time: Generative model G maps the domain end-to-end and discriminative model D estimates the probability of a sample coming from the training data versus G's ouput.
Requires paired CT-MR for training and validation

Residual vision transformers and diffusion probabilistic models (2023)
Creating sCT images starting from pure noise images

Patient model

Technical challenges in sCT generation

- **Bone-air boundaries**

  New MR sequences (Novel Ultrashort Eco Time MR)

- **Differences between MR and CT scanners and acquisition**

- **Uncertainties in RM-CT registration for training data**

  Methods to increase registration accuracy

  Training networks not requiring paired data (CycleGan)

- **"Neural hallucinations** (i.e. metal implants)

  Generation of sCT using independent networks to identify faults in the absence of CT availability

- **Lack of standardised training data**

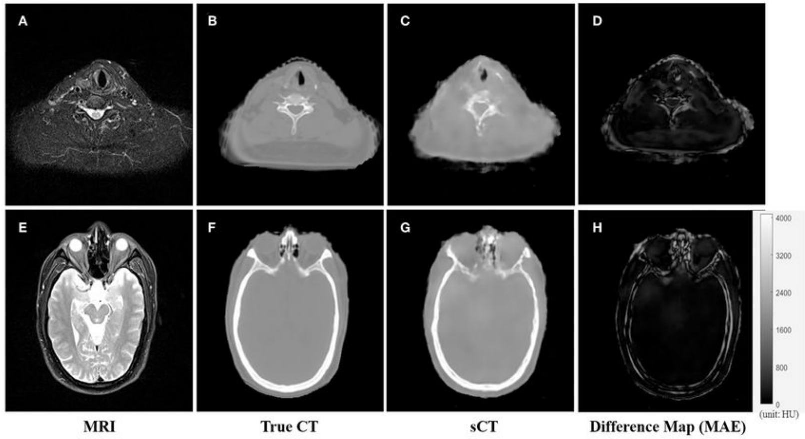
  Gold Atlas y SynthRAD innitiatives

Reference images for IGRT

sCT evaluation: what should we check?

Image metrics

Metric	Strength	Weakness
MAE (mean absolute value) *Voxel to voxel comparison*	Easy to calculate Highly used (references)	Highly penalizes registration inaccuracies Large differences in small volumes compensated by small differences in large volumes
ME (Mean Error) *Voxel to voxel comparison*	More clinically relevant than MAE Correlates more with beam attenuation (errors in HU prediction)	Compensation from positive and negative differences Less representative of the Quality of the sCT
DSC (Dice Similarity Coefficient) *Quantifies overlap between CT and sCT volumes*	Highly used	Penalises small objects Disregards the shape of the evaluated volume NOT appropriate in this context
PSNR (Peak Signal to Noise Ratio)		Lack of spatial information
SSIM (Structural Similarity Index Measure)		Difficult to calculate



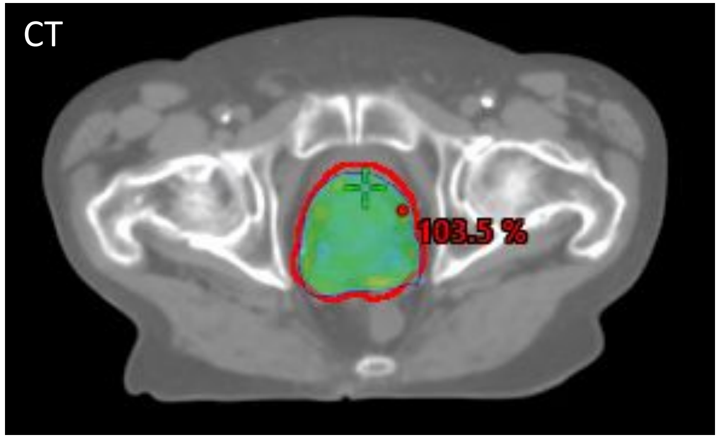
Site	MAE (Median)	ME (range)
Brain	67.8	[-6,+1]
Head and Neck	83	[-14,+25]
Pelvis	34	[-15,+7]

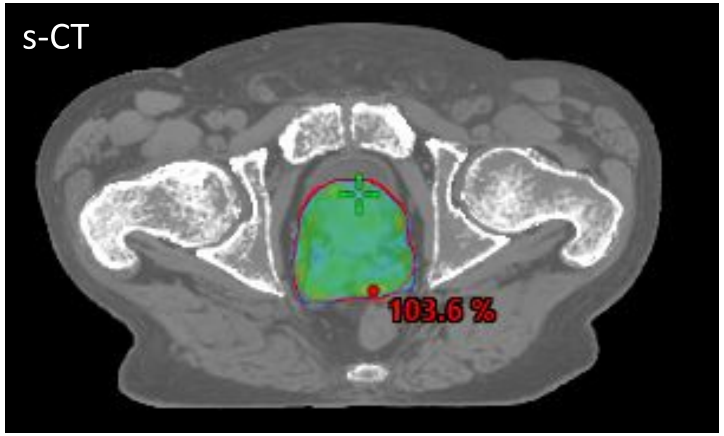
sCT evaluation: what should we check?

Dose metrics

Differences between dose calculated in CT and sCT

Metric	Strength	Weakness
Gamma index *Similarity between dose maps* *3D 10% and 90% Th (1%-1mm local)*	Highly used (references) Identification of local inaccuracies	Results highly depend on technical parameters (local vs global, 2D vs 3D)
DVH point differences	Clinical significance	Depends on Segmentation inaccuracies Depends on contour geometrical differences
DSC (Dice Similarity Coefficient) *On clinically relevant isodose volumes in both set of images*	No dependence on contours	Clinical significance?



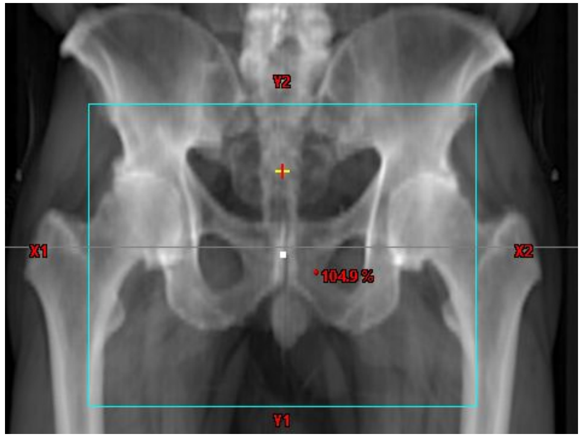


sCT evaluation: what should we check?

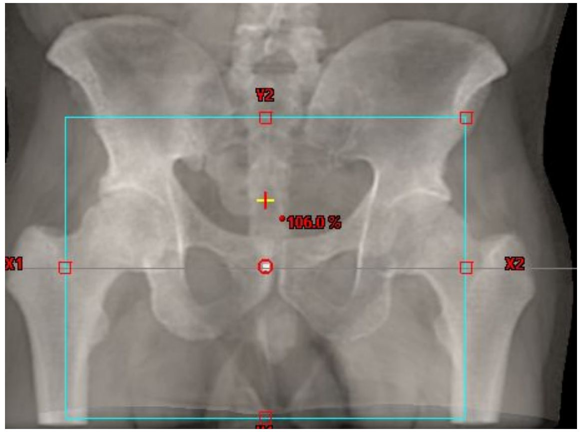
IGRT registration metrics

Patient set-up accuracy (kV based IGRT)

DRR CT



DRR s-CT



CT

s-CT

With most recent sCT developments
Matching accuracy similar to CT

MR-only workflow QA

Dummy run consisting of images from an anonymized patient can be used for some of the tests

- ✔ sCT DICOM data transfer to TPS
- ✔ Visual inspection of sCT for anatomic anomalies (body contour not afected by the coils, no tissue distortion due to metal artifacts, body contour mishaps due to patient motion)
- ✔ Ensure visibility of fixation markers or other immobilisation devices
- ✔ Check auto-countouring tolos compability
- ✔ Check dose calculation and optimisation algorithms in sCT set of images
- ✔ Check image quality of the generated DRRs.
- ✔ Check dose calculation accuracy of independent dose calculation softwares as well as pretreatment verification solutions
- ✔ Check that the body contour generated from sCT is of enough quality to be used for SGRT
- ✔ Check s-CT/CBCT y s-CT/DRR KV matching at the treatment room

MR scanner-QA

Stablish a QA programme for the MR scanner to be used for RT planning

Focus on geometric accuracy and image consistency of the whole FOV

Use commercially available phantoms

sCT generator-QA

AFTER upgrades of the system

↓

Re-commissioning is needed: image/dose/IGRT registration metrics

MR-only workflow patient-specific QA

There is a lack of commercial tools for performing MR-only PSQA

Dose Distribution re-calculation	Data	Strenght	Weakness
1st day CBCT	sCT, CBCT, RT plan	• Easy to implement within the patient workflow	• Results after first fraction • CBCT FOV • CBCT streaking artefacts may compromise accuracy • HU deviations may compromise accuracy • Need DL methods for CBCT image quality enhancement
Use of bulk densities	sCT, MR, RT plan	• Can be performed during planning stage	• Dose calculation accuracy depends on the assigned bulk densities • No availability of auto-contouring for the structures that require bulk density assignment.
Independent sCT	sCT, second sCT, RT plan	• MR data falling outside the range of the training data leads to different network hallucinations in the two sCTs, thus identifying potential outliers.	• Distortions or artefacts in the MR data propagate to both the primary and independent sCT. • Requirement of two independent software for sCT generation.
Patient specific phantom	sCT, RT plan, Patient specific phantom, detectors	• Closest approach to E2E testing • Direct dose measurement	• Dedicated hardware must be developed for PSQA • Not standardised approach • Not applicable for daily PSQA
Planning CT	sCT, pCT,RT plan	• Gold standard for dose calculation • Applicable to cases for which the sCT has insufficient quality or other PSQA methods fail.	• Fall-back approach to the classical workflow, the patient will not be treated with MR-only workflow. • A CT must have been previously acquired.

MR-only workflow QA

Task group 284 report: magnetic resonance imaging simulation in radiotherapy: considerations for clinical implementation, optimization, and quality assurance

PAPER • FREE ARTICLE

IPEM Topical Report: an international IPEM survey of MRI use for external beam radiotherapy treatment planning

Richard Speight[1], Marcus Tyyger[1], Maria A Schmidt[2], Gary Liney[3], Robert Johnstone[4], Cynthia L Eccles[5], Michael Dubec[5], Ben George[6], Ann Henry[7], Trina Herbert[8]

Hospital de la Santa Creu i Sant Pau

Take home messages

- The expected benefits of MR-only workflows in RT have been extensively discussed
- There are limited number of prospective studies on sCT clinical implementation published
- There is a lack of consensus on sCT clinical commissioning and QA
- There are still challenges that need resolving
- Vendors need to develop tools for QA

Future

Experts in the development of solutions for the generation s-CT from MR images (clinical, research and companyies)

Aim: Discuss the integration of sCT solutions into clinics and report the process and its outcomes

OUTCOMES

1º Development and validation of preclinical sCT generators

2º QA for clinical implementation of MR only workflows for Linacs and MR-linacsimplementación clínica en Linac y MR-Linac

3º Improvement suggestions


Contents lists available at ScienceDirect

Radiotherapy and Oncology

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]

- Special thanks to Natalia Tejedor (responsible for the implementation of MR-only workflow at HSCSP) for slide sharing and for discussions on the topic