MR Simulation and MR-only planning

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Advantages of MR in RT

- Superior soft tissue contrast
- Wealth of additional anatomy and pathology information

CT
T2
T1
Gd
Flair
T2 TSE

Disclosure

- Collaborative research agreement with Philips Healthcare

Major differences from Diagnostic MR

<table>
<thead>
<tr>
<th>Diagnostic MRI</th>
<th>Rad Onc MR simulation</th>
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<tbody>
<tr>
<td>Purpose</td>
<td>Detection, characterization and staging of disease</td>
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<tr>
<td></td>
<td>Reduced FOV</td>
</tr>
<tr>
<td>Acquisition parameters</td>
<td>Slice thickness ≤ 5mm, interslice gaps, Non-axial/Oblique</td>
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<tr>
<td>Readout bandwidth (RBW): tradeoff between SNR and fat/water shift</td>
<td>High RBW: reduce water/fat shift and susceptibility artifacts, and distortion</td>
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<tr>
<td>Image distortion and artifacts not as crucial</td>
<td>Distortion and image artifacts need to be quantified and corrected</td>
</tr>
<tr>
<td>Hardware</td>
<td>Curved couch</td>
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<tr>
<td></td>
<td>Optimized receiver coils for each imaging site</td>
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<td></td>
<td>No external lasers</td>
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</table>
Coil configurations

Diagnostic MR

Dedicated Rad Onc MR simulation

Coil configurations

Diagnostic MR

Dedicated Rad Onc MR simulation

Geometric Distortion mitigation

No distortion correction

Vendor 3D distortion correction

Step and Shoot MRI

Major contributor: Gradient non-linearity

Paulson et al., Medical Physics 42(1) 2015:28-39

General Sequence overview

- **T1-weighted**: gross structural information, tumor volume, lymph node involvement and OAR
- **T2-weighted**: pathological information, fat/fluid infiltration
- **Post contrast T1-weighted**: differentiate between tumor enhancement and fat/edema
- **Diffusion weighted imaging**

Metcalfe et al., Tech Can Res & Treatment, 2013

T1: longitudinal relaxation time

T2: transverse relaxation time
**T1 pre and post Gd contrast**

<table>
<thead>
<tr>
<th>T1 Pre-contrast</th>
<th>T1 Post contrast</th>
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- **Tumor**
  - Gd contrast serves as T1 shortening agent, enhancing the tumor volume
- **Organs-at-risk (OAR):**
  - Nerves
  - axillary lymph nodes
- **Prostate post biopsy hemorrhage**
- **Post operative blood products**

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**T2 and T2 Fat-Saturated**

| T2 Prostate | Flair |

- **Tumor:**
  - Edema and infiltration
- **Organs-at-risk (OAR):**
  - rectum, bladder, urethra
  - Spinal cord

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**Diffusion weighted imaging**

- **Tissue cellularity**
  - Apparent diffusion coefficient (ADC)
    - Assessed with multiple b-values
  - Tumors
    - high cellular density → low ADC values
    - Change in ADC can be monitored for treatment response assessment
  - Challenges
    - Severe distortion with standard EPI method
    - Methods with less distortion (TSE) suffer from low SNR

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- **Comprehensive summary specific to radiation oncology applications**
  - Paulson et al., Medical Physics 42(1) 2015:28-39
- **MR sim for RT AAPM guidance**
  - TG 284: Magnetic Resonance Imaging - Simulation in Radiotherapy: Considerations for Clinical Implementation, Optimization, and Quality Assurance (in progress)
**Why MR-only treatment planning**

CT based planning

Axial T2 for Contouring

- Different patient position, organ filling, respiration

Propagated and will persist throughout treatment

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**Synthetic CT generation methods**

- Image source: T1, T2, mDixon fat water separation, UTE
- Voxel-based
  - Uses voxel intensities in the MR to assign electron density
    - Standard or non-standard sequences, often requires information from multiple sequences
- Atlas-based
  - Single or multiple generalized MR atlas → deformed to CT atlas
  - Often have trouble handling atypical anatomy due to reliance on atlas
- Hybrid methods
- Deep learning methods

Johnstone et al., IROBP 2017

Edmund and Nyholm, Radiation Oncology 2017

**Deep learning methods**

- Brain:
  - T1 image as input
  - U-net [1] and Generative adversarial network (GAN) [2]
  - Generative adversarial network (GAN) with mutual information as loss function [3]
    - Retrospective n=77, multi vendor 1.5T
    - Significant improvements in Mean absolute error (MAE):
      - 184 HU (multiatlas methods) → 47.2 HU
      - Average PTV and OAR dose difference <1%
    - Soft-tissue preserving U-net architecture [4]
      - Soft-tissue MAE 17.6 HU
      - CBCT alignment difference <0.2 mm

[1] Ronneberger et al., MICCAI 2015
Deep learning methods

- Head and Neck:
  - Dental artifacts present a larger challenge than other investigated disease sites
  - Larger deformation uncertainties between MR and CT
  - Patch-based deep learning methods:
    - Improve robustness caused by abnormal anatomies
  - Pix2pix and CycleGAN [1]
    - Cross validated MAE 66.9 HU, non-ideal cases: MAE 122.1 HU
    - PTV, OAR dose difference < 2%, DRR alignment < 1 mm
  - 3D Convolutional Neural network (CNN) [2]
    - MAE 75 HU
    - Dental artifact mitigated with in combination with Turbo Spin Echo MRI


Current Clinical Status

- Most widely utilized in pelvis anatomy [1]
  - Primarily in prostate [2-3]
    - OAR and PTV dose differences < 1%
    - Bony match DRR difference < 0.5 mm (AP largest)
    - Fiducial match < 0.8 mm
  - Gyn, rectum, pelvic lymph nodes also implemented [4]
    - OAR and PTV dose differences < 0.5%
    - DRR positioning difference 0.3 mm
- Clinical adoption in brain and head and neck treatments remain limited

[1] Bird et al., IJROBP 2019
[2] Tyagi et al., PMB 2017

Commercial solutions

- Deep learning transfer function estimation based algorithm
- Scanner and vendor independent
- Input T2-weighted image
- CE marked for prostate, brain and head and neck treatments

Persson et al., IJROBP 2017

Commercial solutions

Philips MRCAT (MR for Calculating Attenuation)

- Scanner specific
- 3D mDixon FFE scan
- Online reconstruction of synthetic CT directly on scanner after acquisition
- CE-marked and FDA approved for prostate, general pelvis, and brain
**Our Experience: MRCAT in prostate**

- Exam time 25 minutes
- 4 years, >1300 patients to date

**Main Challenges**

- non-ideal bowel and bladder prep or persistent gas
- Patient motion during exam
  - Could result in synthetic CT reconstruction failures or inaccurate external body contour
- Difficulty in gold fiducial seed identification
  - Biopsy artifacts, surgical clips, LDR seeds
- Metal hip implants or spinal hardware
- FOV limits to satisfy vendor model-based reconstruction requirements
  - AP: 36.8cm, LR: 55.2cm

**Compress Sensing acceleration in MR sim**

- Signal processing technique
  - Variable density incoherent under-sampling of k-space to incoherently distribute artifacts over the image
- Reduce scan time
- Increase resolution, FOV coverage, and SNR
- Average 30% decrease in scan time
- Notable clinical benefit: enabled high resolution 3D T2 scan for urethra visualization
  - SBRT and post brachy cases had foley catheters placed for urethra contouring before
  - only ~10% of patients needed foley catheter after case-by-case sim/physics team assessment

**Continuous HU MRCAT general pelvis**

- <1% dose difference

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Tyagi et al., Radiation Oncology 2017

Tyagi et al., Radiation Oncology 2017

Tyagi et al., MR-in-RT 2019

Zakian et al., ISMRM 2020.

Yu et al., AAPM 2020: PO-GeP-M-420
Custom-designed flexible coil for MR sim

- Placed in between patient immobilization alpha cradle
- Significant SNR improvement
- Reproducible setup to treatment position

Tyagi et al., Medical Physics 2020.

MR-only phantom developments

Singhrao et al., Medical Physics 2020
Singhrao et al., PMB 2020

Next steps

- Further developments of RT-specific imaging sequences
  - Standardization of additional advanced sequences into routine treatment planning workflow
  - Robust MR biomarkers for treatment response assessment
- Further image acquisition acceleration
- Clinical evaluations, implementations and widespread adoption for MR-only planning in Brain and Head and Neck patients remains to be seen

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