Engaging MR and RT physicists in implementation, operation, and optimization of pediatric MR simulation

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Disclosure

• I have no relevant financial relationships to disclose.

• Our current MRI simulators are from Philips Healthcare, but I intended to make the presentation vendor-neutral as much as possible.

Learning objective

Learn how to synergize team efforts in implementing, operating, and optimizing MR simulation for children and adolescents.

After this presentation, you can tell:

• Differences between MR simulation and diagnostic MRI
• Unique needs in pediatric MR simulation
• Limitations of current techniques and potential solutions
• How RT physicists may engage MR physicists
Outline

- **Background**
  - Radiation Oncology at St Jude
  - Significance of MR simulator in pediatric RT
- **Implementation**
  - Site planning, selection of MR system
  - Acceptance test, establishing periodic QA
  - Staff training
- **Operation**
  - MR safety
  - Patient setup
  - Motion management
- **Optimization**
  - Ongoing unmet needs
  - Recent developments

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St. Jude Children’s Research Hospital, Memphis, TN

- NCI-designated comprehensive cancer center devoted to children
- 5,000 employees
- 8,600 pediatric patients annually
- Brain tumor, leukemia, lymphoma, solid tumors, sickle cell disease, infectious diseases

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Radiation Oncology at St Jude

- 3-room scanning beam proton therapy since 2015
- Photon therapy linear accelerator
- MRI (1.5T and 3T), spectral CT, PET/CT, CBCT
- Patient age: 3 months – 30s
- 1/3 patients requires anesthesia (typically < 8 years old)
- Cranial, abdominal, and pelvic tumors are most common
- Multiple treatment phases with boost planning and on-treatment imaging
Dedicated MRI simulators 2004 – present

2004-2012
Philips 0.23T Panorama
Open MRI
Resistive magnet
2012-2016
SciMedix 1.5T SM160
60-cm closed bore
Flat tabletop with coil elements
2016-present
Philips 3T and 1.5T Ingenia MR-RT
70-cm wide bore

Images acquired by our MRI simulators

On-treatment MRI for adaptive RT
On-treatment/post-treatment diffusion-weighted MRI

Response of leukocytic fiber tract to proton therapy

Longitudinal trends in DTI indices and structural connectome features

- Uh et al., Int J Radiat Oncol Biol Phys, 86:292, 2013
- Uh et al., Int J Radiat Oncol Biol Phys, 93:64, 2015
- Uh et al., ASTRO, 2019
- Uh et al., Int J Radiat Oncol Biol Phys, 109:515, 2021

Effects of surgery and proton therapy on white matter

Unpublished data

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Differences between MRI for diagnostic imaging and RT simulation applications

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Diagnostic Imaging (DI)</th>
<th>RT Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection, characterization, and staging of disease</td>
<td>Determination of the 3D disease extent and position relative to adjacent organs at risk</td>
<td></td>
</tr>
<tr>
<td>Field-of-view</td>
<td>Volume of interest</td>
<td>Need to cover OAR, landmarks, and body surface as well as target</td>
</tr>
<tr>
<td>Slice thickness and spacing</td>
<td>4-5 mm with 0-2mm gaps</td>
<td>Thin slice (&lt;3mm) or isotropic (1 cu mm) without gap</td>
</tr>
<tr>
<td>Geometric distortion</td>
<td>Tolerated to long as diagnostic capability not affected</td>
<td>&lt; 2 mm in all planes</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Tradeoff between fat/water shift and SNR</td>
<td>Intentionally set high</td>
</tr>
<tr>
<td>Receiver coil</td>
<td>Dedicated coil</td>
<td>Flexible coil</td>
</tr>
<tr>
<td>Patient posture</td>
<td>Accommodate patients' comfort</td>
<td>Treatment planning position</td>
</tr>
<tr>
<td>Patient table</td>
<td>Curved</td>
<td>Flat</td>
</tr>
</tbody>
</table>

Partly adopted from Fraunhofer et al., Med Phys, 42:28, 2015
Safety zones of St. Jude MR simulators

- Photon center (1.5T)
- Proton center (3T)

- ACR-defined safety zones
- Survey fringe field; mark 5 Gauss line
- RF shielding and waveguide

Considerations for pediatric MR sim site
- Facility and staffing for anesthesia and child life support
- Traffic to/from other imaging and treatment rooms
- Screening and preparation spaces
- Parents waiting area
- AAPM Report No. 100, TG 284 report

Selection of static magnetic field (B0)

- Higher B0: advantageous in high-end imaging
  - Higher signal/contrast to noise
  - Higher spatial resolution
  - Fast imaging
  - Physiological imaging (diffusion, perfusion)
  - MR spectroscopic imaging (MRSI, CEST)
- Lower B0: advantageous in operation/safety and artifact suppression
  - Wide/open bore
  - Lower SAR/PNS
  - Higher B0 homogeneity, lower magnetic susceptibility
  - Less distortion
  - Lower cost
  - MR-Linac

Selection of equipment

- External laser system
- Flat tabletop
- Receiver RF coils for various body sizes
- MR-safe immobilization devices (thermoplastic mask, vacuum bag, head cushion, mounting board)
- Coil support
- Anesthesia equipment
- Safety equipment (metal detector, ear plug, headset)
- QA phantoms
Acceptance tests and baseline QA

- Selected tests and criteria were based on:
  - ACR-MRI quality control manual
  - AAPM TG report No. 100
  - Vendor technical specifications
  - Site-specific requirements

- RT-specific tests
  - Geometric fidelity (over 45-cm DSV)
  - Table positioning accuracy
  - External laser system accuracy
  - Image quality tests with RT coil configurations

https://philipsproductcontent.blob.core.windows.net/assets/20191119/a6fa1f759b434b83b68cab0a00f1905c.pdf

Image quality comparison between receiver coil/phantom configurations

Imaging protocols specific to anatomic site and patient size

- Reduce parallel imaging factor (SENSE, GRAPPA) with RT coil configurations.
- Increase band width to reduce distortion.
- Consider variations in body size, patient posture, target location, and field-of-view:
  - Compensate reduced SNR for a small FOV and a high resolution
  - Concatenate multiple image components acquired at different table positions.
- Incorporate motion suppression techniques (radial acquisition, triggering/gating)
Staff training

- Vendor-provided on-site training for imaging therapists
  - Operation of MR-RT system
    - Patient screening
    - General MR simulation workflow
    - Review of anatomic site-specific workflow:
      - Patient setup
      - Use of appropriate receiver coils
      - Imaging parameters
  - Daily QA and troubleshooting
- Safety walkthrough for Level 1 and Level 2 MR personnel
- Training physicists and physicist assistants for QA procedure

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MRI hardware and safety

- Magnet
  - Safety zone, material labeling, cryogen
- Transmit RF coil
  - Specific absorption rate (SAR)
- Gradient coil
  - Peripheral nerve stimulation (PNS), acoustic noise
Safety considerations for pediatric MR simulation

- Crossing safety zones
  - Doors should be kept closed until the patient is ready.
  - Careful screening with multiple types of metal detectors.

- Patients with implants
  - Restrict SAR/PNS according to manufacturer specifications.

- Secure fitting of earplug and headset

Patient setup and coil configurations

- Brain*
  - Head cushion
  - Face mask
  - Flexible loop coil

- Abdomen/Pelvis
  - Head cushion
  - Torso cushion

- Extremities
  - Various combinations of anterior and loop coils depending on anatomy, FOV, and immobilization devices

- Head & neck
  - Loop coil with anterior coil

- Spine
  - Cervical loop coil
  - Thoracic, lumbar: anterior coil (imbedded in patient table)

  - Anterior coil is mostly added to boost signal

Cranial images with RT coil configuration*

6-year-old patient with orbital rhabdomyosarcoma

Resolution: 1 x 1 x 3.5 mm³

*EPI-based fast imaging (DTI, fMRI, ASL, DSC) and spectroscopic imaging (MRS, CEST) are not feasible with the RT coil configuration.
Motion management (voluntary) without anesthesia

- Immobilization devices (thermoplastic mask, head cushion, vacuum bag)
- Familiarize patients with MRI scan environments: mock scanner, MR sound clip, decorating thermo mask
- Instruction via microphone between scans
- Measures to relieve stress: music, video, audiobook, stress ball, weighted blanket
- Child life support

Motion management (involuntary)

- Managed motion
  - Respiratory
  - Cardiac
- Type of acquisition control
  - Triggering
  - Gating
- Surrogate signal
  - External
    - Bellows pressure sensor
    - Video-based tracking [e.g., BPM]
    - Spirometry
    - ECG, pulse oximeter

- Imaging technique
  - Radial imaging
    - PROPELLER/BLADE/MultiVane
  - Fast imaging
    - TSE/EPI, parallel imaging, partial Fourier
  - Compressed sensing
  - Simultaneous multi-slice excitation

- Internal
  - Navigator RF pulse
  - Self-navigator:
    - Central spoke of radial k-lines
    - Principal component analysis
    - Mutual information
Radial imaging for motion suppression

T2 2D FS radial imaging without triggering/gating

T2 3D FS radial imaging without any motion suppression

*Can be combined with triggering/gating for further improvement.

Unpublished data

Respiratory-correlated 4D MRI

Retrospective sorting of slice-wise dynamic images by principal component analysis

4-year-old patient with rhabdomyosarcoma

Voxel-wise motion trajectory


Challenges in pediatric 4D MRI

- Irregular and asymmetric motion
- Variations in breathing rate and extent of motion
- Anesthesia effect
- Unstable external surrogate signal because of loose bellows belt or shallow breathing

Peak-to-peak organ motion in pediatric patients

Unpublished data

Retrospective sorting of slice-wise dynamic images by principal component analysis

Voxel-wise motion trajectory

Uh et al., AAPM, 2019

Uh et al., Int J Radiat Oncol Biol Phys, 99:227, 2017
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Ongoing unmet needs

- Geometric fidelity with a large FOV
- Accelerated acquisition
  - beneficial for motion management, reducing anesthesia, simpler workflow
- Physiological imaging (diffusion/perfusion, spectroscopy)
  - in a high resolution without severe distortion and motion artifacts
- Metallic artifact reduction
- MR-only simulation

Moving table MRI – stitching image volumes at different table positions

T1 3D radial imaging

with a single table position

with two different table positions

Image discontinuity at the junction of 2 volumes
Fast imaging to reduce scan time

Muckley et al., IEEE Trans Med Imaging, 40:2306, 2021

Metal artifact reduction

- Adjusting imaging parameters
  - Turbo spin echo without parallel imaging and uniformity correction
  - High BW, high resolution, thin slices, short TE, signal averaging, etc.

- View angle tilting (VAT)
  - An extra gradient is applied with the readout gradient to compensate off-resonances in a tilted view.

- Slice encoding for metal artifact correction (SEMAC)
  - Multi-spectral sequence to acquire additional off-resonance data (z-encoding)
  - Limited to 2D spin echo
  - Longer acquisition, increased SAR

2-year-old patient with ependymoma who underwent a VP shunt placement

Alternative posterior receiver coil designs

Fast tabletop with embedded coil elements

Tyagi et al., Med Phys, 47:3143, 2020

Unpublished data
Head and neck receiver coils for RT simulation

McGee et al., Phys Med Biol, 63:08NT02, 2018


Screen-printed flexible RF coils

Corea et al., Magn Reason Med, 78:775, 2017

Corea et al., Nat Commun, 7:10839, 2016

Winkler et al., Radiology, 291:180, 2019

Methods of synthesizing CT from MRI refined for pediatric images


Uh et al., Med Phys, 41:1617, 2014

Challenges and opportunities in pediatric MR simulation

- Diverse body size/FOV and target location
- Motion management (voluntary/involuntary)
- Reducing need/time of anesthesia
- Metallic implant
- Distortion-suppressing techniques
- Automated adjustment of imaging parameters
- Staff training/child life support
- Receiver coil designed for pediatric MR simulation
- Fast imaging
- Moving table MRI

Engaging MR and RT physicists in pediatric RT simulation

- What MR physicists should know – geometric requirements for RT
  - Patient in treatment position
  - A large field-of-view
  - Isotropic resolution
  - Tolerance of distortion
- What RT physicists should know – capabilities and limitations of MRI
  - Limited image coverage
  - Weak signal → deliberate use of coils
  - Trade-off between quality and time
  - Everything depends on specific sequence
- Where diagnostic MR physicists may contribute
  - Identifying most suitable imaging techniques
  - Optimizing imaging parameters
  - Training staff in operation and QA
  - Implementing new developments
- Engaging diagnostic MR physicists in RT simulation
  - Inter-departmental seminar
  - Let MR physicists shadow RT staff
  - Discussion on common needs

- Where diagnostic MR physicists may contribute
  - Identifying most suitable imaging techniques
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