Introduction of MR Pulse Sequences and Potentials of On-Board MRI

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Disclosures

Research Support from ViewRay
Honorarium from ViewRay

What MR guided RT (MRgRT) can give us?
- Better target/OAR delineation for planning
- Reduce patient setup uncertainty
- Adaptive treatment planning
- Motion assessment and management - Accurate gating

Better target localization
Better patient setup
Soft tissue based gating
Outline

- Basic MR sequences
  - Spin-echo based sequence
    - TSE
    - FLAIR (with inversion recovery)
    - HASTE (single shot TSE)
    - SPACE (3D TSE)
  - Gradient-echo based sequence
    - GRE
    - VIBE (3D GRE)
    - MPRAGE (3D GRE with inversion recovery)
  - Functional imaging
    - DWI
    - DCE perfusion
- Current MR developments with MRgRT on-board MRI
  - 3D anatomical MRI
  - 4DMRI
  - Functional MRI

Basics of MRI

Pulse sequence describes the order of events: RF, signal reception, and gradients.

T1 and T2 – MRI Contrast

- Different tissue has different relaxation property
  - T1: longitudinal relaxation time
  - T2: transverse relaxation time
- Various contrast could be obtained by changing the scanning parameter
Basic MR sequence: SE

- Spin echo (SE)
  - A 180° pulse is applied after the 90° excitation pulse to refocus the spins
  - TE: Echo time
  - TR: Repetition time
  - Contrast
    - T1-w, T2-w, PD-w
- Foundation of many other sequences.
- Not used in the clinic due to long acquisition time

http://mriquestions.com/image-contrast-trte.html

Basic MR sequence: TSE

- Turbo spin echo (TSE)/fast spin echo (FSE)
  - Multiple k-space lines acquired during each TR
  - Echo train length (ETL): number of echoes after each excitation
  - Significantly reduced scan time
    - Inversely proportional to ETL
  - T1-weighted TSE
    - Short TR, short TE, small ETL
  - T2-weighted TSE
    - Long TR, long TE, large ETL
- Increased T2 weighting with increasing ETL.
- All images TR=4000 and other parameters unchanged

Images from http://mriquestions.com/what-is-fsetse.html
http://mriquestions.com/fse-parameters.html
Basic MR sequence: HASTE

- Half-Fourier Acquisition Single-shot Turbo spin Echo imaging (HASTE)
- K-space is acquired in a single train
- Half-Fourier is employed

Advantages
- Fast acquisition speed
- Less susceptible to motion
- Non-breath-hold application
- T2 contrast (long echo train length)
- Other contrast via preparatory pulse.

Image from http://mriquestions.com/hastess-fse.html

Basic MR sequence: FLAIR

- Fluid-attenuated inversion recovery (FLAIR)
- An inversion pulse is applied before the imaging readout to null fluids
- By carefully choosing the inversion time (TI), the signal from any particular tissue can be nulled.
  - STIR (Short TI Inversion Recovery) to suppress the signal from fat

Image from http://casemed.case.edu/clerkships/neurology/web%20neurorad/mri%20basics.htm

Basic MR sequence: SPACE

- Sampling Perfection with Application optimized Contrast using different flip angle Evolutions (SPACE)
- 3D turbo spin echo acquisition
- Long echo train length with ultra-short echo spacing
- Rapid 3D isotropic imaging with reasonable imaging time (5-10min)
- Able to create T1-w, T2-w, PD-w, or FLAIR images
- Very useful for brain/H&N/musculoskeletal/spinal cord imaging

Image from https://www.siemens-healthineers.com
Basic MR sequence: GRE

- Gradient echo imaging (GRE)
  - Bipolar gradient to dephase and rephase the FID signal
  - Fast acquisition speed compared to spin echo imaging
- Contrast:
  - TE controls T2* weighting
  - TR controls T1 weighting
  - Flip angle controls T1 weighting

Images from http://mriquestions.com/haste.html
http://mriquestions.com/spoiled-gre-parameters.html

Several variations of GRE sequence

<table>
<thead>
<tr>
<th>Pulse sequence</th>
<th>Siemens</th>
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<th>Phillips</th>
<th>Contrast</th>
<th>SNR</th>
<th>Artifacts</th>
<th>Protocol</th>
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</thead>
<tbody>
<tr>
<td>Balanced SSFP</td>
<td>FISP</td>
<td>FISP</td>
<td>Balanced</td>
<td>T2/T1</td>
<td>High</td>
<td>Blooming</td>
<td>Short TR, T2/T1, moderate to high FA</td>
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<tr>
<td>Gradient- spoiled GRE</td>
<td>SSFP-FF</td>
<td>FISP</td>
<td>Rapid</td>
<td>T2/T1</td>
<td>Mid</td>
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<tr>
<td>SSFP-Echo</td>
<td>PSIF</td>
<td>SSFP</td>
<td>Balanced</td>
<td>T2/T2</td>
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<tr>
<td>SSFP-FFE</td>
<td>FISP</td>
<td>SSFP</td>
<td>Balanced</td>
<td>T2/T2</td>
<td>Mid</td>
<td>Motion</td>
<td></td>
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<tr>
<td>SSFP-FLASH</td>
<td>FLASH</td>
<td>SSFP</td>
<td>Balanced</td>
<td>T1-FSE</td>
<td>Low</td>
<td>Minimal</td>
<td>Short TR, TE, Low FA</td>
</tr>
</tbody>
</table>

Table based on “MRI Acronyms”, Siemens Healthcare and Hargreaves R.
Basic MR sequence: VIBE

- Volumetric interpolated breath-hold sequence (VIBE)
- Modified 3D GRE sequence
- Similar quality as 2D GRE, but higher spatial resolution and lower scan time
- T1 contrast
- Very useful in abdominal/chest/adrenal imaging
  - High resolution 3D images in a single breath hold

Basic MR sequence: MPRAGE

- Magnetization Prepared Rapid Acquisition GRE (MPRAGE)
- An inversion recovery preparation module followed by 3D GRE acquisition
- Rapid 3D isotropic imaging
- T1-weighted imaging technique
- Very useful for brain/face/spine imaging
  - Full brain coverage within 5 min.

Basic MR sequence: Spin Echo EPI
Basic MR sequence: DWI

- Diffusion-weighted imaging (DWI)
  - Pair of gradient cause signal loss of diffusing spins but not stationary spins
  - Apparent diffusion coefficient (ADC) map

- Advantages
  - Restriction in acute ischemia
  - Functional information for tumor detection and early response assessment

- Disadvantages
  - Low resolution
  - Distortion

![Diffusion MRI images](image)

Treatment response assessment: Diffusion MRI

- Measures tissue cellularity
  - Tumors \(\rightarrow\) higher cellular density \(\rightarrow\) lower ADC (Apparent Diffusion Coefficient)

- Extensively studied at high field (\(\geq 1.5T\))
  - May be an early imaging biomarker for tumor response to treatment

Perfusion MRI: T1 weighted DCE MRI

Repeated acquisition of T1w images after contrast agent injection – signal enhancement as a function of time

![Perfusion MRI images](image)
Basic MR sequence: Perfusion

- Time-resolved angiography With Interleaved Stochastic Trajectories (TWIST)
- View-sharing to allow rapid 3D image acquisition (couple of second per volume)

On-board MRI developments: Challenges

- Long acquisition time compared with CT
- Partial Fourier
- Parallel imaging and compressed sensing
- View-sharing
- Simultaneous multi-slice
- Motion management
- Radial acquisition
- Motion gating/triggering
- Distortion
- Distortion correction
- Improved shimming and gradient performance

Improved breath hold MRI: Patient Study

Clinical GRAPPA 7.5x (Clinical sequence): GRAPPA 2×2, partial Fourier(6/8), 25s
Proposed VDPD 15x (Proposed sequence): center 22×16 region fully sampled, 12.5s
Multi-resolution MRI on MR-Linac: MR-RIDDLE

- K-space sampling
  - Golden-angle (GA) rotated stack-of-stars (SOS) sampling trajectory
- Key features:
  - Insensitive to motion (radial trajectory)
  - Better K space coverage (in-plane and through-plane GA rotation)

Improved free breathing MRI: Compensated free breathing 3D MRI for MRgRT

Zhou, et al., MRM 2017

Improved free breathing MRI: MR-Linac

Clinical Protocol

Proposed Protocol
4DMRI on MR-Linac

- 4D-CT – the current clinical standard
- Over-sampled axial 2D slices, each tagged with respiratory signals
- Images sorted based on respiratory tags

4D-MRI
- Better soft-tissue contrast
- Flexible k-space sampling and image reconstruction

Images sorted based on respiratory tags

4DMRI on MR-Linac

- 3D encoding has SNR advantages
- Established theories to retrieve missing k-space lines
- Higher slice resolution
- More flexible sampling design

Exhaust over-sampling
Smart under-sampling

Motion Averaged
Mid-Position
Respiratory Binned

Figure credit: Allen LI, MCW
Inherently distortion-free MRI: Single-Point Imaging (SPI)


Treatment response prediction


MRgRT: On-board longitudinal DWI

- Using features from all three time points provided the best AUC
- Using single time point worked poorly for the treatment response prediction
- SVM with T1-3 (Time point 1-3) provided the best results

CT simulation with GTV contour

DWI & T2 FLAIR with b = 500

ADC map @ 3rd fraction

Using features from all three time points provided the best AUC
Perfusion MRI: T1 weighted DCE MRI

- 3D T1-weighted golden angle radial stack of stars sequence.
- 512 spokes/partition, 80 partitions acquired over 180 s.
- FOV = 349 x 349 x 120 mm, spatial resolution = 1.68 x 1.68 x 1.5 mm, TR = 4.44 ms, TE = 2 ms, flip angle = 12 degrees, BW = 601 Hz/voxel.
- Intravenous injection of 0.1 ml/kg Eovist at a rate of 2 ml/s.

MRgRT: On-board DCE-MRI

- 4 qualitative datasets (T1-weighted, enhanced T1-weighted, proton-density (PD), and FLAIR).
- 3 quantitative maps (T1, PD, R2*)
- Acquired in ~10 mins at 0.35T

On-board multi-contrast MRI: STAGE

- 4 qualitative datasets (T1-weighted, enhanced T1-weighted, proton-density (PD), and FLAIR).
- 3 quantitative maps (T1, PD, R2*)
- Acquired in ~10 mins at 0.35T

Figure credit: Glide-Hurst & Nejad-Davarani, HFCI
Chen Y, et al., Magnetic Resonance Imaging, 2018
Functional MRI on Unity

E Koorenman, et al. Radiotherapy and Oncology, 2019

Cardiac CINE MRI on MR-Linac

- bSSFP Sequence Parameters:
  - TR/TE: 4/2 ms
  - Voxel size: 1.25 x 1.25 x 7 mm³
  - FOV: 320 mm
  - Flip angles: 130°
  - RO bandwidth: 772 Hz/pixel
  - Parallel imaging mode: GRAPPA
  - Cardiac gating with SIEMENS PMU

S Rashid, et al. Quant Imaging Med Surg, 2018

Dose comparison between diastolic and systolic phases

David Geffen School of Medicine

S Rashid, et al. Quant Imaging Med Surg, 2018
Summary

- On-board MRI brings value to each step of RT workflow
- Longitudinal functional MRI became possible
- MRI-guided adaptive: a new RT paradigm?
- Functional imaging in assessment of treatment response
- Comprehensive MRI acquisition: different MRI pulse sequences
- More patients to benefit from MRgRT

Thank you!