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

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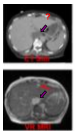
## Disclosures

**Research Support from ViewRay**

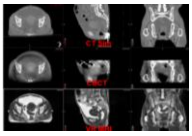
**Honorarium from ViewRay**

## What MR guided RT (MRgRT) can give us?

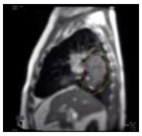
- Better target/OAR delineation for planning
- Reduce patient setup uncertainty
- Adaptive treatment planning
- Motion assessment and management - Accurate gating



*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

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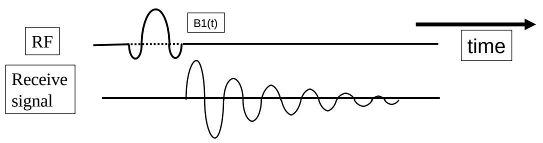
## Basics of MRI




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

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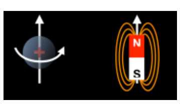
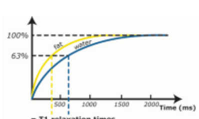
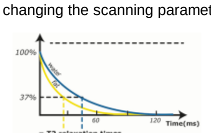
## T1 and T2 – MRI Contrast




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

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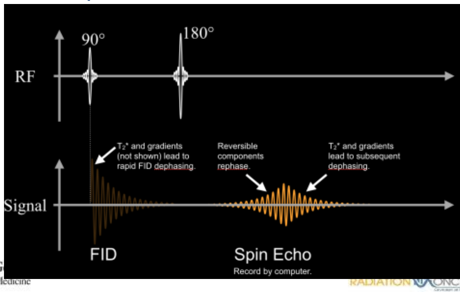
## Basic MR sequence: SE

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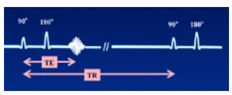
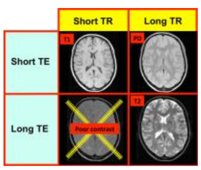
## Basic MR sequence: SE

- 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

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Images from http://mriquestions.com/se-vs-multi-se-vs-fse.html
http://mriquestions.com/image-contrast-trte.html

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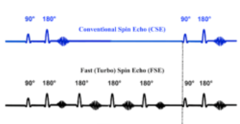
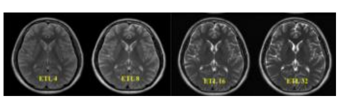
## Basic MR sequence: TSE

- 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

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Images from http://mriquestions.com/what-is-fsetse.html
http://mriquestions.com/fse-parameters.html

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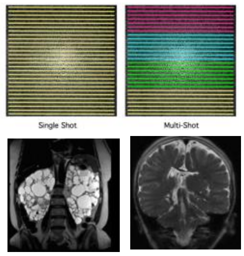
## Basic MR sequence: HASTE

- 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.





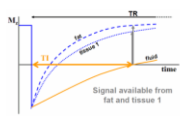

Images from http://mriquestions.com/hastess-fse.html





## 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



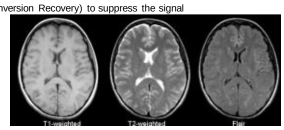






Image from http://casemed.case.edu/clerkships/neurology/web%20neurorad/mri%20basics.htm





## 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 ultrashort 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

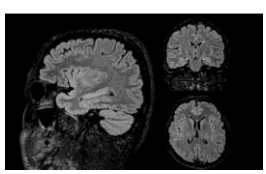
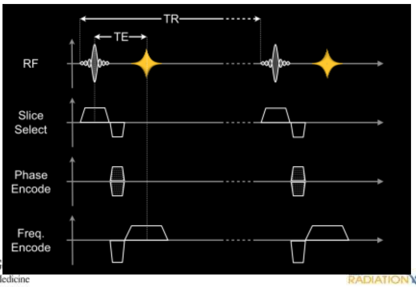




Image from https://www.siemens-healthineers.com

## Basic MR sequence: GRE

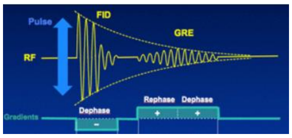


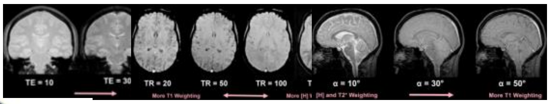





## Basic MR sequence: GRE

- 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/hastess-fse.html
"http://mriquestions.com/spoiled-gre-parameters.html





## Basic MR sequence: GRE

- Several variations of GRE sequence

| Pulse sequence | | Siemens | GE | Philips | Contrast | SNR | Artifacts | Protocol |
|---|---|---|---|---|---|---|---|---|
| Balanced SSFP | bSSFP | TrueFISP | FIESTA | Balanced FFE | T2/T1 | High | Banding | Short TR, TE=TR/2, moderate to high FA |
| Gradient-spoiled GRE | SSFP-FID | FISP | GRASS | FFE | T2/T1 | Mid | Motion | |
| | SSPF-Echo | PSIF | SSFP | T2-FF2 | T2+T2/T1 | Mid | Motion | |
| Grad and RF-spoiled GRE | Spoiled GRE | FLASH | SPGR | T1-FFE | T1;T2* | low | Minimal | Short TR, TE. Low FA |



Table based on "MRI Acronyms", Siemens Healthcare and Hargreaves B, 16

## 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

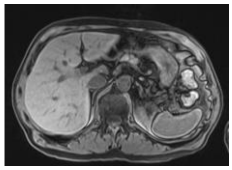


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Image from https://mrimaster.com/characterise%20image%20vibe.html

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## 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 5min.

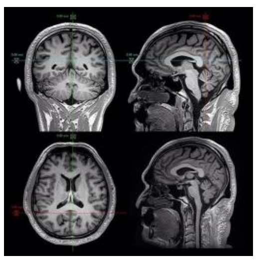

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Image from https://medizzy.com/feed/1412495

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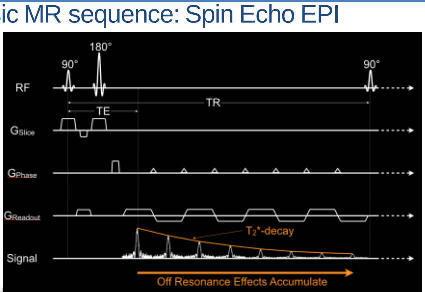
## Basic MR sequence: Spin Echo EPI

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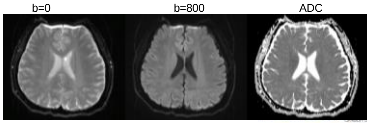
## Basic MR sequence: DWI

- 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

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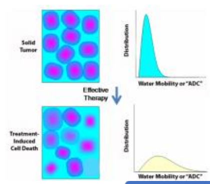
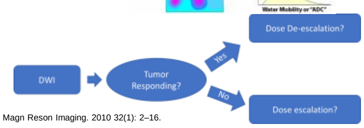
## Treatment response assessment: Diffusion MRI

- **Measures tissue cellularity**
  - tumors -> higher cellular density -> lower ADC (Apparent Diffusion Coefficient)
- **Extensively studied at high field (>=1.5T)**
  - may be an early imaging biomarker for tumor response to treatment

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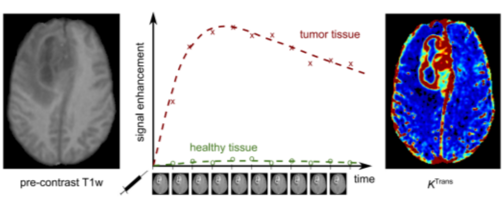
Thoeny et al. J Magn Reson Imaging. 2010 32(1): 2–16.

## Perfusion MRI: T1 weighted DCE MRI

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

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A Heye, et. Al, NeuroImage: Clinical 6 (2014)

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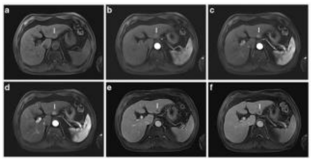
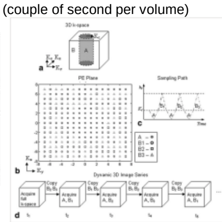
## Basic MR sequence: Perfusion

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



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Hong SB, et al., European Radiology, 2019
Song T, et al., MRM, 2009

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## 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
  - Self-navigator with retro recon
- Distortion
  - Distortion correction
  - Improved shimming and gradient performance

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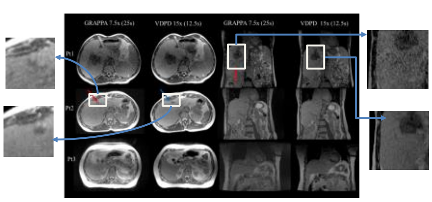
## Improved breath hold MRI: Patient Study

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

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Y Gao, et al. Medical Physics, 2018

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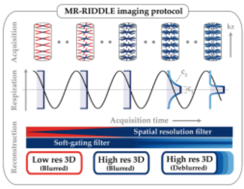
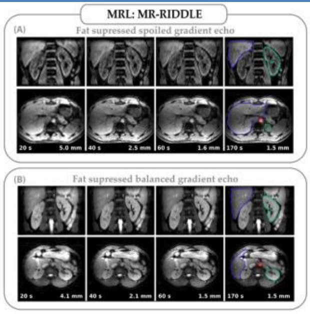
## Multi-resolution MRI on MR-Linac: MR-RIDDLE



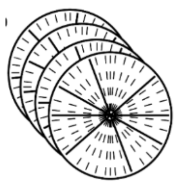




Bruijnen T., et al., PMB, 2019,



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

- **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)



Proposed Strategy

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Zhou, et al., MRM 2017

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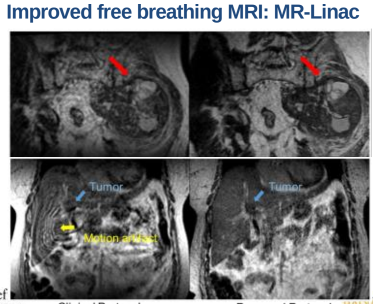
## Improved free breathing MRI: MR-Linac

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Clinical Protocol

Proposed Protocol

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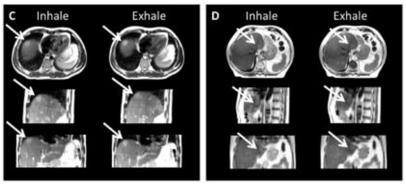
## 4DMRI on MR-Linac

- 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

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TN. van de Lindt, et al, Radiotherapy and Oncology, 2018

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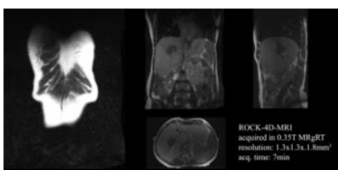
## 4DMRI on MR-Linac

- 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**

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F Han, et al. Radiother. Oncol., 2018

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## 4DMRI on MR-Linac

**Motion Averaged**

**Mid-Position**

**Respiratory Binned**

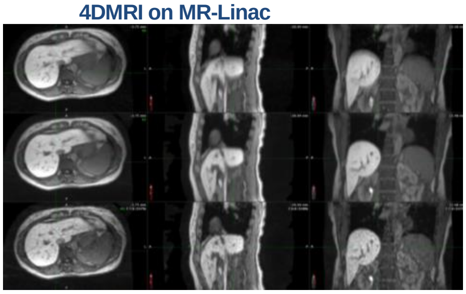
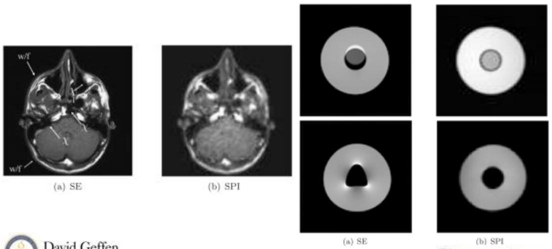


Figure credit : Allen Li, MCW

## Inherently distortion-free MRI: Single-Point Imaging (SPI)

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Crijns, et al. Phys. Med. Biol., 2012

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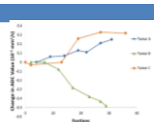
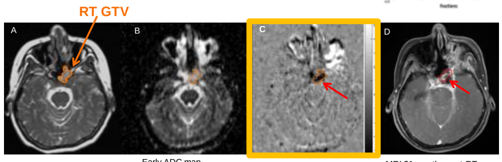
## Treatment response prediction






MRI pre-RT

Early ADC map during RT

ADC change slope map throughout RT

MRI 21 months post-RT – confirm recurrence

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Y Yang et al. Med Phys. 2016.

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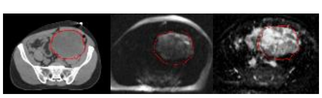
## MRgRT: On-board longitudinal DWI

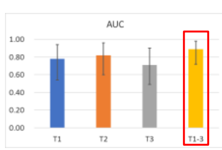
- Using features from all three time points provided the best AUC
- Using single time point worked poorly for the treatment response prediction
- SVM with T1-3 (Time point 1-3) provided the best results



CT simulation with GTV contour

DWI @ 5th fraction with b = 500

ADC map @ 5th fraction

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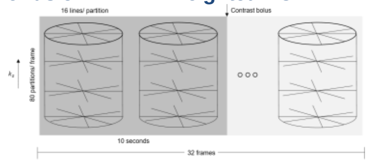
## Perfusion MRI: T1 weighted DCE MRI




- 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.

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C Colbert, et al. AAPM, 2019

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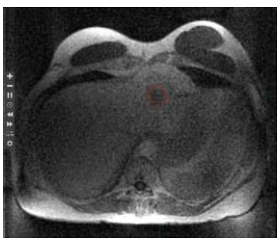
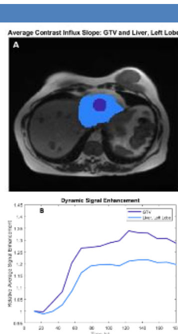
## MRgRT: On-board DCE-MRI



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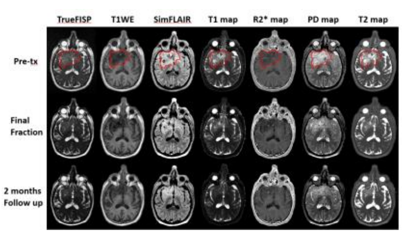
## On-board multi-contrast MRI: STAGE




- 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

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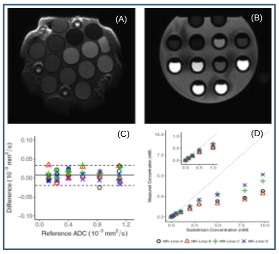
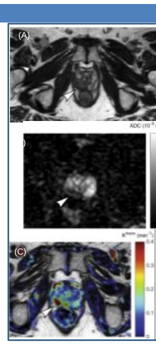
Figure credit: Glide-Hurst & Nejad-Davarani, HFCI
Chen Y, et al., Magnetic Resonance Imaging, 2018

## Functional MRI on Unity




E Kooreman, et al, Radiotherapy and Oncology, 2019

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## 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

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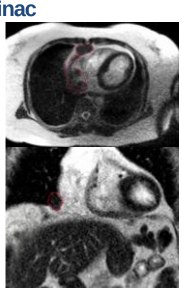

S Rashid, et al. Quant Imaging Med Surg., 2018

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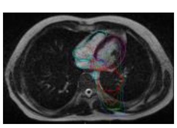
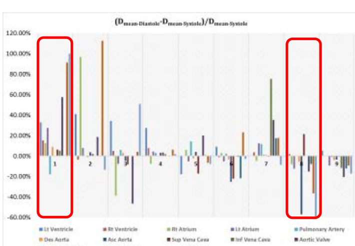
## Dose comparison between diastolic and systolic phases



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## 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

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RADIATION ONCOLOGY

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**Thank you!**