

Real-Time MRI Technology

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Synopsis

Real-time MRI is the ability to continually acquire high temporal resolution data. Technological advances which have enabled high temporal and spatial resolution real-time MRI, include; i) hardware improvements; ii) efficient acquisition strategies (non-Cartesian trajectories and data undersampling); iii) reconstruction algorithms (parallel imaging, temporal encoding, Compressed Sensing), iv) rapid reconstruction (data reduction and parallelization on GPUs).

Highlights

- Hardware improvements: gradient systems and coils

- Acquisition strategy; Non-Cartesian trajectories and data undersampling

- Reconstruction techniques; Parallel imaging, Temporal encoding, and Compressed Sensing

- Reconstruction speed-ups; Data reduction and Graphics Processing Units- Real-time processing

Target audience

Participants interested in how real-time MR can be achieved;

- How we can speed up imaging

- Reconstruction algorithms

- Speeding up of reconstructions

- Real-time processing

Outcome/Objectives

- Understand how fast imaging can be achieved; efficient trajectories and data undersampling

- Understand reconstruction algorithms available; parallel imaging and compressed sensing

- Understood how fast visualization can be achieved; data reduction and GPUs

- Understand how real-time processing can be achieved and used

Real-time MRI Technology

MRI is inherently slow, making imaging of moving structures challenging.

Real-time MRI is the ability to continually acquire high temporal resolution data. Advances which have enabled high temporal and spatial resolution real-time MRI, include;

- Hardware improvements; gradient systems and coils
- Acquisition strategy; Non-Cartesian trajectories and data undersampling
- Reconstruction techniques; Parallel imaging, temporal encoding and Compressed Sensing

As well as fast acquisition, real-time imaging should ideally have:

- Rapid reconstruction and display of the resulting images
- Possible operator control to interact with the acquisition parameters

Real-time MRI is most commonly used for:

- Cardiovascular imaging (1)
- Speech imaging (2)
- Image guidance for interventional procedures (3)
- Joint movement (4)

Hardware improvements;

- Advanced in Gradients; decreased time to traverse k-space
- Advances in Coils; Maximising SNR and allowing maximum acceleration

Acquisition strategy;

Cartesian acquisitions are slow as only a small amount of k-space is covered after each excitation. Alternative, efficient trajectories include;

- Echo Planar Imaging (EPI, figure 1a) (5); single shot or as a multi-shot acquisition
- Radials (figure 1b) (6); robust to undersampling
- Spirals (figure 1c) (7); efficient readout

Undersampling

Reducing the amount of k-space data collected results in spatial aliasing; (figure 1c-e).

Reconstruction techniques;

Reconstruction techniques that allows us to recover images from the undersampled k-space data, include;

- * Parallel imaging; uses spatially independent information from multiple coils
 - SENSE (Sensitivity Encoding) (8); works in image domain. Non-Cartesian SENSE requires use of iterative conjugate gradient algorithm (9)
 - GRAPPA (10); works in k-space. Non-Cartesian GRAPPA uses independent kernels for different segments of space (11)
- * Temporal encoding; alternating the missing lines in k-space in subsequent frames
 - Keyhole imaging (12)
 - TGRAPPA; temporal information used to calibrate weights (13)
 - TSENSE; temporal information used to calculate coil sensitivity maps (14)
 - Further exploited to improve the reconstruction, and enable higher accelerating to be achieved; k-t GRAPPA (15) and k-t SENSE (16)
- * Compressed Sensing (17); exploits data sparseness and compressibility
 - Temporal finite difference; real-time speech (18)
 - Spatio-temporal sparsity (k-t SPARSE-SENSE); real-time cardiac cine (19)

Reconstruction Speed-ups;

Fast reconstruction is challenging due to the large data sets, and complexity of reconstruction algorithms.

*Data reduction; to reduce reconstruction times;

- Selection of most suitable coil subset (20)
- Array compression to combine channels (21)

*Graphics Processing Units (GPUs); massively parallel architecture to speed up algorithms (compared to CPUs; central processing units) that can be parallelized (22)

- Non-uniform FFT (23); up to x85
- Cartesian SENSE (24); up to ~x36
- Spiral SENSE (25); up to ~x15
- Compressed sensing (26); up to ~x27

Post-processing;

*Slice tracking;

- Exercise
- Intervention

*Segmentation;

- Vocal tract analysis (27)
- Flow calculation; Aortic segmentation (28)
- 3D kinematics of the knee (29)

Acknowledgements

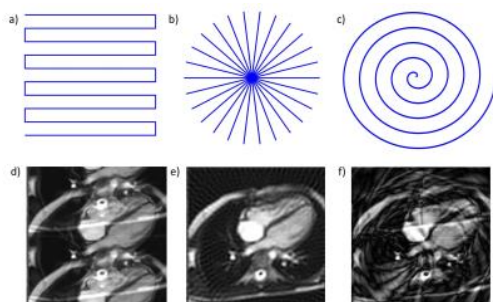
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References

1. Sayin O, Saybasili H, Zviman MM, Griswold M, Halperin H, Seiberlich N, Herzka DA. Real-time free-breathing cardiac imaging with self-calibrated through-time radial GRAPPA. *MRM* 2017;77(1):250-264.
2. Lingala SG, Zhu Y, Lim Y, Toutios A, Ji Y, Lo W-C, Seiberlich N, Narayanan S, Nayak KS. Feasibility of through-time spiral generalized autocalibrating partial parallel acquisition for low latency accelerated real-time MRI of speech. *MRM* 2017.
3. Ozenne V, Toupin S, Bour P, de Senneville BD, Lepetit-Coiffé M, Boissenin M, Benois-Pineau J, Hansen MS, Inati SJ, Govari A, Jaïs P, Quesson B. Improved cardiac magnetic resonance thermometry and dosimetry for monitoring lesion formation during catheter ablation. *MRM* 2017;77(2):673-683.
4. Mazzoli V, Nederveen AJ, Oudeman J, Sprengers A, Nicolay K, Strijkers GJ, Verdonchot N. Water and fat separation in real-time MRI of joint movement with phase-sensitive bSSFP. *MRM* 2016.
5. Mansfield P. MULTI-PLANAR IMAGE-FORMATION USING NMR SPIN ECHOES. *Journal of Physics C-Solid State Physics* 1977;10(3):L55-L58.
6. Glover GH, Pauly JM. Projection Reconstruction Techniques for Reduction of Motion Effects in MRI. *MRM* 1992;28(2):275-289.
7. Meyer CH, Hu BS, Nishimura DG, Macovski A. Fast Spiral Coronary Artery Imaging. *MRM* 1992;28(2):202-213.
8. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: Sensitivity encoding for fast MRI. *MRM* 1999;42(5):952-962.
9. Pruessmann KP, Weiger M, Bornert P, Boesiger P. Advances in sensitivity encoding with arbitrary k-space trajectories. *MRM* 2001;46(4):638-651.

10. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *MRM* 2002;47(6):1202-1210.
11. Griswold M, Heidemann R, Jakob P. Direct parallel imaging reconstruction of radially sampled data using GRAPPA with relative shifts. 2003; Toronto, Canada. p 2349.
12. Duerk JL, Lewin JS, Wu DH. Application of keyhole imaging to interventional MRI: A simulation study to predict sequence requirements. *Journal of Magnetic Resonance Imaging* 1996;6(6):918-924.
13. Breuer FA, Kellman P, Griswold MA, Jakob PM. Dynamic autocalibrated parallel imaging using temporal GRAPPA (TGRAPPA). *MRM* 2005;53(4):981-985.
14. Kellman P, Epstein FH, McVeigh ER. Adaptive sensitivity encoding incorporating temporal filtering (TSENSE). *MRM* 2001;45(5):846-852.
15. Huang F, Akao J, Vijayakumar S, Duensing GR, Limkeman M. k-t GRAPPA: A k-space implementation for dynamic MRI with high reduction factor. *MRM* 2005;54(5):1172-1184.
16. Tsao J, Boesiger P, Pruessmann KP. k-t BLAST and k-t SENSE: dynamic MRI with high frame rate exploiting spatiotemporal correlations. *Magn Reson Med* 2003;50(5):1031-1042.
17. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. *MRM* 2007;58(6):1182-1195.
18. Lingala SG, Zhu Y, Kim Y-C, Toutios A, Narayanan S, Nayak KS. A fast and flexible MRI system for the study of dynamic vocal tract shaping. *MRM* 2017;77(1):112-125.
19. Feng L, Srichai MB, Lim RP, Harrison A, King W, Adluru G, Dibella EVR, Sodickson DK, Otazo R, Kim D. Highly accelerated real-time cardiac cine MRI using k-t SPARSE-SENSE. *MRM* 2013;70(1):64-74.
20. Müller S, Umatham R, Speier P, Zühlsdorff S, Ley S, Semmler W, Bock M. Dynamic coil selection for real-time imaging in interventional MRI. *MRM* 2006;56(5):1156-1162.
21. Buehrer M, Pruessmann KP, Boesiger P, Kozerke S. Array compression for MRI with large coil arrays. *MRM* 2007;57(6):1131-1139.
22. Thomas S, Ti-chiun C, Peter S, Rudiger W. MR image reconstruction using the GPU. In: Michael JF, Jiang H, editors 2006. SPIE. p 61423T.
23. Sorensen TS, Schaeffter T, Noe KO, Hansen MS. Accelerating the Nonequispaced Fast Fourier Transform on Commodity Graphics Hardware. *Medical Imaging, IEEE Transactions on* 2008;27(4):538-547.
24. Hansen MS, Atkinson D, Sorensen TS. Cartesian SENSE and k-t SENSE reconstruction using commodity graphics hardware. *MRM* 2008;59(3):463-468.
25. Kowalik GT, Steeden JA, Pandya B, Odille F, Atkinson D, Taylor A, Muthurangu V. Real-time flow with fast GPU reconstruction for continuous assessment of cardiac output. *Journal of Magnetic Resonance Imaging* 2012;36(6):1477-1482.
26. Smith DS, Gore JC, Yankeelov TE, Welch EB. Real-Time Compressive Sensing MRI Reconstruction Using GPU Computing and Split Bregman Methods. *International Journal of Biomedical Imaging* 2012;2012:6.
27. Silva S, Teixeira A. Unsupervised segmentation of the vocal tract from real-time MRI sequences. *Computer Speech & Language* 2015;33(1):25-46.
28. Mendonça GMQ, Carvalho JLA. Segmentation of aortic flow in real time magnetic resonance images. 2013 3-7 July 2013. p 6059-6062.
29. Lin C-C, Zhang S, Frahm J, Lu T-W, Hsu C-Y, Shih T-F. A slice-to-volume registration method based on real-time magnetic resonance imaging for measuring three-dimensional kinematics of the knee. *Medical Physics* 2013;40(10):102302.

Figures



Efficient k-space trajectories; a) EPI, b) Radial, c) Spiral.

Data under sampling by a factor of 2 in; d) Cartesian imaging (folder artefact), e) Radial imaging (streaking artefact), f) Spiral imaging (ringing artefact)