Time-resolved MR Angiography: Radial Acquisitions

Walter Block, PhD, Departments of Medical Physics and Biomedical Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA

Introduction: The inherently 3D nature of MRI allows for fine depiction of vascular territories. However, as MR samples its data in an alternative Fourier domain, only a relatively few samples can be obtained at one time. As time-resolved MRA requires sampling three spatial dimensions plus the temporal dimension, achieving high frame rates and high spatial resolution in MRA is difficult due to the need to sample this large four dimensional (4D) space.

Achieving a time-resolved image series by simply acquiring the same set of k-space samples at each time point is the simplest method for 4D imaging, but it also fails to exploit the significant correlation of the image volumes between time frames. Only a relatively small percentage of an imaging volume contain vascular signal while the larger amounts of static tissue are intentionally suppressed in MRA. Radial k-space trajectories provide a basis to exploit these characteristics to improve performance of time-resolved MRA.

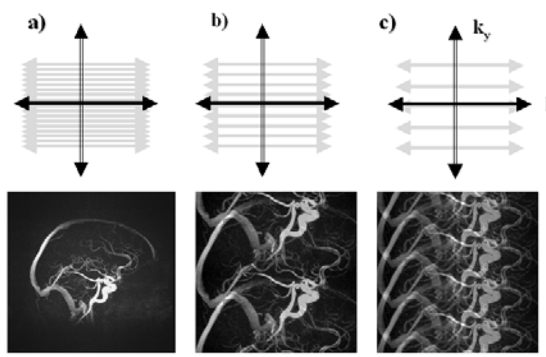
A link to this abstract's corresponding talk presentation will be provided during the short course.

Acceleration with Radial Sampling

Cartesian scans that reduce the number of phase encodes without parallel imaging efforts, as shown in Figure 1, suffer from coherent ghosting. The appearance of undersampling is quite different with radial imaging, as shown in Figure 2 with time of flight imaging. Removing more and more radial lines does not affect the depiction of the location of the vessels. However, the missing data is manifested as aliased signal which have the appearance of streaks.

Radial trajectories sample k-space with projections, which has similarities to how CT scans acquire data. The lower spatial frequencies are oversampled while the higher spatial frequencies are undersampled. If the number of voxels with high signal is relatively low, the image is said to be sparse and the appearance of the undersampled signal will often be tolerable. This is particularly true in contrast-enhanced MR angiography where the vasculature is bright and the static tissue is intentionally saturated or reduced through subtraction of a mask image volume. Vasculature imaging is particularly sparse in phase-contrast imaging, where static spins are removed through subtraction.

Figure 1: Coherent ghosting is caused in Cartesian imaging as scan time is cut by a factor of 2 (b) and 4 (c) by eliminating ½ and ¾ of the phase encodings respectively.



Radial sampling strategies often provide acceleration in 4D MRA through two mechanisms: undersampling and temporal processing. In general, imaging environments with greater sparsity allow greater imaging acceleration through undersampling. Achievable acceleration factors purely from undersampling range from a factor of 4 with CE-MRA to sixteen with phase contrast MRA.

Parallel imaging with Cartesian imaging mitigates some of these performance gains, but the k-space trajectory with radial methods allows temporal processing methods which can transform clinically infeasible methods into feasible methods. These processing methods range from simple methods that exploit the oversampling of the center of k-space to very sophisticated iterative methods based on image estimation theory

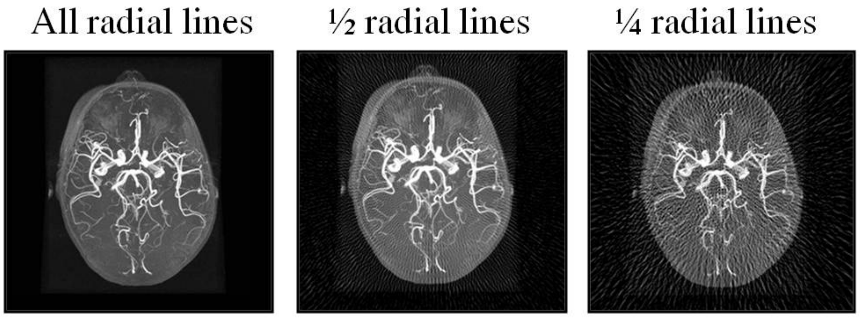


Figure 2 Appearance of undersampling with radial acquisitions. In the leftmost figure with no undersampling, the complete FOV is properly reconstructed using all of the acquired radial lines. In the center image, only half of the radial lines are used in the reconstruction while in the rightmost picture only a ¼ of the radial lines are used. Notice that in the undersampled images, signal is properly resolved in its correct location. However, streak artifacts become more noticeable

Radial data can be simply processed by interpolated (gridded) onto a Cartesian space and then inverse Fourier-transformed to create the imaging volume. Care must be taken to account for system delays and eddy currents during reconstruction.

Radial k-space trajectories are first described followed by a brief overview of temporal processing methods.

Radial Sampling Trajectories

CAPER: An interesting recent approach has been to acquire a 3D Cartesian scan, but arrange the order of the ky-kz encodings into radial-like spokes (1). Known as CArtesian Projection Reconstruction-like (CAPR), this approach supports k-space based Cartesian parallel imaging methods, which are less computationally intensive than non-Cartesian parallel imaging methods. It also is robust to several system instabilities for which non-Cartesian methods much compensate. When combined with parallel imaging, the benefits of Cartesian and radial imaging are merged to produce high image quality with small temporal footprints.

Stack of Stars: Undersampled PR acquisitions in MRA can be acquired in two dimensions with conventional fully sampled slice-encoding in the third dimension (2), as shown in Figure 3. Speedup factors of four or more can be achieved without loss of spatial resolution. Undersampled PR in the in-plane dimensions can be combined with variable rate Cartesian sampling in the k_z dimension technique for time-resolved MRA (3). CAPER and the stack of stars trajectory support asymmetric field of views, where the thinner dimension is usually encoded along k_z.

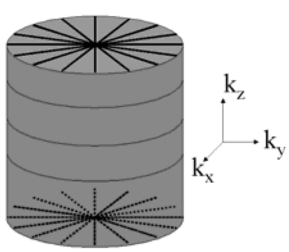


Figure 3: Hybrid 3D PR sequences use fully sampled Fourier encoding in the slice direction and undersampled PR in the other two k-space dimensions. This trajectory is often referred to as the stack of stars.

Instead of using Fourier slice-encoding, 3D projections in all three k-space dimensions can be acquired as shown in Figure 4. By spreading the aliased, undersampled energy from a 2D slice to a far larger 3D volume, the undersampling artifacts further diffuse into a structured background that resembles noise. This technique, termed 3DPR or Vastly undersampled Isotropic PRojection (VIPR) imaging(4-5), provides isotropic resolution over large spherical fields of view.

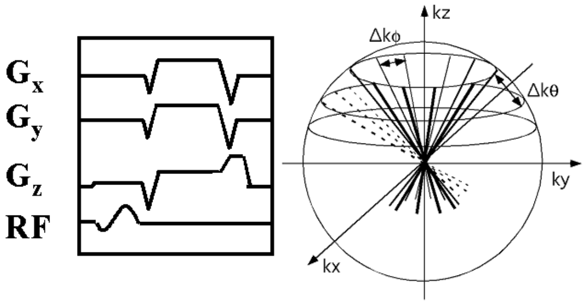


Figure 4 Vastly undersampled Isotropic PRojection (VIPR) sequence (a) Timing diagram: The Gx,Gy, and Gz gradient amplitudes define the orientation of the partial diameter in the overall (b) k-space trajectory – Each excitation can cover one partial diameter as shown, a full diameter, or multiple diameters.

Temporal Processing

The oversampling of the center of k-space with radial methods can be exploited in time-resolved MRA to depict temporal enhancement during a contrast injection or resolve flow throughout the cardiac cycle(6). The projection acquisition order can be subdivided into interleaved sets so that spatial frequency orientations throughout k-space are sampled on an interval less than or equal to the desired frame rate. A sliding window reconstruction technique with a temporal aperture that widens for k-space points acquired at larger radii is utilized (4, 7-10). The aperture widens at higher spatial frequencies to diminish the penalty from aliased, unsampled energy. These methods provide an additional order of magnitude in acceleration, though it should be noted that the acceleration factor is maximized at lower spatial frequencies and decreases for higher spatial frequencies.

The ability to resolve flow velocity throughout the cardiac cycle allows for a range of quantitative measures with clinical significance such as pressure drops across stenoses(6), flow through aberrant vascular networks, and apparent wall sheer stress. Other applications include the assessment of arterial-venous malformations (11) and interventional imaging(12).

Advanced Temporal Processing Newer reconstruction methods aim to speed time-resolved imaging by undersampling while using other information to limit undersampling artifacts. In general, these image estimation methods require sparsity in some domain. These methods include a family of methods that use a high SNR image with little temporal resolution to constrain an image reconstruction using a limited amount of temporal data, known as HIghly constrained back Projection (HYPR)(13) and HYPR Local Reconstruction (HYPR LR) (14). These single pass methods are generally rapid, but their accuracy can vary with the sparsity of the object. Improved accuracy can be achieved with iterative reconstruction methods such as IHYPR(15) or conjugate gradient HYPR (16). The relation of these methods to compressed sensing is developed in Lustig *et al.* (17). Here the requirements for sparsity are more general. For example, sparsity can be present in the actual image itself, the derivative of the image, or the wavelet representation of the image.

1. Haider CR, Hu HH, Campeau NG, Huston J, 3rd, Riederer SJ. 3D high temporal and spatial resolution contrast-enhanced MR angiography of the whole brain. Magn Reson Med2008 Sep;60(3):749-60.
2. Peters DC, Korosec FR, Grist TM, Block WF, Holden JE, Vigen KK, Mistretta CA. Undersampled projection reconstruction applied to MR angiography. Magnetic Resonance in Medicine2000;43(1):91-101.
3. Vigen KK, Peters DC, Grist TM, Block WF, Mistretta CA. Undersampled projection-reconstruction imaging for time-resolved contrast-enhanced imaging. Magnetic Resonance in Medicine2000;43(2):170-6.
4. Barger AV, Block WF, Toropov Y, Grist TM, Mistretta CA. Time-resolved contrast-enhanced imaging with isotropic resolution and broad coverage using an undersampled 3D projection trajectory. Magnetic Resonance in Medicine2002;48(2):297-305.
5. Glover GH, Pauly JM. Projection reconstruction techniques for reduction of motion effects in MRI. Magn Reson Med1992 Dec;28(2):275-89.
6. Lum DP, Johnson KM, Paul RK, Turk AS, Consigny DW, Grinde JR, Mistretta CA, Grist TM. Transstenotic pressure gradients: measurement in swine--retrospectively ECG-gated 3D phase-contrast MR angiography versus endovascular pressure-sensing guidewires. Radiology2007 Dec;245(3):751-60.
7. Pipe JG. Reconstructing MR images from undersampled data: data-weighting considerations. Magn Reson Med2000 Jun;43(6):867-75.

8. Song HK, Dougherty L. k-space weighted image contrast (KWIC) for contrast manipulation in projection reconstruction MRI. Magn Reson Med2000 Dec;44(6):825-32.
9. Liu J, Redmond MJ, Brodsky EK, Alexander AL, Lu A, Thornton FJ, Schulte MJ, Grist TM, Pipe JG, Block WF. Generation and visualization of four-dimensional MR angiography data using an undersampled 3-D projection trajectory. IEEE Trans Med Imaging2006 Feb;25(2):148-57.
10. Song HK, Dougherty L. Dynamic MRI with projection reconstruction and KWIC processing for simultaneous high spatial and temporal resolution. Magn Reson Med2004 Oct;52(4):815-24.
11. Cashen TA, Jeong H, Shah MK, Bhatt HM, Shin W, Carr JC, Walker MT, Batjer HH, Carroll TJ. 4D radial contrast-enhanced MR angiography with sliding subtraction. Magn Reson Med2007 Nov;58(5):962-72.
12. Spuentrup E, Ruebben A, Schaeffter T, Manning WJ, Gunther RW, Buecker A. Magnetic resonance--guided coronary artery stent placement in a swine model. Circulation2002 Feb 19;105(7):874-9.
13. Mistretta CA, Wieben O, Velikina J, Block W, Perry J, Wu Y, Johnson K, Wu Y. Highly constrained backprojection for time-resolved MRI. Magn Reson Med2006 Jan;55(1):30-40.
14. Johnson KM, Velikina J, Wu Y, Kecskemeti S, Wieben O, Mistretta CA. Improved waveform fidelity using local HYPR reconstruction (HYPR LR). Magn Reson Med2008 Mar;59(3):456-62.
15. O'Halloran R L, Wen Z, Holmes JH, Fain SB. Iterative reconstruction of time-resolved images using highly constrained back projection (HYPR) Magnetic Resonance in Medicine2007:in press.
16. Griswold MA, editor Conjugate-gradient HYPR. ISMRM; 2007; Berlin.
17. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. Magn Reson Med2007 Dec;58(6):1182-95.