Imaging Acquisition and Reconstruction Weekend Educational Course

Non-Cartesian k-Space Sampling

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Highlights

- Non-Cartesian sampling methods common in clinical practice include radial, spiral and PROPELLER. Many others are used experimentally.
- Sensitivity to motion and flow artifacts is reduced for sequences where TE is very short and/or gradient waveform shapes result in reduced flow moments. Redundancy in k-space data is beneficial and can be exploited to reduce such artifacts.
- Relatively benign undersampling artifacts allow reduced scan time.
- Scan efficiency (k-space volume covered per unit scan time) can exceed Cartesian acquisition.
- Gradient waveform design is more complicated but considerable work has been done in general and for specific trajectories.
- More complicated reconstruction algorithms are needed, demanding more computing power, especially if parallel imaging and compressed sensing are used.
- Artifacts from unwanted phase (resonance offsets, eddy currents, concomitant fields, and gradient waveform errors) can require better hardware and possibly additional calibrations and corrections.

Target Audience

Scientists and clinicians interested in understanding the benefits and drawbacks of non-Cartesian sampling and how it can be utilized.

Objectives

Understand:

What are the possible benefits of non-Cartesian sampling and why is it used?

What situations are good candidates for its use?

What are the likely problems encountered and how can they be mitigated?

Purpose

Although the first non-Cartesian trajectory (radial) was developed to emulate CT acquisition (1), in modern MRI, the purpose is to improve imaging performance relative to Cartesian methods.

Methods

Commonly used non-Cartesian methods include projection or radial acquisition, spiral (2,3) and PROPELLER (4,5). Both 2D and 3D variations of these methods, including combinations with Cartesian trajectories, have been developed. Examples include stack-of-spirals, stack-of-stars, 3D radial, radial-spiral, twisted projection imaging, rosettes, 3D cones and spiral cones, cones of Fermat spirals (FLORET) and spherical shells (6-10). Echo-train non-Cartesian methods in addition to PROPELLER include radial RARE (11), radial GRASE (12) and spiral RARE (13).

Results

One of the strengths of most non-Cartesian trajectories is reduced sensitivity to motion. With Cartesian sampling, motion (voluntary, cardiac, respiratory, peristaltic and flow) usually results in ghosting artifacts that propagate throughout the image in the phase-encoded direction. Non-Cartesian artifacts are reduced and/or less conspicuous as a result of lack of one-directional coherence and also because of redundantly sampling the center of k-space (14).

The short TE resulting from many non-Cartesian trajectories minimizes the effect of the gradient first moment and reduces signal loss in turbulent flow from intravoxel dephasing. Some sequences also have reduced and oscillating flow moments giving less flow-related signal loss (3,15,16).

The inherent data redundancy of methods like PROPELLER allows rigid body translation/rotation to be corrected by comparing oversampled parts of k-space to mitigate motion artifacts (4). This is especially useful for non-cooperative patients and for diffusion weighted imaging which is highly sensitive to motion (5).

Another strength is that that non-Cartesian undersampling artifacts are multi-directional, incoherent (diffuse) and frequently less objectionable. For example, for radial sampling, the artifacts resemble streaks some distance from the center of the image. The number of spokes can therefore be reduced, shortening scan time without major loss of image quality or reduction in spatial resolution (17,18). Undersampled Cartesian phase encoding gives wrap (coherent phase direction aliasing) but the image is alias-free in the readout direction due to the bandlimiting filter. Conversely, with non-Cartesian acquisition there is no direction in which the image is truly free of undersampling artifacts. The incoherence of undersampling artifacts also makes non-Cartesian sampling compatible with compressed sensing with little or no modification of the acquisition.

The sampling pattern of some non-Cartesian trajectories can make them inherently more efficient for covering k-space. Curved trajectories such as spirals can sometimes cover a desired k-space area in fewer excitations than straight ones (Cartesian or radial for example). For this reason spirals are useful for applications needing high efficiency such as navigators (19), arterial spin labeling (20), fMRI (21), coronary artery imaging (3) and spectroscopic imaging (22).

With trajectories that repeatedly cross, such as rosettes, off resonant spin phase destructively interferes, incoherently smearing off-resonant signal over the entire image. This allows fast multispectral, and 2D and 3D fMRI (23,24).

Since no phase encoding is needed with trajectories that start at the origin such as radial sampling, these are very useful for minimizing TE. Overlapping excitation with radial readout gives nearly zero TE (25,26) and allows imaging of very short T2 tissue, including bone (25,27). Radial sampling has also been used to mitigate acoustic noise by incrementing consecutive spokes by very small angles to minimize gradient waveform changes (25). Nearly silent imaging can also be achieved with phase encoding if the phase encoding and readout are sinusoidally shaped instead of trapezoidal, producing a curved k-space trajectory (28).

Discussion

Non-Cartesian data are usually reconstructed using either non-uniform FFTs (29), gridding (30) or GRAPPA operator gridding (31). The additional computational burden can sometimes be a problem but is becoming less important as computational power is increasing. Non-Cartesian reconstruction can sometimes give more artifacts, although the additional artifacts can be reduced to a negligible level with judicious choice of reconstruction algorithm and parameters (32,33). Combinations of non-Cartesian acquisition and parallel imaging have been developed (34-36) and are more computationally challenging. Similarly compressed sensing reconstruction for non-Cartesian data have also been developed and are sometimes even more computationally demanding.

Gradient waveform design giving time-optimal sampling and incorporating gradient slew rate and amplitude limits is challenging but has been successfully approached using analytical approximations and numerical methods both for specific trajectories (37) and for general shapes (38).

The biggest drawback to non-Cartesian sampling is the effect of unwanted phase error, primarily from resonance offsets. For Cartesian methods that do not use echo trains (for example EPI and variations), off-resonance phase can cause signal loss and geometric shift. For non-Cartesian sampling, the readout direction is not constant and the shift changes direction within the image, usually resulting in degradation of the point spread function and apparent blurring. For spirals, off-resonance blurring can be severe. The effect with radial scans is usually not severe, whereas with rosettes the blurring is so severe that it appears to be a uniform background haze and might actually not be objectionable. Spatially linear resonance offsets shift the k-space locations and can be corrected in reconstruction if the shift is measured (39). Spatially non-linear phase effects can sometimes be amenable to more sophisticated (and computationally intensive) software correction (40-42).

Less severe, but still important phase errors arise from eddy currents (43), concomitant fields (44) and gradient waveform distortion (45). Short duration eddy currents (time constants less than 100 usec) are equivalent to a time shift in the gradient waveforms to first order. If not corrected, they cause a small amount of blurring or other effects (apparent image rotation for spirals for example).

Longer duration eddy currents mostly give rise to a diffuse haze and are less problematic. Eddy currents are best dealt with using gradient pre-emphasis but might also need sequence-specific calibration and/or waveform timing adjustment (46,47). Concomitant fields can be corrected during reconstruction in some cases with a sequence-specific phase shift. Gradient waveform distortion that arises from the amplifier response can frequently be modeled as a group delay (time shift) and the effect reduced with a sequence-specific correction, similar to short eddy currents. Gradients on different physical axes can have different amplifier response properties (gradient anisotropy). This needs to be addressed when waveforms from different logical axes are combined (48,49). The most general approach to such phase errors is k-space trajectory measurement using a special calibration pulse sequence (50,51), or field camera hardware followed by modification of the k-space locations (52,53).

Conclusion

Non-Cartesian methods have reduced motion artifacts, better tolerance of undersampling (and therefore shorter scans), improved scan efficiency and, for some methods, very short TE and nearly silent scanning. These advantages have in many cases overcome the disadvantages of increased artifacts from phase errors, more complicated corrections and greater computational complexity. Non-Cartesian methods will continue to become more important as scanner hardware is improved and their applications are refined.

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