Quick Star:
Overcoming Motion Artifacts for Free Breathing Abdominal MRI

Erin Kelly, Ph.D.
Brian Tymkiw, B.S. R.T. (ARRT) (R) (MR)
Dawn Berkeley
Mo Kadbi, Ph.D.
Manager, Medical Affairs
Canon Medical Systems USA, Inc.

An interesting difference between Magnetic Resonance Imaging (MRI) and other medical imaging modalities lies in the unique method in which the data is acquired and reconstructed. In particular, the manner in which data are acquired in k-space can influence the manifestation of artifacts. One of the most common and problematic MRI artifacts, and one whose appearance is affected by the k-space acquisition trajectory, is the motion artifact. While major strides have been made over the past decades to make MRI more robust against physiological motion, motion artifacts in abdominal imaging remain a significant cause of image quality degradation. Quick Star is a virtually motion insensitive technique that takes clinical MR imaging to the next level, enabling free breathing abdominal 3D T1-weighted imaging.

Background

Important steps have been made over the past decades to make MRI more tolerant to physiological motion. Strategies that are routinely used in the clinical setting for motion mitigation include the use of breath-held imaging, navigator echoes, respiratory gating, and JET (2D motion correction using rotating blades[1]). However, each of these has its own limitations. In clinical practice, the elderly and pediatric patients often have difficulty holding their breath. Navigators and respiratory gating can increase scan time, since data acquisition must fit into a brief temporal window. Finally, JET is designed for two-dimensional imaging, whereas three-dimensional imaging is routine in clinical abdominal MR protocols. Consequently, motion artifacts can still appear in clinical images when using these strategies, obscuring significant diagnostic information. Therefore, there is still a need for improved motion insensitive volumetric imaging. With Quick Star, the three-dimensional acquisition can be performed during free breathing while maintaining diagnostic image quality.

K-Space Basics

MRI data is acquired in the Fourier transformed domain called k-space, which represents spatial frequencies in an MR image. K-space data is most commonly acquired in the rasterized rectangular grid called Cartesian sampling, with axes k_x (horizontal) and k_y (vertical). Each k-space point contains spatial frequency information about the MR image. The low spatial frequency data, such as general shapes and contours are contained in the center of k-space, whereas the high spatial frequency data, such as edges and details, are stored in the periphery of k-space. In brief, k-space (i.e. spatial frequency space) is transformed to image space via the Inverse Fast Fourier Transform (FFT).

The most basic k-space sampling scheme is known as Cartesian sampling, in which data is acquired in parallel lines **(Figure 1, left)**. The k-space values are obtained in a rectilinear manner. Each row in the grid differs by a fixed difference in the signal phase. In this trajectory, just those few lines through the center of k-space hold the data for the overall image contrast. Motion during a Cartesian acquisition manifests as phase perturbations in the phase encoding direction. Given the frequency and phase encoding assignments, Cartesian sampling is therefore prone to propagation of ghosts in the phase encoding direction when motion occurs during the acquisition **(Figure 2).**

Unlike Cartesian k-space sampling, radial sampling **(Figure 1, right)** does not have unique frequency and phase-encode directions[2]; therefore phase perturbations will not result in motion artifacts like they do in Cartesian sampling. In radial sampling, data is acquired in rotating spokes. Those motion induced phase-encoding disruptions that occur in Cartesian sampling are not possible in radial sampling. Using radial sampling, motion during the acquisition does not propagate as discrete ghosts along a single phase-encode direction. Instead, the motion may manifest as streaking artifacts, which are generally viewed as a mild effect, and are not likely to obscure lesions nor degrade the diagnostic utility of the image.[3]

In a radial acquisition, each spoke passes through the center of k-space. As the center of k-space is oversampled with radial acquisitions, any signal inconsistencies due to motion are mitigated by the averaging of the center of k-space. In addition, whereas only a few phase-encoding lines near the k-space center impact the overall contrast and contours in an image acquired using a Cartesian acquisition, every spoke in a radial acquisition contributes equally to the overall contrast. In this way, patient motion during the acquisition is not likely to affect image quality.

Implementation into Clinical Practice

The advantages of overcoming motion artifacts with radial k-space sampling are clear and have been known since the early years of MR. Like most theoretical advances, practical limitations often delay the direct benefit in clinical practice. Despite the known benefits, there were two technical limitations that prevented early

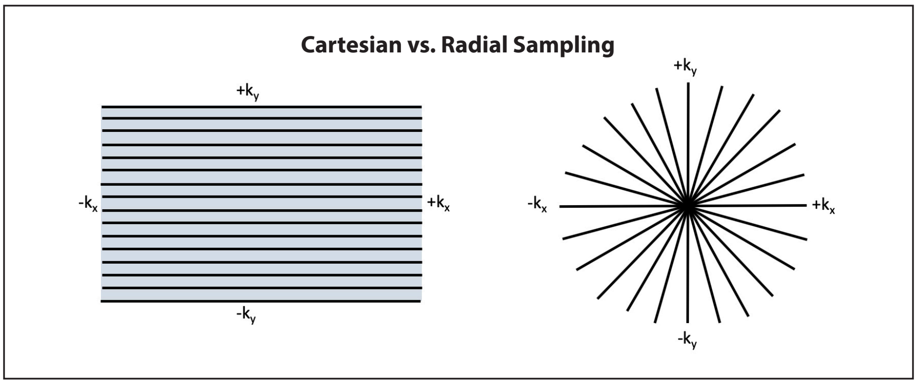

Figure 1. Cartesian k-space (left) is usually rectangular and evenly spaced on a grid. Regular spacing makes data acquisition and processing easier, faster, and more efficient. Non-Cartesian methods, such as radial (right), use rotating lines along the k_x-k_y plane. The data samples undergo regridding process before an inverse FFT can be performed.

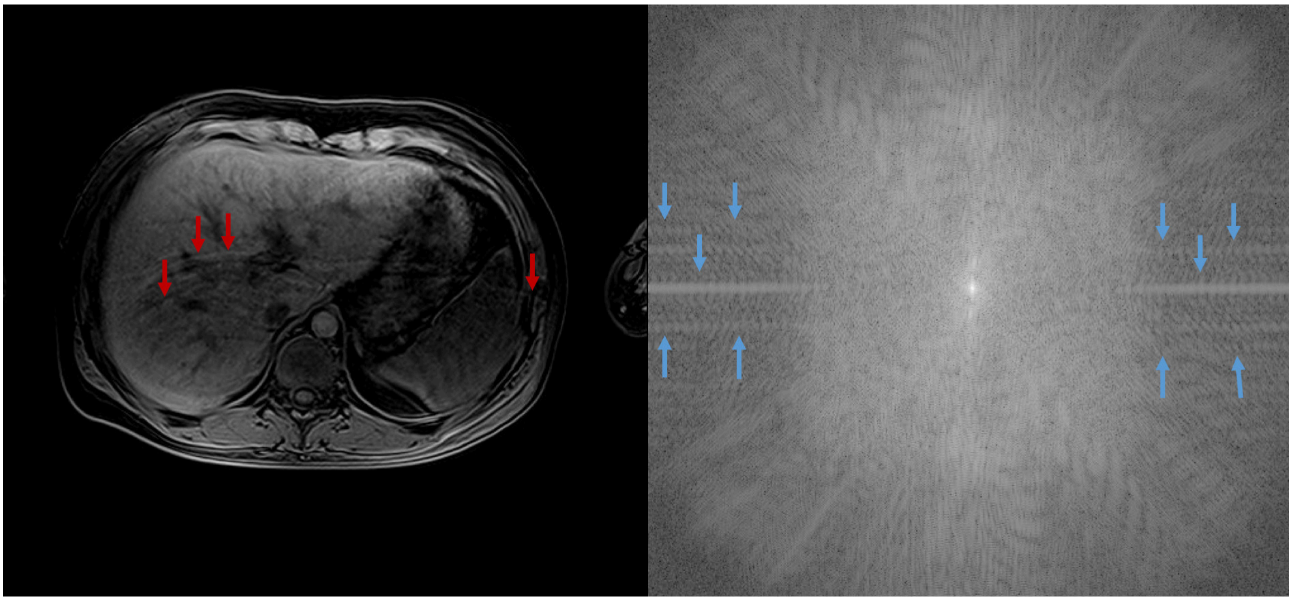

Figure 2. Motion artifact from free-breathing 3DFFE acquisition seen in the magnitude image (left, red arrows) appears as discrete phase errors in k-space (right, blue arrows).

adoption. These are **1.** the need for very high accuracy of gradient waveform timing and **2.** the ability to perform more complex image reconstruction. These limitations were difficult to address in the early years.

Encoding gradients can have a delayed response as well as overshooting.[4,5] This causes shifts along the readout direction in k-space for sequences with conventional readouts. Since all lines experience an equal shift with Cartesian sampling, the effect is negligible and not detectable on magnitude images. Therefore, Cartesian sampling is not very demanding on gradient timing accuracy. But for radial sampling, because the readout orientation changes with each spoke, gradient timing delays cause a shift that is unique to each radial spoke. This causes streak artifacts and image blurring. **Figure 3** shows an illustration of how gradient timing delays affect k-space. Modern MRI systems have drastically improved the accuracy of the gradient waveform timing, significantly reducing these effects.

The reconstruction of conventionally acquired samples on a Cartesian grid is naturally efficient via the FFT. When the samples are acquired along radial spokes, on the other hand, they do not correspond to points on an equally spaced grid, and conventional inverse FFT reconstruction is not possible. Instead, the radially sampled data must first undergo regridding onto a Cartesian grid before inverse FFT reconstruction. See **Figure 4** for an illustration of Cartesian gridding vs Radial gridding.

The advances in MR hardware and algorithm development have now made it possible for 3D radial sampling schemes to emerge from primarily the research arena into routine clinical practice.

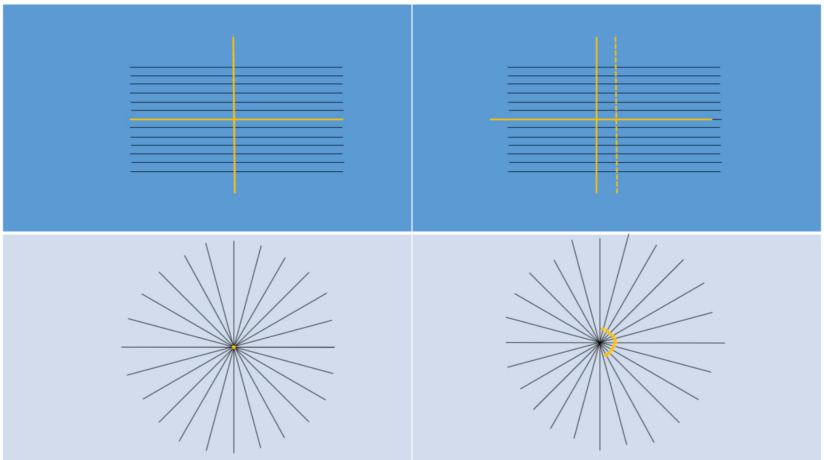

Figure 3. An illustration of how gradient timing delays (right) affect Cartesian sampling (top) compared to radial sampling (bottom). The left figures represent the ideal Cartesian (top), and radial (bottom) acquisitions, in which the yellow lines, and dot represent the center of k-space, respectively. A gradient timing delay causing a uniform shift on Cartesian sampling would not affect the overall image quality because the center of k-space is still aligned. These same delays would effectively disperse the center of k-space in radial sampling (yellow dots), which would cause image blurring and artifacts. Accuracy of gradient timing in modern MRI systems has allowed radial k-space sampling to enter the clinical realm.

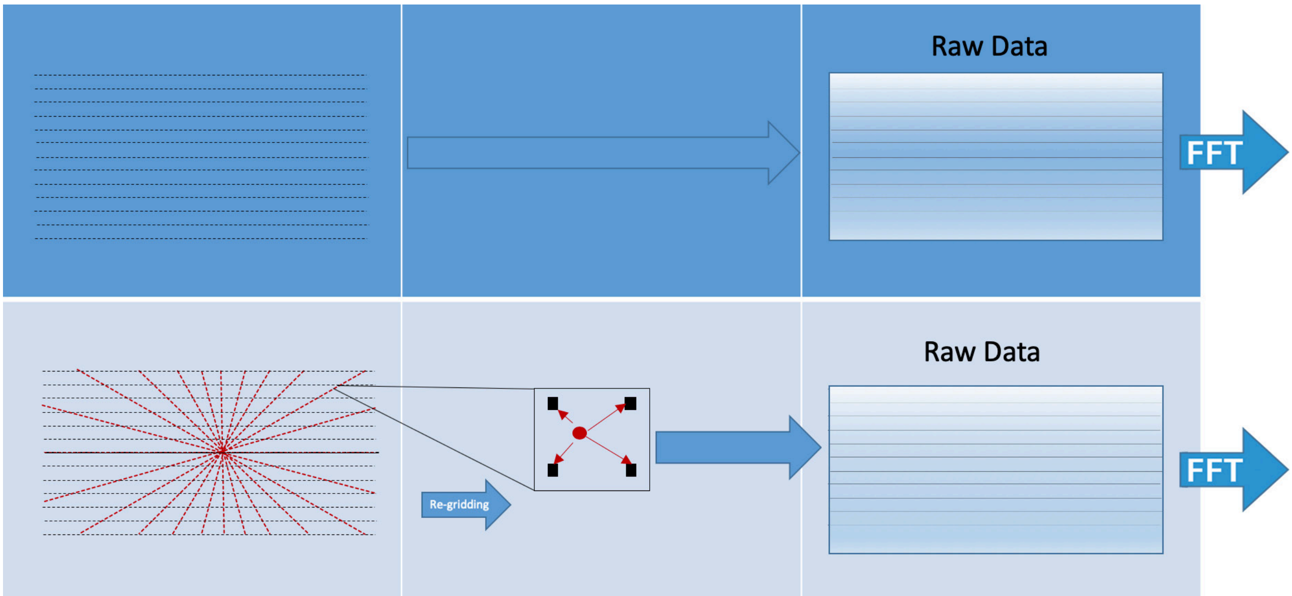

Figure 4. Since Cartesian sampling fits naturally on a grid, the sampling points can be copied directly to a grid before the inverse FFT transforms the frequency space into image space. In radial sampling, the sampled points do not fit directly on a grid and therefore direct inverse FFT is not possible. The radial sampled points are first interpolated to the neighboring grid points. Once the samples are re-gridded, inverse FFT can be performed to create the image.

Quick Star

Quick Star combines the advantages of radial k-space sampling with volumetric imaging to virtually eliminate motion artifacts from routine clinical practice and allow for patient friendly free-breathing 3D abdominal studies.

Quick Star combines T1 weighted 3D Fast Field Echo (FFE3D) with a radial approach that acquires k_x and k_y with oversampled rotating spokes. The radial spokes are implemented by acquiring the readout and phase directions simultaneously, while rotating around the center of k-space, as depicted in the sequence timing diagram over one repetition time (TR) **(Figure 5)**. Note, in Figure 5, G_x and G_y axes are executed simultaneously, resulting in the acquisition of rotating spokes, while the G_z direction is executed as in a conventional FFE3D sequence.

The process continues along the z-direction of the 3D sequence, using Cartesian sampling along the kz axis, while maintaining radial sampling in the x-y plane. The combination of Cartesian phase encoding in the slice direction and radial encoding in-plane results in cylindrical k-space coverage known as "Stack of Stars" **(Figure 6)**. Periods of Cartesian sampling are kept short, thus maintaining both data consistency and motion robustness of radial sampling.

In summary, Quick Star is inherently robust against motion artifacts, allowing 3D free breathing MRI exams for the following reasons. First, the overlap of spokes in the k-space center effectively averages the signal in the center of k-space, so that motion averages out over the acquisition window, in particular for longer scan durations. Second, due to the varying angled readout directions, object movements do not translate into shifted image copies ("ghosting") the way they do for Cartesian sampling.

Scanning with Quick Star

Quick Star's implementation at the scanner interface can easily be enabled by selecting "Quick Star" when choosing the "trajectory type" in an FFE3D basic sequence. By simply selecting this option, data are acquired using the stack of stars trajectory. The key parameter for balancing image quality with scan time is the number of trajectories. The number of trajectories sets the number of radial lines and affects the k-space fill ratio. The number of trajectories affects the effective spatial resolution and appearance of streak artifacts. Approximately 600-900 trajectories can adequately fill k-space, provide high effective spatial resolution and minimize streak artifacts. **Figure 7** compares the appearance of streak artifacts and image quality increasing number of trajectories. As illustrated in the figure, streak artifacts become negligible with a higher number of trajectories.

Benefits of Quick Star

- Relatively unaffected by motion
- Designed for free breathing abdominal imaging
- Provides flexibility to scan at higher resolution without compromising patient comfort
- Mild streaking artifacts can be seen, but are generally considered benign and can be read through

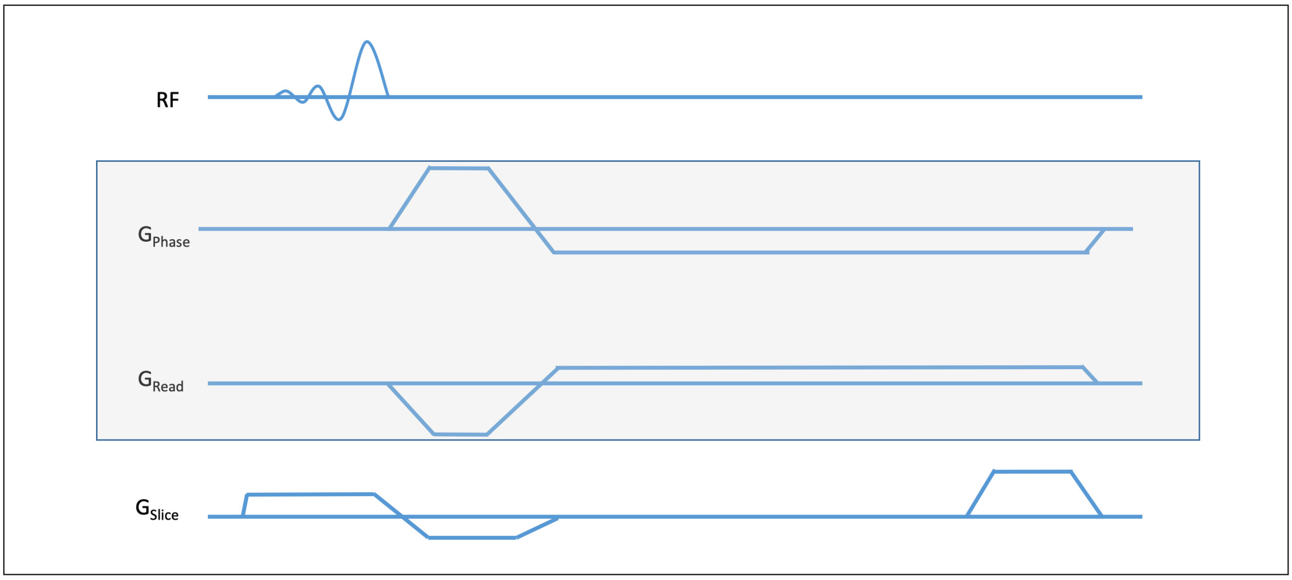

Figure 5. Basic Quick Star sequence diagram during TR. The gradients on the Readout and Phase directions are played out simultaneously resulting in radial k-space traversal.

Quick Star provides the flexibility to scan at higher resolutions, placing image quality over speed without compromising patient comfort. Cartesian scan times are typically minimized to avoid motion artifacts, forcing the compromise between high resolution and patient comfort. Quick Star can be programmed for longer continuous scanning, providing high resolution, virtually artifact free and reproducible image quality, all during free breathing. The following chart represents basic Quick Star parameters for high quality reduced motion abdominal imaging during free breathing.

Basic Quick Star Protocol	T1 Weighted Abdominal
Base Sequence	FFE3D-qstar
TE/TR	1.1ms-1.9ms/3.6ms-4.2ms
Matrix	224-320
Field of View	35 x 35
Flip Angle	12-15
Fat Saturation	On; enhanced
Number of Trajectories	600-1200

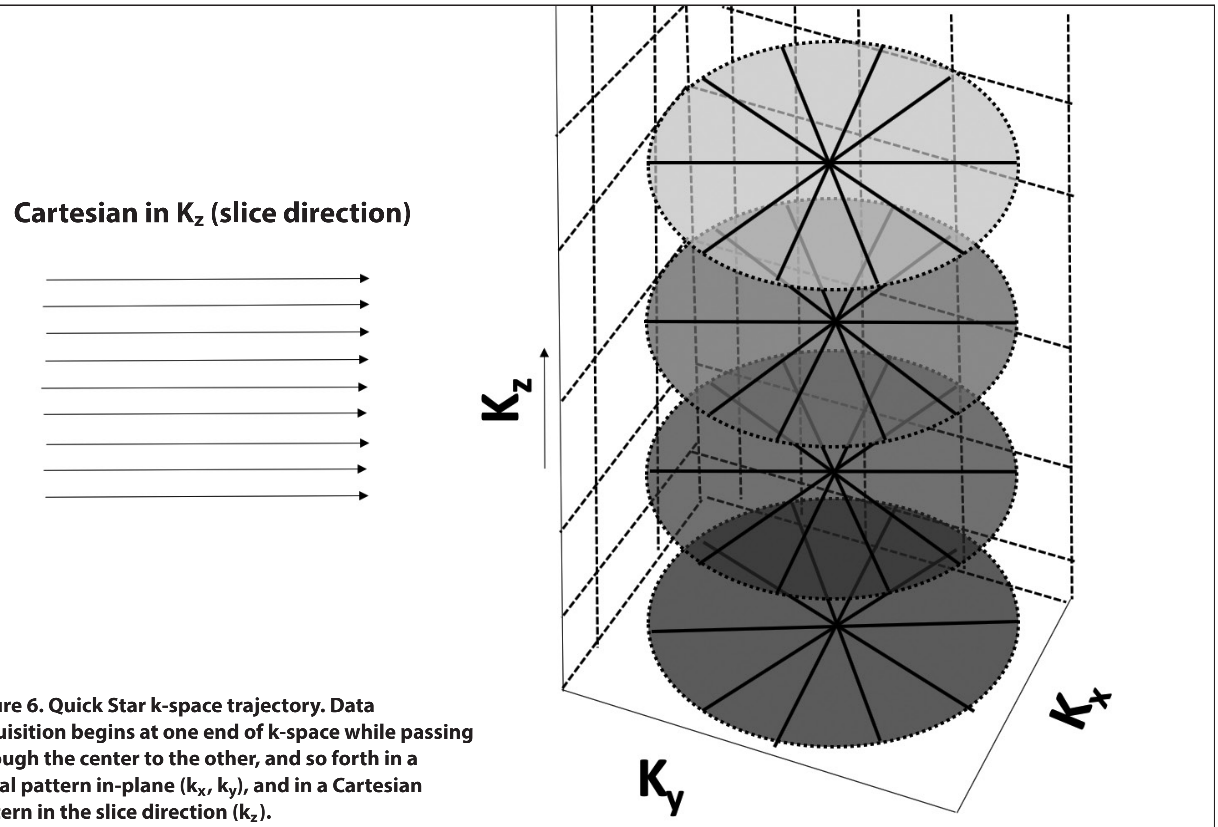

Figure 6. Quick Star k-space trajectory. Data acquisition begins at one end of k-space while passing through the center to the other, and so forth in a radial pattern in-plane (k_x, k_y), and in a Cartesian pattern in the slice direction (k_z).

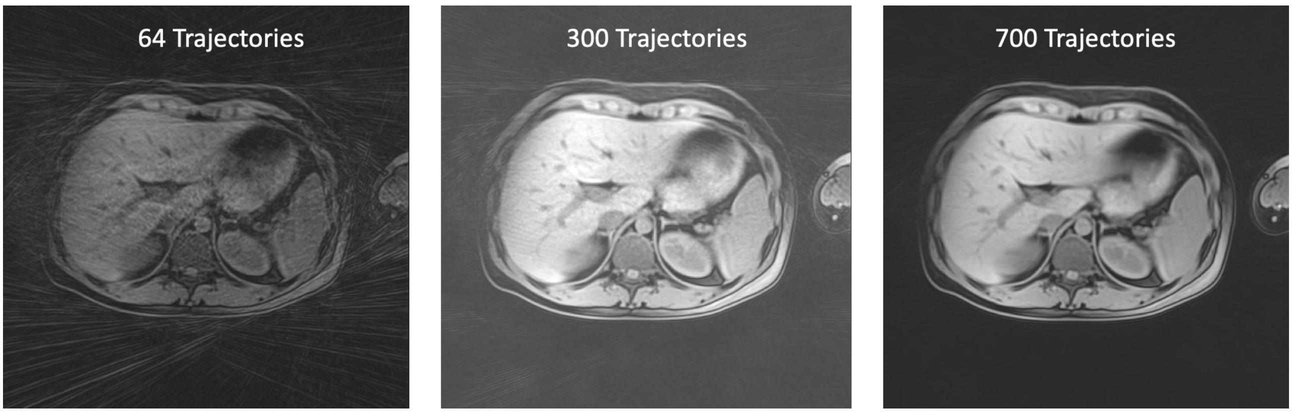

Figure 7. Illustration of known "streak" artifacts encountered in Stack of Stars implementations with changes in the number of trajectories. Left: 64 trajectories, Center: 300 trajectories, and Right: 700 trajectories. As demonstrated above, streak artifacts become negligible with a higher number of trajectories.

Clinical Applications

Free Breathing Abdominal

Due to the sensitivity to motion, conventional T1-weighted abdominal exams generally have to be acquired during breath-holds. Breath-hold lengths of 15-20 seconds may be very difficult for patients, especially the elderly, sick, pediatrics and noncompliant. When they struggle to maintain breath-holds during the exam, severe motion artifacts are seen. These artifacts can obscure pathology. Other motion mitigating options, including respiratory gating and real time motion correction (RMC), enable scanning without breath-holds, but the image quality may be reduced. Additionally, these techniques are highly dependent on patient breathing efficiency and may take longer than nominal scan time, particularly in patients with irregular breathing or sleep apnea.

Figure 8 compares various implementations of 3D FFE acquisitions, including free breathing, breath-hold, respiratory gated, real time motion correction, and Quick Star (600 and 900 trajectories). These images were acquired on a Vantage Galan 3T scanner. Compared to the other acquisitions Quick Star provides high SNR and virtually motion free imaging with reduced blurring. In addition, the scan time in Quick Star with 600 and 900 trajectories is significantly shorter than the actual scan time in respiratory gated and RMC scans.

High Resolution Liver Imaging

For conventional Cartesian imaging, the need for increased spatial resolution translates directly to increased scan time. Thus, the need to acquire during breath-holding directly limits the maximum spatial resolution possible. Longer breath-hold times are difficult even for patients

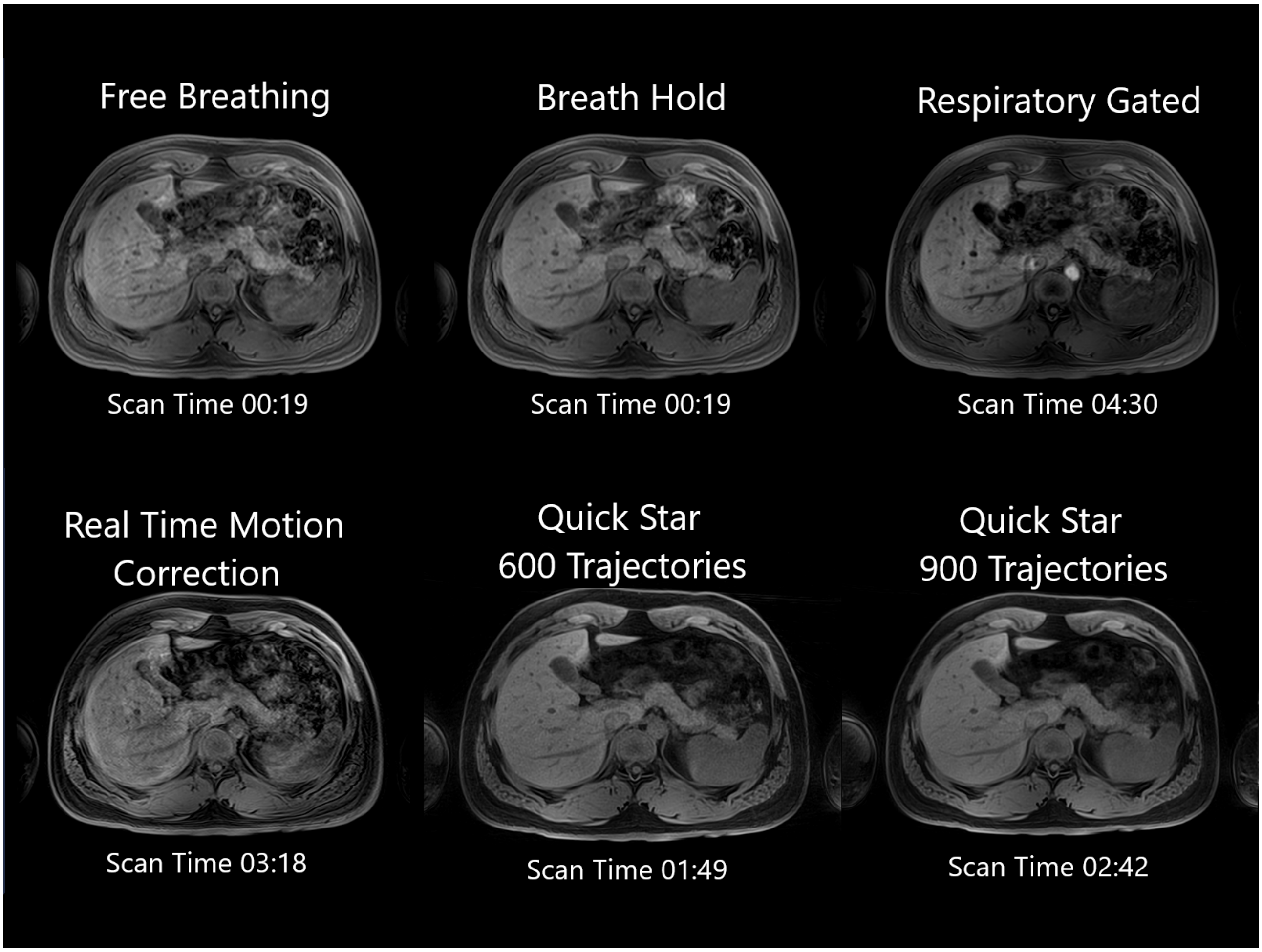

Figure 8. Comparison between FFE3D liver acquisitions in a volunteer with irregular breathing pattern using 4 different clinical implementations. From Top left to bottom right: Cartesian FFE3D (free breathing and breath-held, respectively), Cartesian FFE3D with respiratory gating, Cartesian FFE3D with Real Time Motion Correction (RMC), and Quick Star acquired with 600 and 900 trajectories, respectively. Note the expected presence of motion artifact in the free breathing, respiratory gated and RMC acquisitions. While motion mitigation techniques used in the other acquisitions partially remove the artifact, the image quality of Quick Star is higher. Respiratory gating and RMC may not completely remove motion artifacts and the actual scan time is significantly longer than Quick Star scans due to poor breathing efficiency in the volunteer. Quick Star acquired with 800 trajectories offers slightly better image quality than 600, but 900 is clinically adequate at a shorter scan time.

who are capable of typical breath-hold times. Quick Star is beneficial in these cases since radial acquisitions can be performed continuously during free breathing making it possible to scan for longer acquisition times.

Summary

Radial k-space sampling is a concept that has been known since the early days of MRI but had not been used routinely for clinical applications due to initial technical challenges. Now, with the more advanced technologies on MRI systems, Quick Star FFE3D is possible for clinical use, particularly for patients who are not able to hold still, maintain breath-holds, and for applications where organ motion is unavoidable.

The primary application of Quick Star is free-breathing 3D abdominal imaging. It provides similar image contrast to conventional fat-suppressed FFE3D without the sensitivity to motion and less impactful artifact behavior. Quick Star is advantageous over other techniques for two main reasons: **1.** patients can comfortably breathe freely during the acquisition without imparting motion artifacts on the images, and **2.** Quick Star eliminates timing constraints typically experienced in breath-held and respiratory gated exams, allowing for increased spatial resolution.

Many more opportunities exist for exploring Quick Star's advantages in additional anatomical regions.

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CANON MEDICAL SYSTEMS USA, INC.
https://us.medical.canon

2441 Michelle Drive, Tustin, CA 92780 | 800.421.1968

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