MR Physics for Clinicians – Ultrafast Imaging

Jeffrey Tsao, Ph.D
Novartis Institutes for BioMedical Research
Global Imaging Group, Laboratory Head
jeffrey.tsao@novartis.com

Goal

This lecture aims to give an overview of ultrafast image techniques such as echo-planar imaging (EPI) and spiral imaging. While these techniques offer significant speed improvement, they are often accompanied by practical issues that degrade the quality of the images, thereby compromising their benefits. Therefore, it is important to take proper control of the tradeoff between imaging speed and the sensitivity to artifacts. The goal of this lecture is to demystify the origin of these artifacts and to describe solutions that allow ultrafast imaging to be practiced in a routine and robust manner.

Introduction

The motivation for ultrafast imaging is clear. From a practical standpoint, it is useful to reduce scan time as much as possible, so that patients can keep still for the full duration of the scan in order to acquire high-quality images. For certain types of examinations, such as in cardiovascular applications, it is necessary to achieve a sufficiently high frame rate (on the order of tens of milliseconds) in order to freeze the physiological motion, such as the cardiac cycle.
However, the image quality is often compromised in ultrafast imaging techniques such as EPI and spiral imaging compared to slower techniques. Thus, it is important to understand how imaging speed affects image quality so that an appropriate tradeoff can be chosen for each application.

How to go faster and fundamental origin of artifacts

To get a proper handle on ultrafast imaging, it is helpful to recapitulate how acquisition and reconstruction work on a conceptual level (Fig. 1). During acquisition, the scanner acquires a series of data, which are arranged into a data matrix, the so-called *k*-space. This process is

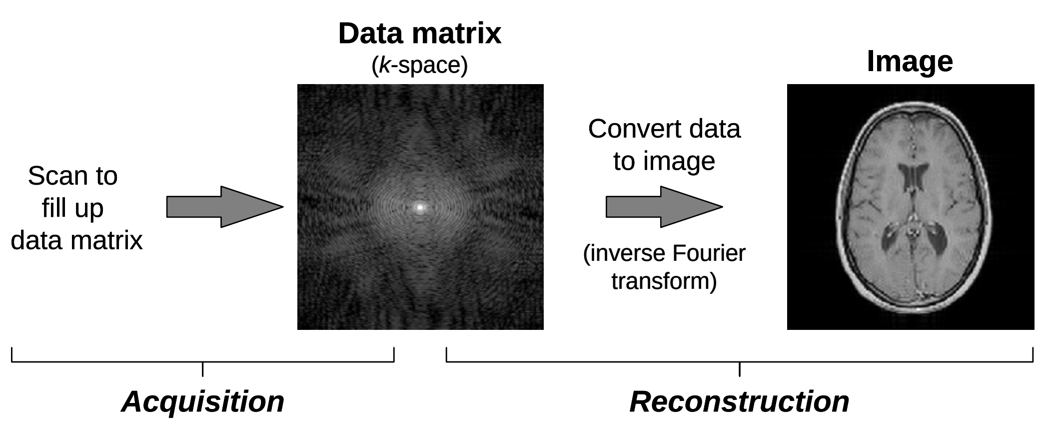

Fig. 1. Schematic of acquisition and reconstruction to generate an image.

repeated until the data matrix is filled up. Each repetition takes a duration determined by the repetition time, TR, during which the pulse sequence performs a number of tasks such as setting up the proper image contrast, slice selection, data acquisition, among other. The total time to acquire an image is then given by the repetition time multiplied by the number of repetitions. When the data matrix is filled, the data are converted into an image by reconstruction. To reach "ultrafast" imaging speed, the basic concept is to fill up the data matrix as quickly as possible. This is achieved by spending a larger proportion of each repetition time on acquiring data (i.e. to increase the "readout window"), while having fewer repetitions overall, thereby shortening the total scan duration.

Unfortunately, spending more time per repetition to acquire data also means that there is more time for artifacts to arise. Fig. 2 shows a series of gradient echo images of a phantom at a fixed repetition time TR, but at increasing echo times, TE. The phantom contains a mixture of water, oil, and air to reproduce many of the artifacts that are typically observed *in vivo*. These artifacts worsen with increasing echo times. They include 1. signal voids close to water-air interfaces (susceptibility artifacts), 2. constructive and destructive interference between the water and oil signals due to differences in frequency (off-resonance, chemical shift effects), and 3. signal attenuation (T_2* decay). Not captured in this example are additional causes of artifacts such as blood flow, patient motion, etc.

By increasing the readout window, part of the data matrix will be filled with data from an earlier echo time, while others will come from a later echo time. Conceptually, this is equivalent to mixing parts from different images in Fig. 2 to form a single image. Since the images have considerably different appearances at increasing echo times, there are inherent mismatches in the combined data. This mismatch is the fundamental cause of the compromised image quality for ultrafast imaging.

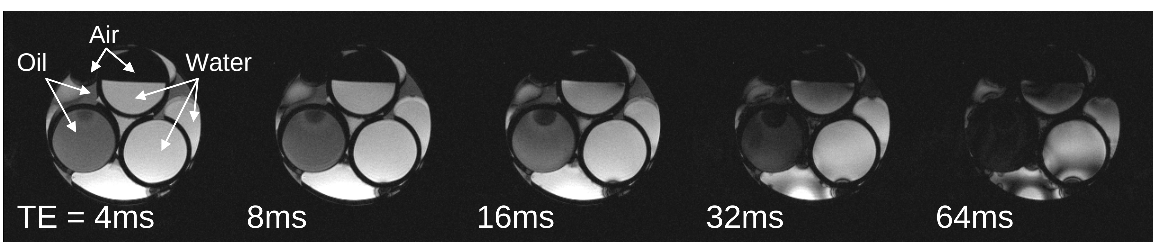

Fig. 2. Gradient echo images of a phantom containing a mixture of water, oil, and air, at increasing echo times (TE). Artifacts increase with TE.

How to acquire more data for ultrafast imaging?

The majority of today's imaging techniques relies on an approach called spin-warp or Cartesian sampling (1). In this approach, the scanner fills the data matrix one row at a time. This process is repeated until all rows of the data matrix has been filled (Fig. 3, left).

To increase imaging speed, the central idea is to acquire more than one line of data at a time. The two most popular approaches are echo-planar imaging (EPI), which acquires an alternating line of data through the data matrix (2), and spiral imaging, which acquires a curved line of data (3,4). Fig. 3 shows how these readout trajectories move through the data matrix in order to acquire more data each time. In turn, the entire data matrix can be covered with fewer repetitions of these longer readouts (Fig. 3, middle column). At the extreme case, these readout trajectories can cover the entire data matrix in a single shot (Fig. 3, right column). Of course, as mentioned above, the longer duration of the readout also causes it to be more sensitive to artifacts. This is the primary tradeoff between acquisition speed and image quality. The single-shot approach is the fastest, but image quality tends to be compromised. The multi-shot approach is not as fast, but it leads to significantly improved image quality as a result of a shorter readout duration.

There is one important exception where the multi-shot approach is more problematic than the single-shot approach. In diffusion imaging, the sequence is sensitized to diffusion, so it is also extremely sensitive to the general motion of the subject. As a result, the data acquired by each shot are corrupted to a different extent each time, thereby leading to image artifacts. Additional acquisition and post-processing techniques are needed to correct for the shot-to-shot variations so that the multi-shot approach becomes feasible for diffusion imaging (5,6).

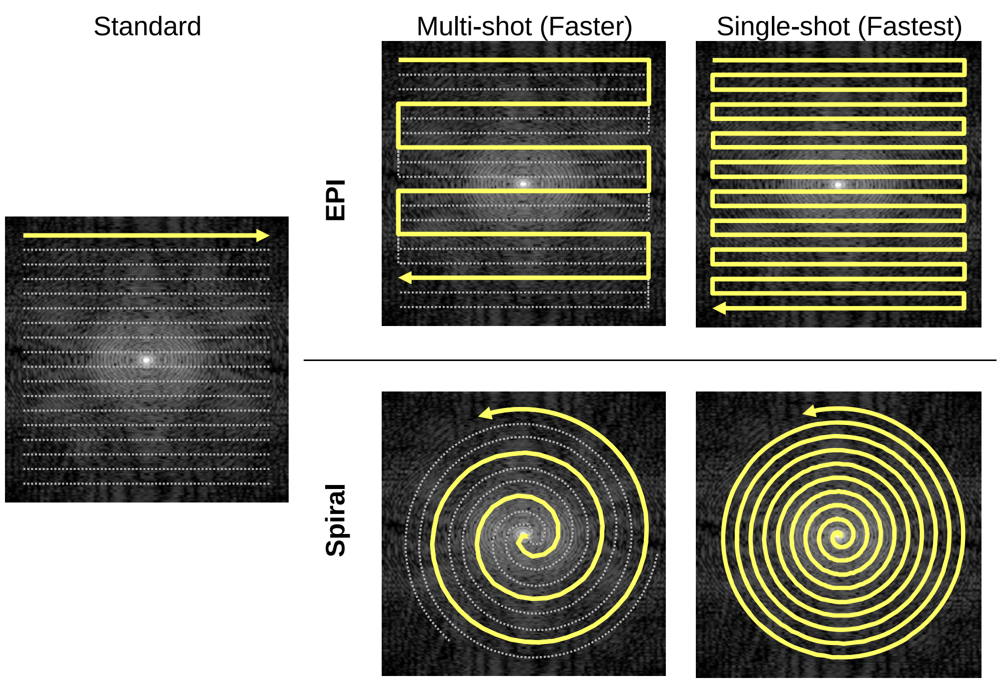

Fig. 3. Fast imaging methods amount to covering more of the data matrix per readout. However, this is achieved at the expense of having a longer readout window, which also increases the sensitivity to artifacts.

Artifacts in EPI and spiral

Since EPI and spiral cover the data matrix along different paths, data from various echo times are combined in the data matrix in different regions. For example, EPI collects data along a zig-zag path from top to bottom of the data matrix, so the top part of the data matrix are acquired from a different echo time than the bottom part. Conversely, in spiral, the center of the data matrix is acquired from a different echo time than the periphery. These differences translate to different appearances for susceptibility artifacts and off-resonance effects. They appear as geometric distortions in EPI, while they appear as blurring in spiral. A wide variety of post-processing approaches have been proposed that correct these problems to some extent retrospectively (7,8). As above, the problems can be alleviated prospectively by the multi-shot approach to shorten the readout window.

Instrument imperfections as an origin of artifacts

Another source of artifacts for ultrafast imaging is instrumentation. As imaging speed is pushed to the maximum, slight errors in timing (on the order of microseconds) or in gradient switching (e.g. from eddy currents) result in position errors between the intended and actual locations where the data are acquired. The net effect is that the data are misplaced from their proper locations in the data matrix, and the consequence on the image depends on the pattern and extent of those displacements. In EPI where the readout alternates left and right through the data matrix (Fig. 3, top row), the common displacement is that the data acquired in one direction (e.g. from left to right) are not exactly aligned with those in the opposite direction (e.g. from right to left). This leads to a lateral shift in the data matrix that repeats periodically from top to bottom. The resulting image artifact resembles a fold-over artifact, and it is called Nyquist ghosting. This problem has been extensively studied. The solution is to correct the misalignment problem, often by a prospective calibration scan, or retrospectively by image processing. Similarly, for spiral imaging, instrument imperfections lead to displacement of the data, leading to intensity variations in the image (9).

Summary

The main techniques for ultrafast imaging are EPI and spiral imaging. Both techniques achieve faster imaging speed by increasing the readout window. In doing so, they also open up more time for artifacts to contaminate the data. As a result, there is an inevitable tradeoff between acquisition speed and the sensitivity to artifacts. The appearance of artifacts in EPI and spiral imaging is quite different, which is due to how data from different echo times are gathered in the data matrix. In EPI where data are gathered in a zig-zag fashion through the data matrix, artifacts appear as geometric distortions and fold-over artifacts. In spiral, where data are gathered in a concentric fashion, artifacts appear as blurring. In general, these artifacts can be reduced significantly by increasing the number of shots to reduce the readout window. Moreover, over the past couple of decades, there has been significant progress in artifact reduction, either by prospective adjustments or by retrospective correction, which has allowed robust ultrafast imaging to be applicable on a routine basis.

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