Echo-Planar Cardiac MRI using Parallel Imaging

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Introduction

Since it's original proposal by Mansfield et al. in 1977 [1], echo-planar imaging (EPI) has had a key role in the evolution of cardiac MRI. EPI involves the rapid acqusition of k-space data in a raster-like fashion, requiring a fewer number of excitations compared to conventional 2DFT imaging. This is crucial in cardiac imaging as respiratory and cardiac motion places high demands on imaging speed. EPI has been used for a wide array of cardiac applications including the imaging of myocardial function, perfusion, and coronary arteries, and real-time localization.

EPI can be used as a single-shot technique or can be used with multiple excitations with a variety of ordering schemes (e.g. sequential, interleaved, center-out, top-down). It can also be used in a 'fly-back' mode which involves traversing k-space in the same direction during each echo [2]. There are many subtle *variations* of EPI, each with its own advantages and disadvantages.

Limitations of EPI are well-known [3–6] and include:

- sensitivity to gradient timing delays and eddy-currents, which produces data misalignment in k-space and ghosting artifacts in images,
- sensitivity to motion, which produces a data-inconsistency artifact in multi-shot EPI and ghosting artifacts or blurring in images, and
- sensitivity to off-resonance, which produces phase artifact in k-space, and causes geometric distortion in images.

These artifacts in EPI cardiac imaging were tolerated for many years (because of the need for speed), however with the emergence of parallel imaging in the late 1990s [7, 8], many cardiac MRI protocols that used to employ echo-planar imaging, are being replaced by 2DFT acquisitions combined with parallel imaging.

Parallel imaging is a powerful technique for accelerating image acquisition, which relies on simultaneous acquisition with multiple receiver coils that have different sensitivities over the region of interest. This simultaneous spatial encoding can be used to reconstruct images with a reduced amount of k-space data [7–9].

Artifact Correction using Parallel Imaging

This talk will cover novel ways in which parallel imaging can be used to mitigate artifacts in EPI that diminish diagnostic value (listed above). These methods suggest the simultaneous use of EPI and parallel imaging to obtain improved image speed compared to either method alone, as well as artifact free image reconstruction. Combined EPI parallel imaging protocols will be appropriate in applications such as real-time imaging, imaging of ventricular function during stress, and first-pass perfusion imaging.

The following artifact correction methods will be discussed:

- **Benefits of Acceleration.**

  At a very basic level, parallel imaging can be used to mitigate EPI artifacts by shortening echo-train length (ETL) and/or reducing the number of excitations required. Shortening

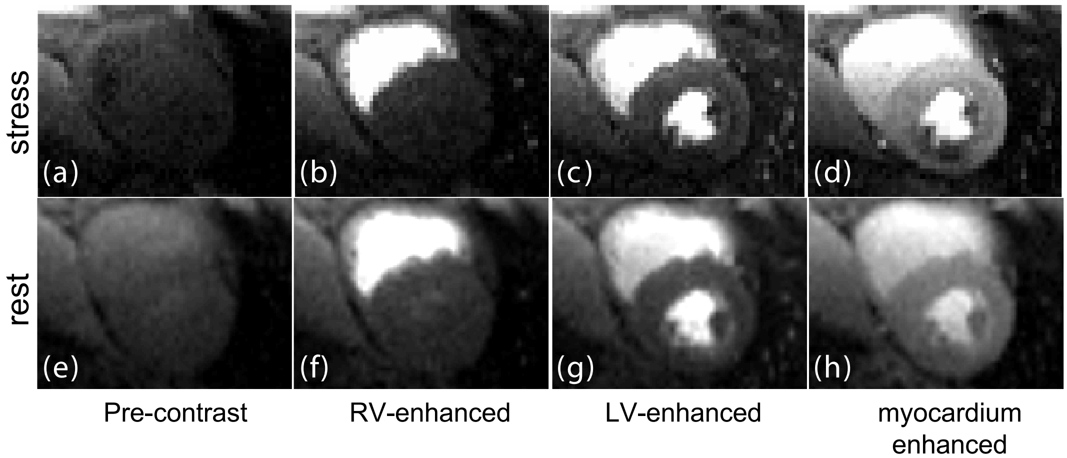

Figure 1: Example first-pass contrast-enhanced perfusion images for a patient with stress perfusion deficit in the inferior and lateral wall shown in a single-slice, acquired using GRE-EPI with rate-2 TSENSE. Shortening image acquisition time, in this case using TSENSE, has been shown to reduce the incidence of "dark rim" artifacts in first-pass perfusion imaging.

the ETL mitigates off-resonance effects, while shortening overall image acquisition time reduces motion artifacts. [10, 11]

To take a clinical example, coverage of the entire heart during first-pass contrast enhanced MRI with single heartbeat temporal resolution is desirable for quantifying perfusion abnormalities. Multislice coverage may be achieved using saturation recovery with a relatively short preparation time (TI) and gradient echo (GRE) sequence with a multi-shot EPI readout [12].

Parallel imaging may be applied to yield better spatial resolution or increase spatial coverage (number of slices) for a fixed temporal resolution. Accelerated parallel imaging may also be used to improve the temporal resolution (reduce the imaging duration per slice) which reduces the possibility of motion blur or artifacts [13]. An example of first-pass perfusion using GRE-EPI with TSENSE [14] is shown in Figure 1. Accelerating the image acquisition reduces incidence of sub-endocardial "dark rim" artifacts which appear as perfusion defects (false positives).

- **Corrections for Interleaved EPI.**

In cardiac imaging, where T_2^* values can be relatively short, images are typically acquired using multiple shots with short echo-trains. Images are frequently acquired using an interleaved phase encode order [5, 6].

Various artifacts in interleaved EPI can be corrected using parallel imaging. In interleaved EPI acquisition, odd phase encodes and even phase-encodes in k-space can begin their k-space traversals from left to right and from right to left, respectively, so that the net k-space traversal direction pattern is similar to that of a single shot EPI [15]. In order to avoid echo-misalignment problems caused by asymmetric gradient delays and eddy currents, left-to-right and right-to-left k-space raw data can be reconstructed separately, which results in images with FOV reduced by a factor of 2. Parallel imaging with an acceleration factor of 2 can then be used to recover the full FOV [16].

When applied to continuous imaging, coil sensitivity maps must be constantly updated [14]. A recently proposed method [17] utilizes flipping of the k-space traversal pattern (flipping the readout gradient) at every time frame. This acquisition scheme enables coil sensitivity maps to be updated from the two most recent time frames. These coil sensitivity maps are themselves free from ghosting artifacts, because two sets are are separately made from left-to-right traversal and right-to-left traversal data. This method has been used to produce ghost-free real-time EPI cardiac images (see Figure 2).

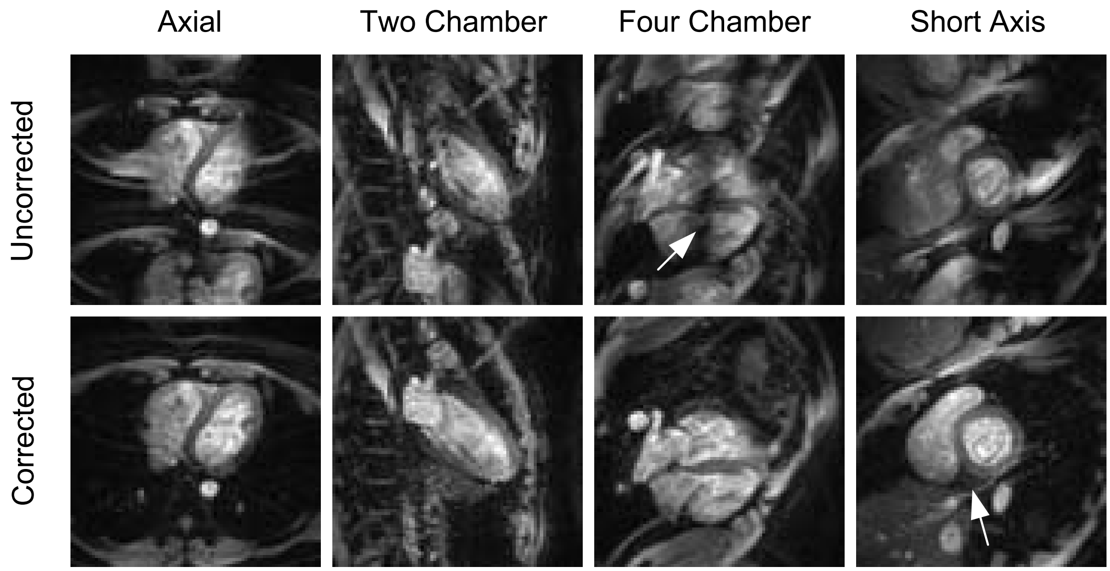

Figure 2: Automatic correction of k-space errors caused by asymmetric gradient delays and eddy currents, in real-time EPI cardiac MRI: (top row) uncorrected, and (bottom row) corrected, using the method described by Y-C Kim, et al. [17].

A key feature of this method is that it works for arbitrary scan-planes, and requires no knowledge of the axis-dependent hardware gradent delays or eddy currents that would ordinarily cause ghosting artifacts.

- **Corrections for Sequential EPI**.

  Interleaved phase encode ordering has drawbacks which include: geometric distortion caused by off-resonance [4], distortion due to in-plane flow, increased readout duration when using echo-shifting, and distortions related to echo misalignment caused by gradient timing errors and eddy-currents (discussed above).

  Using a sequential (non-interleaved) phase encode order will cause ETL-1 ghosts, spaced at FOV/ETL, and therefore has not been commonly used.

  The phased array ghost elimination (PAGE) method, originally described in 2001 [18, 19], can be used in cardiac functional imaging to mitigate EPI ghosting resulting from periodic phase and amplitude errors in k-space (between echoes). Cancellation of ghosts by means of phased array processing makes sequential non-interleaved phase encode acquisition order practical, and yields benefits such as reduced distortion due to off-resonance, in-plane flow, and EPI delay misalignment, and it does not require echo-shifting.

  The drawbacks of an interleaved acquisition are traded for widely spaced ghosts, which are cancelled by phased array processing. The PAGE approach has been successfully applied to non-interleaved EPI using an SSFP sequence with ETL=3 [20]. Figure 3 compares images before and after phased array ghost cancellation.

Summary

Artifacts have plagued clinical EPI imaging, and have resulted in EPI's limited use in today's clinical cardiac MRI protocols (which rely predominantly on parallel imaging for acceleration). Several methods that combine EPI with parallel imaging have been recently developed. These methods shorten acquisition times and eliminate ghosting artifacts, by sacrificing a portion of the parallel imaging acceleration factor.

This successful merger of EPI and parallel imaging has provided promising approaches for rapid and robust cardiac magnetic resonance imaging.

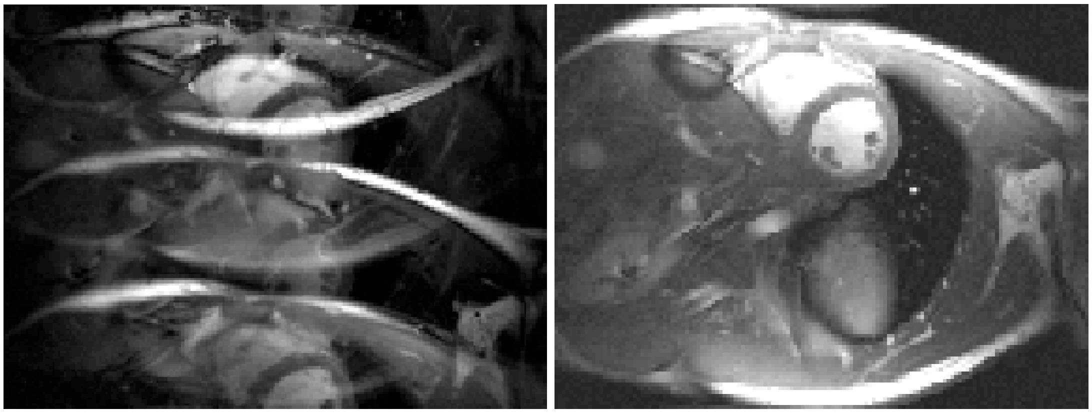

Figure 3: Cardiac short axis images acquired using SSFP-EPI with echo-train length=3, and sequential phase encode order. One temporal frame is shown (left) with ghosts due to rapid phase variation and (right) after PAGE reconstruction.

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