Magnetic Resonance Imaging 34 (2016) 832–838

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.mrijournal.com

Original contribution

Motion and distortion correction of skeletal muscle echo planar images

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ARTICLE INFO

Article history:
Received 18 July 2015
Revised 28 February 2016
Accepted 3 March 2016

Keywords:
Magnetic resonance imaging
Skeletal muscle
Echo planar magnetic resonance imaging
Motion correction
Distortion correction
Image pre-processing

ABSTRACT

This paper examines two artifacts facing researchers who use gradient echo (GRE) echo planar imaging (EPI) for time series studies of skeletal muscles in limbs. The first is through-plane blood flow during the acquisition, causing a vessel motion artifact that inhibits proper motion correction of the data. The second is distortion of EPI images caused by B_0 field inhomogeneities. Though software tools are available for correcting these artifacts in brain EPI images, the tools do not perform well on muscle images. The severity of the two artifacts was described using image similarity measures, and the data was processed with both a conventional motion correction program and custom written tools. The conventional program did not perform well on the limb images, in fact significantly degrading image quality in some trials. Data is presented which proves that arterial pulsatile signal caused the impairment in motion correction. The new tools were shown to perform much better, achieving substantial motion correction and distortion correction of the muscle EPI images.

1. Introduction

Gradient echo (GRE) echo planar imaging (EPI) is often employed to examine skeletal muscles in research studies. Authors are commonly interested in the blood oxygenation level dependent (BOLD) effect in health and disease, through exercise and ischemic tests [1,2]. This paper discusses solutions to two challenges encountered in EPI imaging of muscle that are not encountered when imaging the brain: through-plane arterial blood flow and a lack of software tools for pre-processing muscle images.

1.1. Vessel motion artifact

The first problem salient to this paper occurs when the lower leg is imaged axially, with blood flowing through-plane in three arteries entering the imaging plane at a right angle. When an EPI time series of this type is visualized, the arteries appear to vary in brightness and oscillate across the image by several millimeters from one time point to the next. The anterior tibial, posterior tibial, and peroneal arteries have fast flow at some points in the cardiac cycle, causing increased signal intensity due to the inflow or time-of-flight (TOF) effect [3]. This accounts for the varied brightness. The apparent motion is more difficult to explain, but can be understood by referring to a pulse sequence diagram for GRE EPI [4]. Since the flow is through-plane (in the z-direction), only the slice select gradient could cause a phase accumulation in the flowing spins. Flow with constant velocity during such a bipolar gradient pulse causes a phase shift to develop that is proportional to velocity [5]. Because of this phase shift in the intra-arterial spins in frames acquired during fast flow, the vessels appear displaced compared to their true location after EPI reconstruction.

The vessel motion artifact is hypothesized to be problematic for image motion correction, since linear registration schemes will tend to align the bright arteries across frames and drag the rest of the image along with the artifactual motion. This may lead to a time series of images with motion introduced by the software intended to perform motion correction, degrading image quality instead of improving it.

To the best of the authors' knowledge, this is the first time the arterial inflow confound to MR motion correction has been described in the literature. This problem is likely to be encountered by researchers in the future as the use of GRE EPI to study muscle continues. The problem of apparent vessel motion due to through-plane flow may be mitigated by applying saturation bands inferior and superior to axially acquired slices, as is commonly done in TOF studies to eliminate venous flow signal. This decreases the signal from inflowing blood to make the artifact less apparent. This strategy is unlikely to completely eliminate the artifact,

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http://dx.doi.org/10.1016/j.mri.2016.03.003

however, since the saturation of spins adjacent to the imaging slice is imperfect. Spins from this region as well as from the imaging slice itself may still be excited and produce a TOF artifact. If the artifact is still present with spatial saturation bands in place, processing schemes may be employed to de-weight the area of the arteries or hide them from the registration optimizer during motion correction.

1.2. EPI distortion

The second problem addressed in this paper is the high sensitivity of GRE EPI imaging to B_0 field variations. The relatively long time (approximately 50 ms) that the RF read-out window is open during an EPI scan causes artifacts; these manifest as blurring in spiral images, or spatial shift in the phase encoding direction in the blipped cartesian EPI images used in this study as well as many others. The distortion (warp) artifact due to B_0 field variations in EPI images is well known and has been described previously [6], and an algorithm for correction of the images been developed [7]. Software tools implementing GRE EPI unwarping exist, but are typically designed for brain images. One such widely used tool is FUGUE from the FSL toolbox [8]. The brain-centric design is evident given that a 3D volume matching the size of a human head is expected, and slices at the margins may be discarded. It also performs skull stripping and 3D registration which has unpredictable results on small field-of-view limb data, resulting in partially or completely lost slices. Presumably as a result of the lack of available tools, this significant GRE EPI artifact is not usually addressed in muscle imaging studies [2]; a B_0 field map correction has been applied successfully to forearm DTI, however [9]. When EPI images are unwarped, co-registration of functional and anatomical data may be improved, allowing high quality ROIs drawn on anatomical images to be applied to functional data.

The purpose of this paper is to draw attention to the severity of these two problems facing GRE EPI studies of muscle, and to explain solutions for overcoming them.

2. Materials and methods

2.1. Image acquisition

GRE EPI time series data was collected with approval from our local institutional review board using a 3 T GE HD Signa MR scanner with a single channel, receive-only, GPFLEX coil (GE Healthcare, Milwaukee, WI). Six male volunteers participated (mean age 31 ± 9 years). Subjects were positioned in a custom-built MR compatible exercise ergometer for the scanning session (Fig. 1). Following localization, second order shimming, and anatomical imaging, three 10 mm thick, axial slices were acquired with a single-shot gradient echo EPI pulse sequence [10] at the largest cross section of the right leg calf muscles (FOV $=16$ cm, matrix size (MS) $=64 \times 64$, $T_E =$ 35 ms, $T_R = 250$ ms, $\alpha = 33^{\circ}$, receive bandwidth (rBW) $=500$ kHz). The long T_E was used to match typical values of BOLD muscle studies. Spatial saturation bands (40 mm thick) were prescribed continuously above and below the imaged volume to reduce artifacts produced by through-plane flowing blood. For each EPI image series acquired, a pair of fast spoiled gradient echo (SPGR) images were acquired to generate B_0 field maps from the phase images ($T_E = 4.55/6.82$ ms for $\Delta T_E = 2.27$ ms; MS $=128 \times 128$; FOV, T_R, α matched EPI images; rBW $=62.5$ kHz). EPI images were acquired before, during, and after exercise. First, 10 min of baseline data was acquired before the start of exercise. Next, isotonic plantar flexion exercise (2.5 min of dynamic (0.5 Hz) plantar flexion at 50% of a subject's previously measured one-repetition maximum) commenced, and image acquisition was started with 30 s of exercise remaining. Data acquisition continued after exercise for 12.5 min. This time series was examined for each subject, and all exercise frames were removed. Thus, two sets of GRE EPI time series data were acquired from each subject: the 10 min pre-exercise data set (denoted *rest*), and the 12.5 min data set immediately following exercise (called *post-ex*). A diagram of the experiment timeline is shown in Fig. 1.

2.2. Image post-processing

Although spatial saturation bands were applied, arterial flow artifacts were still present with enough severity to spoil motion correction (Fig. 2). Thus, steps were taken to remove the influence of the artery voxels on the registration. A hand drawn binary mask was used which applied a value of zero (i.e. False) to the area around three major through-plane arteries in the lower leg and a value of one (i.e. True) elsewhere. The masked area was roughly elliptical, with dimensions 20 × 50 mm on each slice, masking approximately 5% of image. The mask was applied to the cost function during registration, which caused the registration algorithm to ignore the areas of the arteries when optimizing the motion correction parameters. Masking the cost function is an improvement over masking the images themselves, as it does not generate artificial edges which may confound the motion correction process. A conservative intensity based mask was also generated to eliminate the image background areas, which contained phase ghosts capable of influencing registration. The motion correction scheme was implemented in a shell script (mocorib – **mo**tion **cor**rection with **i**nflowing **b**lood) using FSL's FLIRT tool for registration [11,12], as well as other command line utilities from the FSL [8] and AFNI [13] toolboxes. Given that FLIRT is not optimized for motion correction

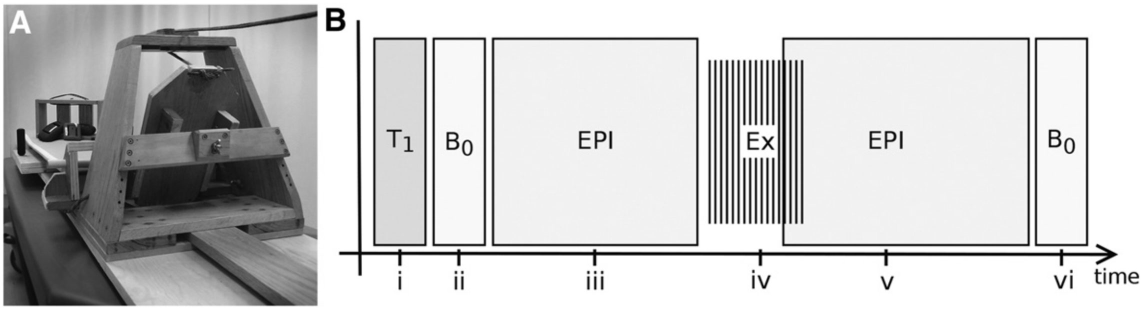

Fig. 1. Experiment Description. **(A)** The photo shows the exercise ergometer used in this study. The apparatus is pictured outside the magnet, with weights for adding resistance visible in the background. **(B)** The diagram shows the events that occurred during an experimental trial (not to scale): **(i)** Subject attached to ergometer in scanner, anatomical images acquired (see Section 2.1 for details); **(ii)** Two GRE images acquired for B_0 map creation; **(iii)** Ten min GRE EPI time series images acquired (*rest* condition); **(iv)** Plantar flexion exercise for 2.5 min; **(v)** GRE EPI images acquired. Images acquired during exercise were discarded, leaving 12.5 min time series (*post-ex* condition); **(vi)** Two additional GRE images acquired for B_0 map creation.