Magnetic Resonance Imaging 34 (2016) 1026–1033

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.mrijournal.com

Background field removal technique using regularization enabled sophisticated harmonic artifact reduction for phase data with varying kernel sizes

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ARTICLE INFO

Article history:
Received 10 December 2015
Revised 3 April 2016
Accepted 17 April 2016
Available online xxxx

Keywords:
Background field removal
Quantitative susceptibility mapping (QSM)
Regularization enabled sophisticated harmonic artifact reduction for phase data with varying kernel sizes (REV-SHARP) Sophisticated harmonic artifact reduction for phase data (SHARP)

ABSTRACT

An effective background field removal technique is desired for more accurate quantitative susceptibility mapping (QSM) prior to dipole inversion. The aim of this study was to evaluate the accuracy of regularization enabled sophisticated harmonic artifact reduction for phase data with varying spherical kernel sizes (REV-SHARP) method using a three-dimensional head phantom and human brain data. The proposed REV-SHARP method used the spherical mean value operation and Tikhonov regularization in the deconvolution process, with varying 2–14 mm kernel sizes. The kernel sizes were gradually reduced, similar to the SHARP with varying spherical kernel (VSHARP) method. We determined the relative errors and relationships between the true local field and estimated local field in REV-SHARP, VSHARP, projection onto dipole fields (PDF), and regularization enabled SHARP (RESHARP). Human experiment was also conducted using REV-SHARP, VSHARP, PDF, and RESHARP. The relative errors in the numerical phantom study were 0.386, 0.448, 0.838, and 0.452 for REV-SHARP, VSHARP, PDF, and RESHARP. REV-SHARP result exhibited the highest correlation between the true local field and estimated local field. The linear regression slopes were 1.005, 1.124, 0.988, and 0.536 for REV-SHARP, VSHARP, PDF, and RESHARP in regions of interest on the three-dimensional head phantom. In human experiments, no obvious errors due to artifacts were present in REV-SHARP. The proposed REV-SHARP is a new method combined with variable spherical kernel size and Tikhonov regularization. This technique might make it possible to be more accurate backgroud field removal and help to achive better accuracy of QSM.

1. Introduction

The phase of the gradient echo shows more sensitivity to magnetic susceptibility of tissues than the magnitude image. In particular, the phase of the intracranial tissues provides excellent contrast among the white matter, gray matter, iron-rich tissue, and venous vessels [1–3]. Susceptibility weighted imaging (SWI) developed by Haacke et al. [4] is a well-known method for enhancing the contrasts related to the tissue magnetic susceptibilities. However, the magnetic resonance imaging (MRI) phase is affected by dipole interactions between the neighboring tissue susceptibilities and angle between the main magnetic field and the objects. To evaluate the tissue susceptibility without the influence of the dipole interactions, quantitative susceptibility mapping (QSM) was developed for direct estimation of magnetic properties calculated from tissue phase images [5–19]. QSM provides useful information about iron metabolism as a biomarker reflecting the tissue magnetic properties [20–22].

QSM essentially requires the application of three post-processing steps to the original MRI-acquired phase image: phase unwrapping, background field removal, and dipole inversion. The obtained original phase image requires unwrapping, because the phase dynamic range is limited to $-\pi$ to π in the volume of interest (VOI). Because the total field is the sum of the tissue local field and the background field induced by external susceptibility sources such as air–tissue interfaces and imperfect shimming, the background

Abbreviations: QSM, Quantitative susceptibility mapping; SWI, Susceptibility weighted imaging; PDF, Projection onto dipole fields; SHARP, Sophisticated harmonic artifact reduction for phase data; VOI, Volume of interest; SMV, Spherical mean value; TSVD, Truncated singular value decomposition; VSHARP, Sophisticated harmonic artifact reduction for phase data with varying kernel sizes; RESHARP, Regularization enabled sophisticated harmonic artifact reduction for phase data; BET, Brain extraction tool; REV-SHARP, Regularization enabled sophisticated harmonic artifact reduction for phase data with varying kernel sizes.

None of the sponsors of research contain in this paper.

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http://dx.doi.org/10.1016/j.mri.2016.04.019
0730-725X/

field is then subtracted from the unwrapped phase, i.e., the total field, to obtain the intrinsic tissue field. Finally, the local tissue field is deconvolved using the dipole kernel to obtain the tissue susceptibility map. Therefore, an effective and accurate background field removal technique is desired for estimating the susceptibility map prior to dipole inversion. Numerical background field removal techniques have recently been proposed to calculate the local tissue field without an additional scan [13,23–30]. An effective projection onto dipole fields (PDF) developed by Liu et al. [24] is one of the major background field removal techniques. PDF estimates the background susceptibility that would best explain the field inside the VOI. Sophisticated harmonic artifact reduction for phase data (SHARP) is another widely used background field removal technique. [25]. SHARP utilizes the spherical mean value (SMV) property to remove the harmonic component, i.e., background field, from the measured total field. Although the SHARP is a simple and powerful tool for separating the background field from the total field, it exhibits two major drawbacks that necessitate further development and improvement of this method. First, the amount of boundary loss in the VOI depends on the kernel size of used SMV operation. Second, a predefined threshold must be used for the truncated singular value decomposition (TSVD) in the deconvolution process. To improve the boundary loss in the VOI, SHARP with varying spherical kernel (VSHARP) was proposed by Wu et al. [13]. VSHARP applied an SMV operation that gradually reduces the spherical kernel sizes for the total field until the boundary loss is minimized. Then, the field applied SMV operation with varying kernel sizes is deconvolved by its operator with the largest kernel size using the predefined threshold value for TSVD. As a result, the VSHARP method exhibits reduced boundary loss compared with the original SHARP method. In another approach, Sun. et al. [27] proposed the regularization enabled SHARP (RESHARP) method which uses Tikhonov regularization in the SHARP deconvolution process, instead of TSVD. RESHARP obtained smaller phase errors and better suppressed obvious artifacts compared to SHARP.

In this paper, we propose a new background field removal technique that exploits a combination of SMV operation with varying kernel sizes and Tikhonov regularization. The purpose of this study is to assess the accuracy of regularization enabled sophisticated harmonic artifact reduction for phase data with varying kernel sizes (REV-SHARP) Sophisticated harmonic artifact reduction for phase data (SHARP). We then compared the effectiveness of REV-SHARP, VSHARP, RESHARP, and PDF methods using a three-dimensional head phantom and human brain data.

2. Theory

The purpose of a background field removal technique is to separate the local field from the total field. Because the background field induced by the susceptibility source outside the VOI satisfies Laplace's equation, the background field is harmonic and exhibits the mean value property [25,27]. Due to this, SMV-operated background

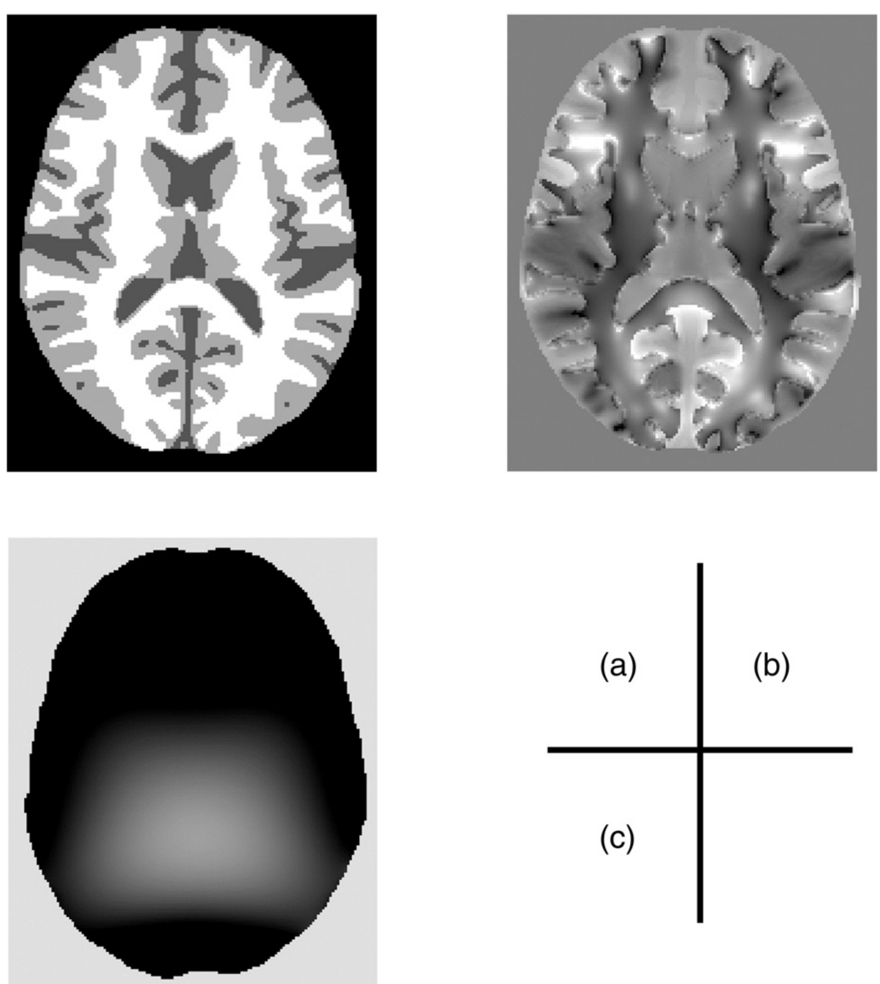

Fig. 1. Illustration of 3D head phantom created from MNI152 T1-weighted structural template image. (a) Simulated susceptibility source segmented to white matter, gray matter, cerebral spinal fluid. (b) Local field calculated by convolution of simulated susceptibility and dipole kernel. (c) Simulated background field.