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Artifactual microhemorrhage generated by SWI processing

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Abstract

Purpose—To report that artifactual microhemorrhages are introduced by the 2D homodyne filtering method of generating susceptibility weighted images (SWI) when open-ended fringelines (OEF) are present in phase data.

Materials and Methods—SWI data from 28 traumatic brain injury (TBI) patients was obtained on a 3T clinical Siemens scanner using both the product 3D gradient echo sequence (GRE) with GRAPPA acceleration and an in-house developed segmented echo planar imaging (sEPI) sequence without GRAPPA acceleration. SWI processing included (1) 2D Homodyne method implemented on the scanner console and (2) a 3D Fourier-based phase unwrapping followed by 3D high pass filtering. Original and enhanced magnitude and phase images were carefully reviewed for sites of type III OEFs and microhemorrhages by a neuroradiologist on a PACS workstation.

Results—Nineteen of 28 (68%) phase datasets acquired using GRAPPA-accelerated GRE acquisition demonstrated type III OEFs. In SWI images, artifactual microhemorrhages were found on 17 of 19 (89%) cases generated using 2D homodyne processing. Application of a 3D Fourier-based unwrapping method prior HP filtering minimized the appearance of the phase singularities in the enhanced phase, and did not generate microhemorrhage-like artifacts in magnitude images.

Conclusion—The 2D homodyne filtering method may introduce artifacts mimicking intracranial microhemorrhages in SWI images when type III OEFs are present in phase images. Such artifacts could lead to overestimation of pathology, e.g. TBI. This work demonstrates that 3D phase unwrapping methods minimize this artifact. However, methods to properly combine of phase across coils are needed to eliminate this artifact.

Keywords

susceptibility weighted imaging; homodyne filter; phase unwrapping; microhemorrhage

INTRODUCTION

Susceptibility weighted imaging (SWI), allows superior detection of intracranial microhemorrhages (1–3). Since microhemorrhages are an imaging hallmark of traumatic brain injury (TBI), SWI is increasingly used to establish a diagnosis of TBI (4). Microhemorrhages are also identifiable in other pathologies (e.g amyloid angiopathy) (5). Particularly for small microhemorrhages, the lesions are mostly visible using SWI sequence with no corroborating pathology on other sequences (6, 7). Therefore, it is essential to minimize artifacts that can mimic microhemorrhages.

SWI combines information from magnitude and phase images to emphasize susceptibility contrast in a single image. Crucial to this process is accurate estimation of signal phase, which is wrapped on the interval $[-\pi, \pi)$. These wraps are referred to as fringelines which can be classified as a *closed fringeline (CF)* which forms a closed loop or traverse the image, or an *open-ended fringeline (OEF)* which terminates at a singularity (pole) within the image. CFs are natural consequences of phase measurement that can be removed through conventional path-following phase unwrapping methods. OEFs can be further separated into three types: 1) the Type I OEF occurs in areas with little or no signal (e.g. air) where phase is not properly defined; 2) the Type II OEF passes through sufficiently high signal area but ends in low signal areas (e.g. inner table of skull); and 3) the Type III OEF ends in a region of high signal where phase should be smoothly varying (8–12). Here we are concerned primarily with the type III OEFs which should not occur from actual data. Because the magnetic field is a continuous function, signal phase must by necessity be continuous as well. Thus, the type III OEF represents a non-physical process typically introduced by errors in reconstruction such as the incorrect phase combination from multi-channel data (9–12). In particular, combining phase images using adaptive combination or a complex summation may lead to incorrect phase images with singularities (10–12). Phase data from single channel acquisition do not demonstrate the type III OEF.

To generate an SWI image, the high frequency components of the phase image are combined with the magnitude image. Phase wraps are non-anatomic high frequency components which must be removed so that only high frequency components that derive from true anatomy are included in the image. In general, two methods are used to remove phase wraps and the background gradients in phase images. Homodyne filtering is a simple division between the original data and a low-pass (LP) filtered version of itself (13). Homodyne filtering bypasses the phase unwrapping process by removing large varying background gradients, which cause phase to exceed the $[-\pi, \pi)$ range and thus be wrapped. Alternatively, phase unwrapping followed by high-pass (HP) filtering restores anatomical phase by subsequently removing the phase wraps and background gradients (14–16). Fourier-based phase unwrapping takes advantage of the Fourier properties and trigonometric identities of the Laplacian operator to unwrap phase through computation in k-space, instead of voxel-by-voxel in image space (17). Although the Fourier-based method unwraps phase efficiently, the resultant phase has low frequency deviations from the true anatomical phase (15, 16). Subsequently, HP filtering followed by phase unwrapping removes the low frequency deviations.

Typically microhemorrhages are seen on both the magnitude and phase enhanced components generated by an SWI acquisition. We have found cases in which microhemorrhages were observed only on the phase enhanced SWI and not on the magnitude. The purpose of this paper is to determine whether these are artifactual, and if so, present methods to mitigate this artifact.

METHODS

SWI data were obtained from 28 TBI patients under an IRB-approved protocol using the 8-channel head coil on a 3T Siemens Biograph mMR system running syngo MR VB18P software (Erlangen, Germany). Written informed consent was obtained from all TBI patients. To generate SWI, magnitude and phase images were obtained using both 3D GRE and 3D in-house developed sEPI methods (18) in each patient. Geometric parameters were identical for both sequences: in plane resolution $0.5 \times 0.5 \times 2.0$ mm, matrix size 448×343 , 72 slice. Acceleration was achieved using GRAPPA $\times 2$ for the single echo GRE and an echo train length of 15 for the EPI without GRAPPA. To balance susceptibility weighting, a TE of 25 ms was used in both the GRE and sEPI. Other contrast parameters for GRE: TR 64ms /FA 20°, for sEPI: TR 40ms /FA 15°. Whole brain coverage was under 10 minutes using the GRE sequence and under 2 minutes using the sEPI sequence with the above imaging parameters.

Magnitude and phase images were saved for further SWI processing. Because the 2D homodyne filtering appeared to accentuate the phase abnormality at the OEF, we examined whether a different filtering method might prove less sensitive to this phase reconstruction artifacts. SWI images were generated from magnitude and phase data in two ways: 1) using the TWIX software (v. VB18P) on the Siemens scanner console which implements the 2D homodyne filtering and 2) applying 3D Fourier-based phase unwrapping followed by HP Gaussian filtering on the raw phase (15, 16) implemented in Matlab (R2012b).

After data acquisition and post-processing, SWI, filtered phase, and raw phase images were anonymized and sent to a clinical picture archiving and communications systems (PACS) (Carestream VuePACS 11.3). All images were reviewed on PACS by a CAQ neuroradiologist (17 years of experience, J.A.B.) for the presence or absence of punctate foci of signal loss on the magnitude images, SWI images, and correlated with the presence of singularities at the free ends of OEFs. Raw phase data from both GRE and sEPI acquisitions were examined slice by slice to determine whether or not type III OEFs were present. For each identified artifactual microhemorrhages, a 20 by 20 pixel zoomed in area in original and enhanced magnitude and phase images were further reviewed.

RESULTS

Review of the 28 TBI cases acquired from the Siemens scanner showed that type III OEFs were present in 19 (68%) phase datasets obtained using GRAPPA-accelerated GRE and in none of the phase datasets acquired using sEPI. Figure 1 shows example raw phase data from GRAPPA-accelerated GRE and sEPI acquisitions from two patients. While GRAPPA-accelerated GRE datasets demonstrated obvious type III OEFs, the corresponding sEPI

phase data show no evidence of such artifacts. Since type III OEF were only observed with parallel imaging using GRAPPA, this phenomenon was very likely due to the inaccurate phase combination from the multi-coil elements within the product reconstructions.

Figure 2 shows 4 examples of artifactual microhemorrhages generated by SWI processing applied to phase data with Type III OEFs. On the magnitude images, there are no foci of susceptibility induced signal loss to suggest microhemorrhage. Each corresponding phase image includes a phase wrap classified as a type III OEF. Applying homodyne filtering to this data created a pole at the free end of the OEF. In the final step of SWI processing, combining filtered phase data with the magnitude images introduced a punctate focus of hypointensity in each case. Such foci precisely mimic microhemorrhages. Note that no signal loss is present at all on the magnitude images. Inspection of the sites of type III OEFs in all cases demonstrated that artifactual microhemorrhages were generated on the homodyne filtering-based SWI images in 17 (89%) of the 19 cases. In these cases, the wrapped phase images show that artifactual microhemorrhages and the free ends of the OEFs corresponded.

For each case where we identified a focus of signal loss corresponding to the free end of the type III OEF, no corresponding signal loss was present on SWI generated using the sEPI sequence which had no type III OEFs. Figure 3 demonstrates 2 examples. Note that flow compensation was turned on for GRE acquisitions, which restored some image intensity flowing vessels.

Figure 4 compares the filtered phase images and phase enhanced SWI images processed using the standard 2D homodyne filtering approach and by using a Fourier-based phase unwrapping followed by 3D HP filtering. In contrast to the SWI images generated by the homodyne processing, the Fourier-based approach minimized or largely improved the artifactual appearance of a microhemorrhage. Although the Fourier-based approach still left some residual phase variation artifacts, they did not appear as microhemorrhages in the final SWI images. Upon closer inspection at the free end of an OEF in the 20×20 pixel zoomed in area, it is found that in most cases, the Fourier approach resulted in a smoothed, “bow-tie” or dipole-shaped area centered at the phase singularity (Figure 5), rather than the pole generated by the homodyne approach.

DISCUSSION

This study reports that SWI processing in which magnitude and phase information is combined following 2D homodyne filtering of phase data can introduce artifactual microhemorrhages that correspond to the free end of type III OEF. Since SWI processing using 2D homodyne filtering is in clinical use, radiologists should raise their attention when microhemorrhages are identified on SWI images, but are not found on the corresponding magnitude images. In such cases, retrospective inspection of the filtered phase images and even the raw (wrapped) phase images may be necessary. Because the production of the raw (wrapped) phase images is typically suppressed in clinical SWI processing, it is not typically feasible to check an SWI image against the raw phase data to confirm that a suspected microhemorrhage is not an artifact generated by OEF. It is theoretically possible that

microhemorrhages could be identified on phase images that are not at all identifiable on magnitude images, but we have not observed this.

Because phase is smoothly varying, type III OEFs cannot represent true phase. Type III OEFs typically result from the incorrect combination of phase from different coil elements in multi-element array coils (8–12). This study confirmed that these OEFs are indeed artifactual by demonstrating that the type III OEFs seen in the phase images obtained with GRAPPA-accelerated GRE were not present in the phase images obtained with sEPI. Since the same TE was used for both methods, the phase data should be very close. Observing type III OEF mostly when using GRAPPA acceleration than EPI acceleration suggests that this artifact is most likely related to the GRAPPA reconstruction. Because the comparable GRE sequence without GRAPPA was prohibitively long (~20 minutes), we were unable to obtain phase information from the identical sequence without GRAPPA. Nevertheless, it has been previously noted that both adaptive combine and a complex summation of phase across receiver elements can result in incorrect phase images with singularities (8). Correct phase combination can be enforced if a reference phase data set is obtained with a single coil (e.g. body coil) which overlaps each of the individual coil elements that need to be combined. Such recombination is employed in the SENSE algorithm, in which phase data from each individual coil is appropriately referenced to the body coil (19). Alternative phase combination strategies, such as unwrapping phase from individual channel prior the combination, may avoid these physically unrealistic phase artifacts.

Type III OEF may be difficult to unwrap using conventional path-following phase unwrapping approaches, which usually start at a manually selected seed point and progress by subtracting or adding 2π repeatedly. On the other hand, the Fourier-based method unwraps phase by solving for the Laplacian operator of the difference between the raw and unwrapped phase. Because the Fourier-based method handles the unwrapping globally, the free end of OEF is often resolved across a larger and smooth area, rather than the singularities which remain after applying the conventional phase unwrapping approaches. However, the Fourier-based method does not constrain the difference between the unwrapped phase and the raw phase as integer multiples of 2π . The numerically unwrapped results from Fourier-based method may deviate from the true phase by a small amount or a constant (16, 20). Fortunately, global phase shift or low frequency deviations may not be critical in SWI processing as the HP filtering substantially reduces the effects of low frequency phase deviation, leaving only the high frequency information in focus. The final SWI images using the Fourier based method appear very similar to SWI images processed using the traditional path-following phase unwrapping approaches (16).

One limitation of the current study is that there may be true microhemorrhages appearing only on SWI images but not on magnitude images. In our experience we have not observed this. Therefore the precise method of filtering for phase enhancement is not likely to alter sensitivity for microhemorrhage to a large degree and we have noted no overt differences between the methods outside the region of the OEF. Another limitation is the indirect characterization of the artifactual microhemorrhage. This study relied on comparing phase data using two different methods, i.e. sEPI and GRAPPA-accelerated GRE for obtaining phase data which should be very close. Type III OEFs appeared only with one method,

indicating that the GRAPPA-accelerated GRE was subject to errors occurring from the method of combining phase information across multiple coils. Obtaining raw phase data from the individual coil elements may directly demonstrate that the choice of coil combination resulted in the nonphysical fringelines and, hence, the artifactual microhemorrhages.

In conclusion, an artifact which mimics the appearance of intracranial microhemorrhage on SWI image results from 2D homodyne processing of phase data when type III OEF are present is described. Since SWI detects microhemorrhages that cannot necessarily be confirmed on other sequences, one must be cognizant of this artifact to avoid overestimation of pathology, particularly TBI. Implementation of 3D unwrapping methods prior HP filtering may minimize this artifact. However, correct combination of phase information from multiple receiver elements to avoid type III OEF is the best solution to this problem.

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Figure 1.

Example phase data from axial images at the level of the basal ganglia in one patient (*right column*) and at the level of the cerebellar nuclei in a different patient (*left columns*) acquired using GRAPPA-accelerated GRE (*top row*) and sEPI (*bottom row*) demonstrate type III OEFs (*black arrows*) only on GRE. Actual phase data in regions of high signal should contain only CFs (*white arrowheads*) and Type II OEFs which traverse the portion of the image with high signal and terminate in regions of noise (e.g. skull) (*black arrowheads*).

Figure 2.

Original and enhanced magnitude and phase images computed using 2D homodyne filtering, as implemented on the clinical Siemens scanner from 4 different patients (*different rows*). Artifactual microhemorrhages (*black arrows*) are artifactually introduced through the filtered phase images (*black arrowheads*) to the SWI images at the precise location of the free end of OEF in the original phase image (*white arrows*). No microhemorrhage was found in the corresponding regions within the original magnitude image (*white arrowheads*).

Figure 3.

Comparison of SWI generated from GRE (*top row*) and sEPI (*bottom row*) acquisitions in two different patients (*A, B*). Magnitude images demonstrate no microhemorrhage. Artifactual microhemorrhages (*black arrows*) in GRE-based SWI images appear at the exact locations of the free end of type III OEFs (*white arrows*). Neither type III OEFs nor artifactual microhemorrhages was present in the corresponding sEPI-based phase and SWI images.

Figure 4.

Comparison of 2D and the proposed 3D SWI processing for 2 different subjects (*A, B*). Top rows are magnitude and SWI images. Bottom rows are original phase and filtered phase. In each case, no microhemorrhage is noted on the magnitude image (*white arrowheads*). The 2D homodyne SWI demonstrates an artifactual microhemorrhage (*white arrows*) corresponding to the singularity of the type III OEF (*black arrows*) in phase images. The 3D approach minimized the artifacts appearance in the enhanced phase (*black arrowheads*) and shows no evidence of artifactual microhemorrhage in SWI images (*grey arrowheads*).

Figure 5.

Original phase (A) and enhanced phases using 2D (B) and the proposed 3D SWI processing (C) zoomed in area with a type III OEF. An artifactual microhemorrhage artifact is presented at the center of the 2D homodyne filtered phase. The 3D unwrapping-HP filtering approach minimizes the artifact and possesses a smooth appearance around the phase singularity of the type III OEF.