High contrast susceptibility weighted imaging: Reliable Unwrapping Susceptibility Technique (RUST SWI) improved visualization of midbrain nuclei for deep brain stimulation

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Introduction

During deep brain stimulation surgery (DBS) for Parkinson Disease (PD), sterotactic guidance is used to insert stimulating electrodes by reference to pre-operative volumetric MRI datasets registered to the patient's brain. The target for stimulation is the subthalamic nucleus (STN), one of the midbrain nuclei implicated in Parkinsonian tremor. Iimproved visualization of the STN and other landmark midbrain nuclei including the substantia nigra pars compacta (SNc), substantia nigra pars reticulata (SNr) and red nucleus (RN), and important midbrain structures such as the cerebral peduncles (CP) is desirable to improve targeting of the electrodes during the first pass in order to increase patient safety and reduce the length and expense of the procedure by reducing the number of electrode adjustments required.

While it is now possible to obtain stereotactic T1-weighted image guidance datasets with the whole brain coverage required for stereotactic surgical navigation and sub-millimeter spatial resolution in under 10 minutes using radiofrequency (RF) spoiled gradient recalled echo sequences (SPGR, MPRAGE, etc), targeting of the midbrain nuclei remains problematic because of the poor image contrast in T1-weighted imaging between the nuclei and adjacent structures. The GRE pulse sequences are most widely used because they allow very fast acquisition of volumetric high resolution data. Unfortunately, the intrinsic R2* contrast between the nuclei revealed in these images are not adequate for optimal visualization of the nuclei, especially at 1.5 T.

Conventional image reconstruction techniques discard the phase information recorded in the imaginary term of the complex number matrix used to digitize the analog phase sensitive RF signal and base image reconstruction only on the magnitude data. SWI is an alternative image reconstruction method that saves and makes use of the phase data to produce a phase image exactly registered to the magnitude image reconstructed by the scanner console which is then recombined with the magnitude image. When SWI reconstruction is performed on T2*-weighted GRE data, the phase image can be inverted before recombination to produce an image in which the R2* image contrast is additive with the R1 or R2 contrast intrinsic to SPGR or GRE images respectively, taking maximum advantage of the intrinsic R1, R2 and R2* tissue contrast, without additional scan time or image registration issues.

Regardless of the SWI reconstruction technique used, a distinction is made between low spatial frequency magnetic susceptibility variation that predominantly arises from skull base, cranial sinuses, dental hardware and other nearby structures outside the brain parenchyma and high spatial frequency susceptibility variation that predominantly reflects the relatively smaller magnitude susceptibility shifts induced by heterogenous paramagnetic composition of the brain parenchyma. Since the midbrain nuclei in question sequester tissue iron and other metallic ions, the high spatial frequency phase data from midbrain images contains information that can be used to improve visualization of the midbrain nuclei. SWI reconstruction thus aims to remove susceptibility artifact in order to allow depiction of the high spatial frequency phase shifts (referred to a "phase contrast") in the final images without significant distortion or data loss.

Methods

Image data from three healthy volunteers was acquired with 0.94 x 0.94 x 1.00 mm voxel size using 3D SPGR T1WI, 3D GRE T2*WI, and 3D FSE T2WI on both 1.5T and 3.0T conventional MRI imaging systems (GE Medical Systems). The imaging echo time was 50 msec at 1.5 T, and 30, 40, or 50 msec at 3.0 T. Phase data from T2*-weighted imaging sequences was captured at the time of scanning, reconstructed off-line, and recombined with the magnitude images through two different implementations of SWI post-processing methods.

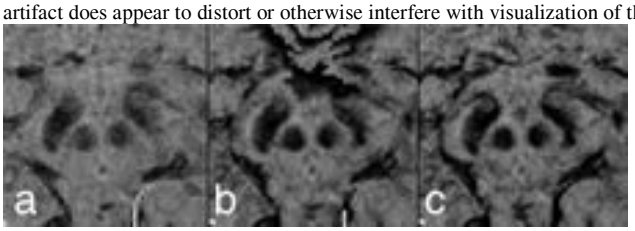
In the first SWI implementation, originally reported by Haacke et al. (Haacke SWI), the image domain background phase was estimated from central k-space data of matrix size 24 x 24, and this information was applied to remove the low spatial frequency components (phase artifacts) from the phase images. The remaining high-frequency phase data (phase contrast) is combined with the magnitude images to form the SWI. In the second SWI implementation, a reliable phase unwrapping SWI technique (RUST SWI) developed in house was first applied to eliminate the wrap-around effects from phase reconstructed images. The unwrapped phase images were then spatially smoothed for estimation of the low spatial frequency components. After thus mathematically removing the estimated low spatial frequency components, the remaining high-spatial frequency components in phase data set are extracted and then combined with the magnitude images.

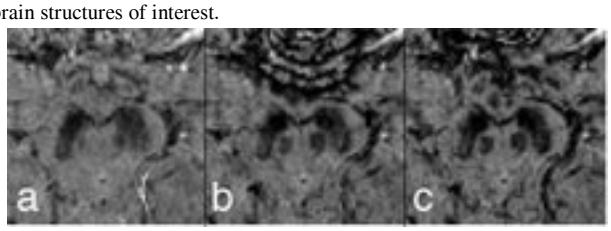
The recombined GRE-SWI, SPGR-SWI, and T2WI-SWI based on each of these two different SWI implementations were reviewed independently by both the participating neuroradiologist and imaging scientist and compared to the magnitude images from the source sequences. ROIs of the midbrain nuclei (SN and RN) were chosen, and imaging contrast achieved with conventional imaging methods and the SWI methods are compared quantitatively.

Results and Discussion

At both 1.5 T and 3.0 T, both SWI post-processing methods improve the imaging contrast between the midbrain nuclei of interest and the background brain tissue in comparison to conventional magnitude reconstruction of T2*WI, but image artifacts differ significantly between the two different implementations of SWI. For example, in a selected axial slice of the acquired 3D dataset, the 1.97 ratio signal instensity from the background brain tissue to that from the midbrain nuclei of interest (SN and RN) encountered in the magnitude reconstruction of conventional T2*-weighted SPGR images (magnified image in Figure 1a) was improved to 3.96 by Haacke SWI processing (Figure 1b), and further to 4.17 (Figure 1c) by RUST SWI processing.

Significant amplification of skull base phase artifacts is encountered in Haacke SWI images (Figure 1b). The qualitative effect of these artifacts differed significantly between volunteers, but as expected from the anatomic location of the midbrain near to the skull base and paranasal sinuses, in all cases the artifacts were located near to or actually involving the nuclei of interest. In one volunteer the artifacts partially obscured the midbrain nuclei, suggesting that in some patients artifacts may interferre with the use of SWI images to guide DBS surgery. In comparison, the RUST SWI images demonstrated significantly reduced phase related artifacts and slightly improved tissue contrast. The resulting overall image quality was felt to be significatly improved, as shown an axial slice with pronounced susceptibility artifact on Haacke SWI (Figure 2a magnitude GRE, Figure 2b Haacke SWI, Figure 2c RUST SWI). The background brain tissue to midbrain nuclei contrast was calculated to be 3.26, 7.69, and 7.90 in figures 2a, 2b and 2c respectively. As shown in Figure 2c, some minor residual phase related artifacts is encountered in brain regions affected by significant extra-parenchymal susceptibility field gradients despite RUST SWI post-processing, but in the volunteers scanned, this residual artifact does appear to distort or otherwise interfere with visualization of the midbrain structures of interest.





Summary & References By reducing artifact and improving image quality in volumetric imaging of midbrain nuclei RUST MRI may contribute significantly to MRI guidance of DBS.

1.Haacke EM et al. Magn Reson Med. 2004 Sep;52(3):612-8. 2. Rauscher A et al. J Magn Reson Imaging. 2003 Aug;18(2):175-80.