Improved contrast in multi-echo susceptibility-weighted imaging by using a non-linear echo combination

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Purpose: Susceptibility-weighted imaging (SWI) has proven to be useful in several clinical applications, notably for the assessment of iron deposition and the visualization of blood products[1]. Traditionally, SWI has been performed using a 3D single-echo gradient-echo sequence[2]. However, the relatively long echo time needed for sufficient susceptibility contrast leads to low SNR. More recently, the use of a 3D multi-echo gradient-echo sequence has been proposed as a way to increase SNR in SWI[3,4,5]. However, one concern with the use of a multi-echo acquisition is that the inclusion of information from short echo times containing less susceptibility contrast could dilute the targeted contrast. In this work, a new non-linear echo combination is introduced to optimize susceptibility contrast in multi-echo SWI. As shown both experimentally and analytically, the proposed approach provides enhanced susceptibility contrast when compared with previous single-echo and multi-echo approaches.

Methods: The proposed approach performs independent magnitude and phase echo combinations prior to phase masking. For magnitude images, a voxel-wise non-linear combination is employed and given by: $I = \sqrt[-p]{\frac{1}{N}\sum_{i=1}^{N} S_i^{-p}}$, where N is the number of echoes, S_i is the magnitude of the ith echo , $p > 1$ and typically $p = 2$. This combination puts emphasis on susceptibility contrast and it can be readily proven that the SNR of the combined magnitude image is governed by $\frac{\sum_i S_i^{-p}}{\sigma\sqrt{\sum_i S_i^{-2(p+1)}}}$,and Contrast to Noise Ratio (CNR) between two tissue signals Sa and Sb is calculated as SNR(Sa) - SNR(Sb). Phase images are first independently homodyne-filtered and then combined by using a weighted linear regression of the phase evolution as a function of the echo time[3]. The least-squares solution to that weighted linear regression is given by $\Delta\varphi = \frac{\sum_i S_i^2 \varphi_i TE_i}{\sum_i S_i^2 TE_i^2}$, where $\Delta\varphi$ is the phase variation in units of [rad/ms]. A final combined phase image, equivalent to that obtained from a single-echo sequence, is produced by multiplying $\Delta\varphi$ by a reference echo time (for example, TE = 20 ms at 3T). A phase mask is finally calculated from this combined phase image and multiplied with the combined magnitude image.

In vivo experiments were performed on a clinical Philips Ingenia 3T system. A 3D multi-echo gradient-echo acquisition (TR=28 ms , TE=6.9, 12.6, 18.3, 24.0 ms, resolution=0.6mm x 0.6mm x 2mm) and a 3D single-echo acquisition (TR=24 ms, TE=20 ms, same resolution) were performed. Images obtained with the proposed approach were compared to single-echo images and multi-echo images combined using existing approaches[4,5].

Results: Figure 1 displays magnitude images for a single-echo acquisition (a) and a multi-echo acquisition using a simple average (i.e. the mean image) (b), a sum-of-squares combination (c) and the proposed non-linear combination (p=2) (d). It can be observed that the proposed combination leads to improved susceptibility contrast at vessels in comparison to the other multi-echo algorithms, while providing a significant SNR gain with reference to the single-echo acquisition. A similar behavior can be observed for the final SWI images shown in Figure 2 for the single-echo acquisition (a), the average combination (b), the sum-of-squares combination (c), the averaged echo-by-echo SWI processing[4] (d) and the proposed approach (p=2) (e). The improved susceptibility contrast for the proposed approach can be assessed notably by the improved contrast for the deep gray matter nuclei. Figure 3 compares the CNR of the magnitude images between an arbitrary T2* value ranging from 5 ms to 100 ms and the T2* value of 50 ms (the typical value for White Matter) for the proposed and existing approaches using the above sequence.

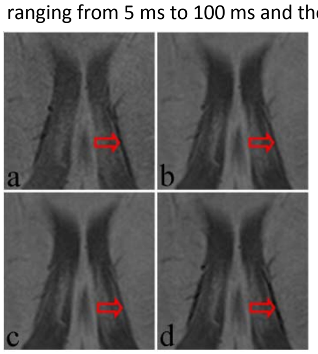

Figure 1: Magnitude image for a single-echo acquisition (a) and the multi-echo combinations investigated (b-d).

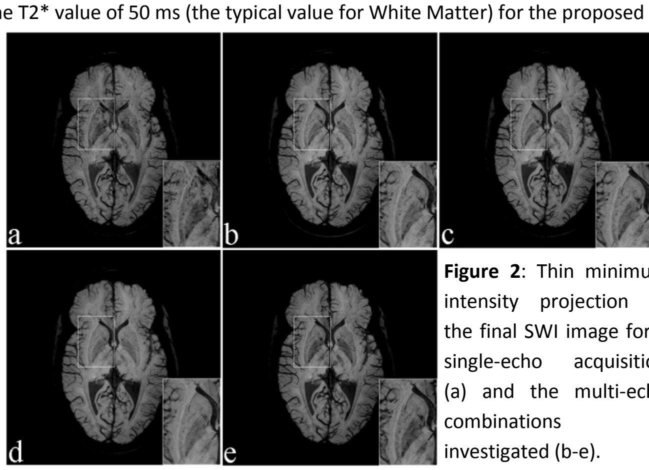

Figure 2: Thin minimum intensity projection of the final SWI image for a single-echo acquisition (a) and the multi-echo combinations investigated (b-e).

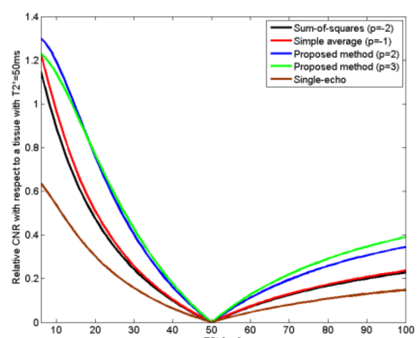

Figure 3: Comparison of theoretical CNR of the combined magnitude images between an arbitrary T2* value and the T2* value of 50 ms (typical WM) in different approaches.

Discussion and Conclusion: In this work, we have introduced a new multi-echo SWI approach and have derived the analytical SNR. As shown from the examples using the 3T data, this proposed multi-echo SWI approach provides enhanced susceptibility contrast in comparison to existing single-echo and multi-echo approaches.

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