Enhancement of Venous Vasculature in the Brain with Multi-Scale Filtering

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Introduction: Conventional susceptibility weighted imaging (SWI) provides remarkable venous contrast with the use of both magnitude and phase images [1]. However, artifacts arise in the phase mask in regions with severe field inhomogeneity due to the off-resonance effect. Minimum-intensity projection (mIP) is commonly used for the display of 3D SWI data because of the negative venous contrast. The low intensity in air or bone results in the loss of brain tissue signal in the peripheral brain regions in the mIP display [2]. In this study, we present a novel approach based on a 3D multi-scale filter to enhance the venous vasculature by using magnitude images alone. Using this approach, the resulting venography is not sensitive to rapid phase variation in regions with severe field inhomogeneity. The venous vasculature has positive venous contrast in the filtered venography. The veins in the peripheral regions of the brain can be properly displayed using the maximum-intensity projection (MIP) of the filtered 3D venography.

Methods: A 4-echo flow-compensated 3D gradient-echo pulse sequence was used to acquire SWI dataset on a GE 3T scanner with a matrix size of 256x256x32 and TE1/TE2/TE3/TE4/TR/α=8.1ms/16.3ms/24.4ms/32.5ms/42ms/14^o. The field-of-view was 22$\times$22cm and the slice thickness was 1.6mm. The scan time was 5 min and 50 sec. Zero padding was applied along the slice direction to obtain a matrix size of 256x256x64. Fifty-six slices were used in the mIP or MIP display after removing the top and bottom 4 slices to avoid wrap-around artifacts. Conventional SWI processing was applied on the data with a 48$\times$48 high-pass filter. At each scale of the 3D multi-scale enhancement filter, eigenvalue analysis of Hessian matrix was used to enhance veins. Hessian matrix was a 3x3 matrix based on second order derivatives of magnitude images, which was defined as a convolution with normalized derivatives of Gaussian function. Given the eigenvalues of Hessian matrix of $|\lambda_1| \le |\lambda_2| \le |\lambda_3|$, three quantities had been used as similarity measures to a line structure [3]: $R_A = \lambda_2 / \lambda_3$, $R_B = |\lambda_1| / \sqrt{|\lambda_2 \lambda_3|}$, $S = \sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}$. V=0 for $\lambda_2 < 0$ or $\lambda_3 < 0$. Otherwise $V = \left(1 - \exp\left(-R_A^2 / 2\alpha^2\right)\right)\exp\left(-R_B^2 / 2\beta^2\right)\left(1 - \exp\left(-S^2 / 2c^2\right)\right)$, where α, β and c were set to 0.5, 0.5, and 0.5max(S). Four scales were grown according to power law rule ($\sigma_0 \times 1.2^n$, n=0, 1, 2, 3), where σ_0 was set to 1.0. The maximum response over all these 4 scales was selected at each voxel.

Results: A phase mask was obtained using a 48$\times$48 high-pass filter. Figure 1 shows the mIP of conventional SWI at TE=16.3ms (a) and TE=24.4ms (b). The contrast of the veins and the severity of off-resonance artifact were increased at a longer TE. Figure 1 also shows the MIP of 3D multi-scale filtered venography with positive venous contrast at TE=16.3ms (c) and TE=24.4ms (d). Off-resonance artifact observed in conventional SWI in the brain regions with severe field inhomogeneity, as indicated by an arrow in Fig. 1b, was removed in Fig. 1c and 1d. The MIP display of the filtered venography in Fig. 1c and 1d does not suffer from the signal loss observed in the peripheral regions of the brain in Fig. 1a and 1b.

Discussion: This study demonstrates that the venography generated using the proposed 3D multi-scale filtering has minimal off-resonance artifact. With the positive venous contrast, the venography can be displayed using MIP without signal loss commonly seen in the peripheral regions of the brain in conventional SWI. MR venography with 3D multi-scale filtering substantially enhanced the visibility of the veins in the brain. The visibility of small veins in the filtered images acquired at TE=16.3ms was only slightly reduced compared to that in the filtered images acquired at TE=24.4ms.

References: [1] Haacke EM, et al., MRM 2004;52:612-8; [2] Jin Z, Xia L, Du YP. JMRI 2008;28:327-33. [3] Frangi AF, et al., MICCAI-98, LNCS 1496.

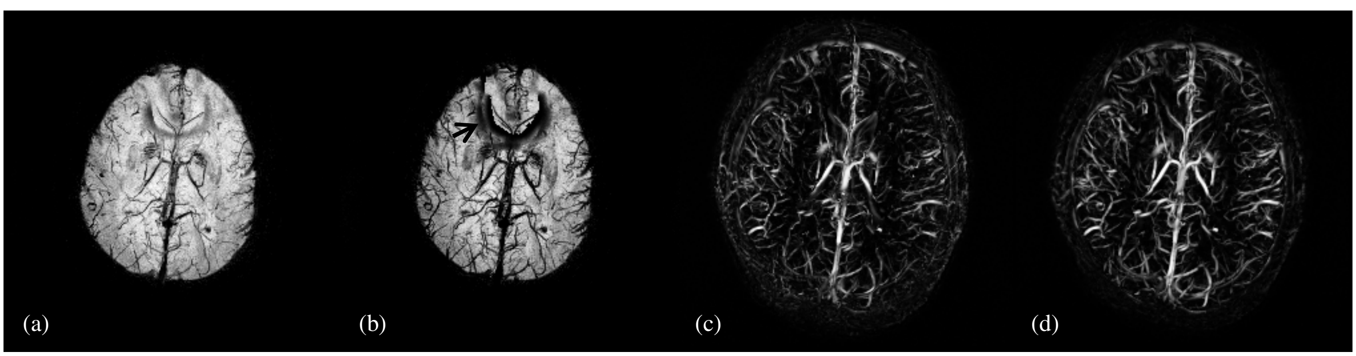

Fig. 1. mIP of conventional SWI at TE=16.3ms (a) and TE=24.4ms (b). MIP of 3D multi-scale filtered venography at TE=16.3ms (c) and TE=24.4ms