Quantitative Susceptibility Mapping of Intracranial Hemorrhage: Artifacts Reduction

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Purpose: Hemoglobin evolves into different forms during the evolution of intracranial hemorrhage (ICH) [1]. Quantitative susceptibility mapping (QSM) is sensitive to heme-iron contrast, enabling iron tracking of ICH [2]. However, in cases of insufficient T2* signal intensity, which is common in the acute stage, QSM of ICH presents a challenge to current reconstruction methods, resulting in overwhelming artifacts [3], particularly in cases of standard susceptibility-weighted imaging (SWI) using a single long echo. Here we propose a masking dipole inversion and superposition QSM reconstruction method to reduce these artifacts associated with ICH.

Methods: Nine patients with ICH at different stages were scanned using the 1.5 T clinical stroke protocol that included standard 3D SWI: TE/TR 40/49 ms, voxel dimensions 0.72 x 0.72 x 1.9 mm, 320 x 256 x 72 matrix, 15˚ flip angle, parallel imaging with 2-fold GRAPPA, 1st order flow compensation, scan time 5.9 mins. The raw data was saved, enabling QSM reconstruction off the scanner.

A numerical simulation was also performed using a customized 3D Shepp-Logan phantom (256^3) with magnitudes and susceptibilities assignments, including a 3D bean-shaped structure (extracted from an in vivo dataset) modelling a hemorrhage with low magnitude (10% of background) and strong susceptibility (1.5 ppm) as shown in Fig. 1. Phase map was forwardly calculated with TE of 40 ms at 1.5 T, after downsampling k-space to 3/4 size (192^3) and adding complex Gaussian noise with variance of 0.01, to simulate resolution and noise effects.

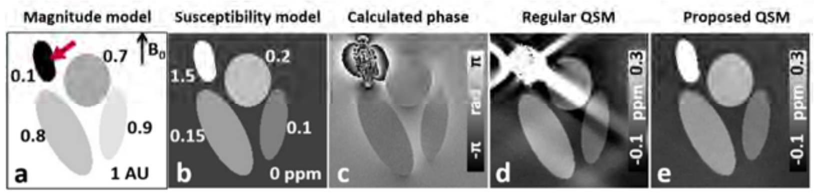

Fig. 1: Numerical simulation models and QSM results of regular and masking inversion.

The proposed masking and superposition QSM reconstruction scheme is shown in Fig. 2. Phase images were unwrapped using the best path 3D unwrapping method [4]. Local phase map ψ_{local} was obtained after removing air/tissue background using RESHARP [5]. An initial full brain susceptibility map χ_{local} was reconstructed with proposed masking dipole inversion method, incorporating a weighting matrix that nulls the unreliable phase of low MR signal in the data fidelity term:

$$argmin_{\chi}\ \|W(F^{-1}DF\chi-\Delta B)\|_2^2+\lambda\, TV(\chi).$$

The masking weighting matrix is generated as $W=|S|\cdot M_{brain}\cdot \widetilde{M}_{hemo}$, where $|S|$ is the signal magnitude; M_{brain} is the brain tissue mask from Brain Extraction Tool; $\widetilde{M}_{hemo}$ is the hemorrhage mask with regions of low signal intensity assigned to zeros while others one. Low intensity is defined as lower than 40% of the median intensity, after smoothing the magnitude images. A superposition method was proposed to further suppress the artifacts as: (1) Dipole field from the hemorrhage ψ_{hemo} was modelled and removed from the remaining field, using RESHARP applied a 2nd time on $\widetilde{M}_{hemo}$ that treats the hemorrhage as the background source; (2) Susceptibility inversion was carried out restrictively on the remaining field ψ_{rem}, leading to a susceptibility map χ_{rem} excluding the hemorrhage; (3) Susceptibility of the hemorrhage from the previous full brain susceptibility map χ_{local} was extracted and filled back, composing a superposed full brain susceptibility map χ_{super}.

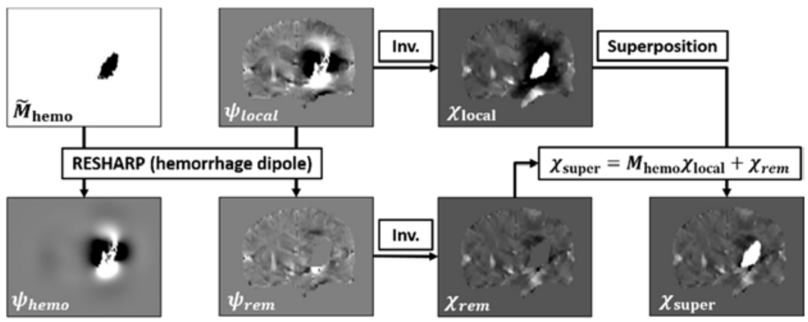

Fig. 2: QSM reconstruction steps of ICH using proposed superposition method.

Results: As shown in the simulation results (Fig. 1), there are significant amount of phase errors inside ICH (c), which lead to streaking artifacts using regular QSM reconstruction (d). However, with proposed masking inversion method by nulling corrupted phase inside ICH, QSM artifacts are removed (e).

For in vivo experiments, the masking and superposition inversion method enabled significant artifact suppression in QSM of ICH for all nine patients, with two of the subjects illustrated. In Fig. 3, the hemorrhage is hypointense on gradient-echo magnitude (a), and the raw phase inside ICH looks random and unsolvable (b) just like as in the phase of phantom simulation (Fig. 1c). Regular QSM reconstruction leads to streaking artifacts from ICH and propagate a long distance (c), but are substantially reduced with masking and superposition method (d).

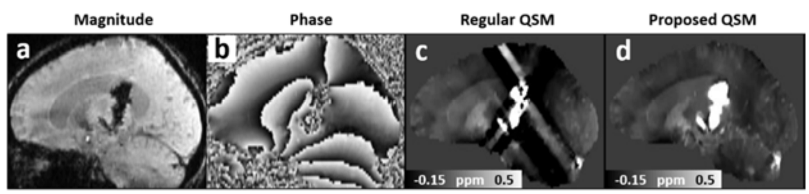

Fig. 3:QSM results of ICH in 79 yr old male, 2 days from onset, using regular QSM reconstruction compared with proposed masking and superposition inversion method.

A short TE (5.1 ms) SWI was compared with the standard long TE (40 ms) in Fig. 4. Regular QSM from long TE displays severe streaking artifacts from ICH (b), but are greatly reduced in masking and superposition QSM (c). A line profile across ICH from all three methods in the graph, shows that susceptibilities in ICH from masking and superposition QSM of long TE are similar to those of short TE QSM, which are considered as the true susceptibilities of ICH. The QSM from short TE was carried out using standard reconstruction, and streaking artifacts from veins are pointed by the arrows, due to the lack of flow compensation in order to achieve a short echo.

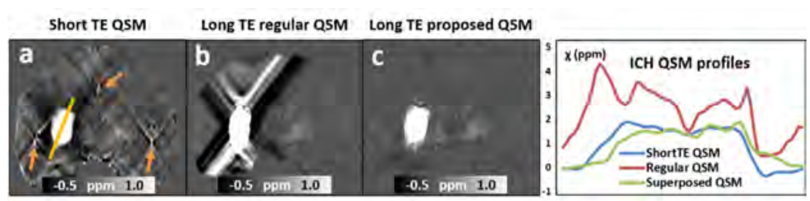

Fig. 4: QSM results of ICH in 72 yr old male, 2 days from onset, using short TE as the true susceptibility reference, and compared with long TE of two methods. Arrows point to streaking artifacts from veins (no flow compensation in short TE). Profiles (orange line in a) of three methods are shown in the graph.

Discussion: Low signal intensity and poor SNR in ICH can lead to errors in phase measurements, which can be largely amplified after ill-posed susceptibility inversion, causing large streaking artifacts using regular QSM method. With our proposed method, the corrupted phase within ICH are masked from inversion and the ICH dipole effect was also isolated, preventing contamination in non-hemorrhage regions. However, due to the erosion of the hemorrhage mask from RESHARP, artifacts presented in initial full brain susceptibility of eroded areas are filled back during the superposition step. In addition, even in short TE QSM, some degree of artifacts from ICH are still observed, which requires further understanding of its origin. Short TE SWI, with sufficient T2* signal intensity, can be helpful for QSM of ICH, however it does not provide subcortical GM susceptibility contrast due to lack of phase evolution. In addition, many clinical protocols still use a single long TE SWI for microbleed detection.

Conclusion: A masking inversion and superposition method was proposed for QSM of ICH, resulting in vastly improved susceptibility maps in cases of low MR signal intensity within ICH. Susceptibility values of ICH from standard long TE using proposed QSM reconstruction were similar to short TE QSM.

References: [1] WG Bradley, Radiology, 1993;189(1):15-26. [2] T Liu, MRM, 2013;69(2):467-76. [3] H Sun, ISMRM 2014, #0898. [4] HS Abdul-Rahamn, App. Opt., 2007;46(26): 6623-35. [5] H Sun, MRM, 2013;71(3):1151-7.