

Quantitative Susceptibility Mapping of Intracranial Hemorrhage: Clinical Results and Numerical Simulation

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Purpose: Quantitative Susceptibility Mapping (QSM) in intracranial hemorrhage (ICH) presents a challenge to current reconstruction methods due to intense susceptibility, variable magnitude signal and rapid, early changes in the form of iron. Nevertheless, QSM would be a valuable tool to track susceptibility changes in ICH, but further understanding of the capability and robustness is needed for this application. Recent QSM works in hemorrhage have evaluated QSM volume with echo time variation [1], and its capability of distinguishing iron from calcium [2]. Our purpose was to determine the potential of QSM in ICH, by performing clinical QSM studies in comparison to standard MRI and x-ray CT, and by performing a numerical simulation to understand QSM artifacts.

Methods: *Patient studies:* Nine patients (mean age 76) with ICH were studied mainly at the late subacute and chronic stage (time from hemorrhage 7 to 90 days). Each patient had a standard 1.5 Tesla brain MRI exam including Susceptibility-Weighted Imaging (SWI). Raw data from the SWI was saved allowing offline computation of QSM. X-ray CT scans were also collected on most subjects. The SWI sequence was a 3D gradient echo with 8 element head coil (15° flip angle, TE/TR 40/49 ms, voxel dimensions 0.72 x 0.72 x 1.9 mm, 320 x 256 x 72 matrix, parallel imaging GRAPPA, slice and read 1st order flow compensation, scan time 5.9 mins). QSM images were reconstructed using a previous described processing scheme [3], including proper coil combination, phase unwrapping, first order polynomial fit receiver phase offset removal, RESHARP background phase removal, and total variation susceptibility inversion. QSM results in ICH were compared to standard MRI and to CT scans obtained earlier in the course of disease (2 days or greater before MRI). QSM results were examined for artifacts and susceptibility values in ICH were measured through 2D region-of-interest analysis.

Numerical simulation: Two models of simulations were performed to examine the effects of intense susceptibility, low signal magnitude and limited voxel dimensions on QSM, to gain insight into findings from patient studies. A 3D Shepp-Logan phantom (256³) with simple ellipsoid structures inside was created, modeling iron-rich deep grey matter (susceptibility: 0.2 ppm and magnitude: 80% of background tissue) and a hemorrhage (susceptibility: 2.0 ppm and two magnitude intensity models, (1) only 10% of background (model 1) and (2) the same as background (model 2)). Susceptibility induced field was forward calculated [4] and the complex images were down-sampled to half size (128³) by truncating in k-space. Phase was measured by extracting the angle of down-sampled complex images. Susceptibility inversion was then performed on phase for both models.

Results: *Patient studies:* Averaging across all 9 subjects, the core susceptibility in ICH was ~8 times greater than iron-rich globus pallidus, exceeding it by 1.42 ± 0.29 ppm. Example ICH studies are shown in Figs 1 and 2, illustrating a small and large ICH. Fig. 1a, b, and c show a small hemorrhage in CT, T2* weighted magnitude and QSM. Fig 1d shows subcortical nuclei for comparison. In Fig. 2, a large hemorrhage is observed as hyperintense on CT (2a) and hypointense on T2* (2b). Measured raw phase (2c) is highly variable due to the low magnitude signal. The QSM derived from this phase displays artifacts inside and outside the hemorrhage that propagate in streaking patterns.

Numerical Simulation: Susceptibility and magnitude models are shown in Fig 3. Forward calculated phase (Fig. 3), simulating 40 ms echo time at 1.5T, shows highly variable errors inside the hemorrhage in model 1 (low magnitude signal) as compared to model 2. Susceptibility map displays non-uniformity inside and also dark artifacts surrounding the hemorrhage in model 1 as compared to model 2. After eliminating phase errors inside the hemorrhage in model 1 and keeping only the dipole field outside, susceptibility of hemorrhage improves significantly.

Discussion: When the hemorrhage is relatively small, phase errors inside are negligible compared to the large dipole fields outside, producing acceptable QSM results without major artifacts. However, if the hemorrhage is large with substantial magnitude signal loss, measured phase can no longer represent the actual field perturbation, resulting in unsolvable phase inside the hemorrhage and susceptibility maps showing severe streaking artifacts. Not only do these artifacts make susceptibility measurements of hemorrhages inaccurate, they also contaminate distant structures, such as subcortical deep grey matter. For simple structures, eliminating phase inside the hemorrhage can improve QSM. However, eliminating phase inside hemorrhage and only fitting the dipole field outside can be problematic for large complicated-shaped hemorrhages. Future studies can evaluate short echo times to reduce the T2* decay in hemorrhage. More advanced QSM reconstructions accounting for phase errors are also needed.

Conclusion: This study examined QSM of ICH using a standard SWI acquisition. Artifacts from patient studies were largely explained by numerical simulation. QSM for ICH remains promising. However, current QSM reconstruction often failed due to the signal decay in magnitude and the inaccuracy of measured phase to represent the actual field perturbations.

References: [1] Chen W. Radiology (2013) PMID: 24126366. [2] Wang S. Stroke (2013) 44(8):2315-7. [3] Sun H. MRM (2013) doi: 10.1002/mrm.24765. [4] Salomir R. Concepts MRB MRE (2003) 19:26-34.

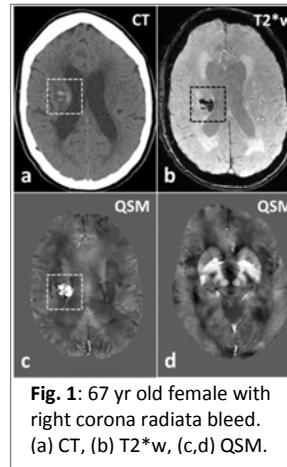


Fig. 1: 67 yr old female with right corona radiata bleed.
 (a) CT, (b) T2*^w, (c,d) QSM.

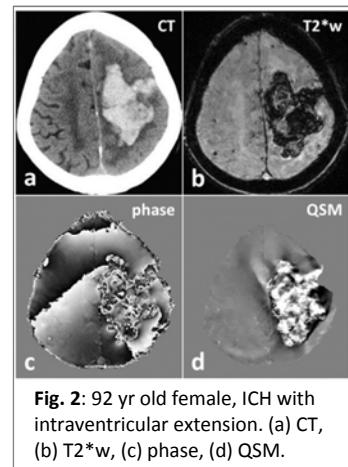


Fig. 2: 92 yr old female, ICH with intraventricular extension. (a) CT, (b) T2*^w, (c) phase, (d) QSM.

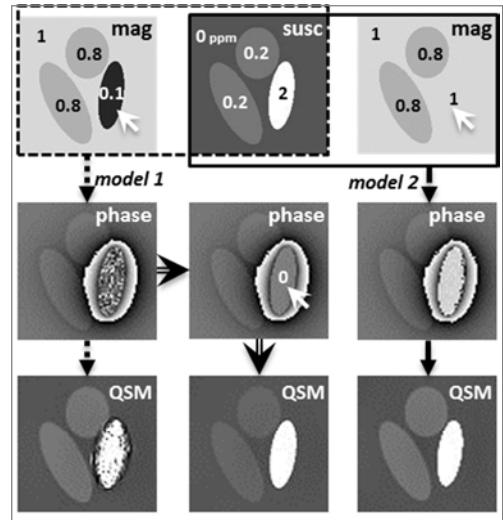


Fig. 3: Two hemorrhage (white arrow) simulation models (boxes) of different magnitudes. Phase and QSM of each model are shown following black arrows. Effects of nulling phase inside hemorrhage are shown in the middle column.