On the feasibility of QSM in MR-invisible regions

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Target Audience: Researchers interested in Quantitative Susceptibility Mapping (QSM).

Purpose: QSM has the potential to probe MR-invisible objects, based on the effect of their magnetic susceptibility on the nearby B_0 field in MR-visible regions. A technique was recently introduced to map susceptibility in MR-invisible tissues by extending a previous QSM method[1]. However, the fundamental ability to map magnetic susceptibility of MR-invisible objects based on nearby B_0 measurements has not yet been well characterized. ***The purpose of this work is to characterize the feasibility of QSM in MR-invisible objects*** with a specific focus on two cases of different difficulty: 1) the case where the MR-invisible object is assumed to possess homogeneous (although unknown) susceptibility, and 2) the case where the object may have spatially-varying susceptibility (and thus mapping of the spatial susceptibility distribution is desired).

Methods: Scanning was performed in a 1.5T clinical scanner (GE HDxt, GE Healthcare) using a 3D multi-echo spoiled gradient echo pulse sequence[2] (FOV=41.0 cm, slice thickness=2.5mm, 56 slices, matrix=224×224, TE_{init}=1.5, ΔTE=2.6, TR=16.6ms, 6 echoes/TR, and flip angle=5°) in order to provide measurements of the B_0 field map and R2*. Five cylindrical vials, each with ***homogeneous magnetic susceptibility***, were built using Gadolinium (MultiHance, Bracco Diagnostics, Princeton, NJ) solutions (0%, 1%, 2%, 3%, 4% by volume) in deionized (DI) water. A sixth vial with ***heterogeneous magnetic susceptibility*** was built by inserting a balloon filled with 4% Gadolinium solution into the vial and filling the remaining volume of the vial with 2% Gadolinium solution. Vials were scanned one at a time while immersed in a DI water bath as depicted in Figure 1. Each vial was scanned in a fixed location within the bath. An initial scan of the 0% vial was used to provide a B_0 field reference to enable removal of background B_0 fields.

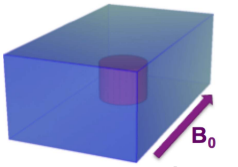

Fig 1: Experimental setup.

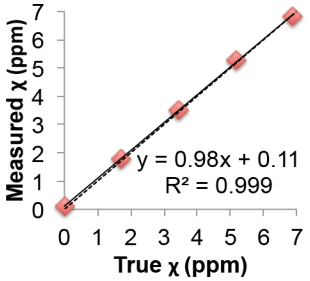

Fig 2: Susceptibility (relative to the surrounding DI) measured in vials with homogeneous Gd concentration using B_0 measured in surrounding regions (but not in the vial itself). The constant susceptibility in the vial can be estimated very accurately.

In order to simulate QSM in MR-invisible regions, the location of the vial was masked based on the R2* map of the 2% vial scan, and the susceptibility in the vial was estimated using the B_0 field map measured in the surrounding water bath, after removal of the background B_0 background field using the 0% vial B_0 map. Additionally, the susceptibility of the vial using the entire B_0 map (including the vial itself) was also calculated for comparison. Susceptibility in the vial was estimated using both a homogeneous susceptibility assumption, as well as mapping susceptibility throughout the vial using l_2 smoothness regularization[3].

Finally, the ability to perform QSM in MR-invisible regions was characterized analytically using the singular value decomposition (SVD) of the linear mapping between susceptibility in a cylindrical vial, and the B_0 field measured in a surrounding region (replicating the experimental geometry in Figure 1). SVD analysis of the mapping between susceptibility in a vial and B_0 field in the entire region (vial and surrounding water) was also performed for comparison.

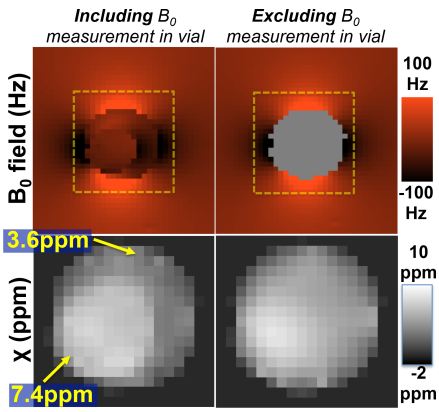

Fig 3: Susceptibility mapping over an MR-invisible region with heterogeneous susceptibility is challenging. (Top) B_0 map in and surrounding a vial with two compartments (different Gd concentrations). Using the B_0 measured both in the vial and surrounding region (bottom-left) the susceptibility map is able to distinguish the two compartments (estimated χ=3.6ppm and 7.4ppm; true χ=3.4ppm and 6.9ppm, respectively). However, the susceptibility map from the B_0 measured only in the surrounding region (bottom-right) is unable to distinguish the two compartments.

Results: Susceptibility estimation imposing constant susceptibility in the vial is feasible using only the B_0 field measured in the region surrounding the vial (Figure 2). Susceptibility mapping of heterogeneous susceptibility distributions is feasible using the entire B_0 field (including the vial) but challenging using only the B_0 field measured in the region surrounding the vial (Figure 3). SVD analysis demonstrates the different degree of ill-conditioning of QSM when including versus excluding the B_0 field values in the vial. If the B_0 field in the vial is excluded, there is a rapid decay of singular values, and information regarding localized susceptibility features far from MR-visible regions is largely lost (as depicted by the last few right singular vectors shown in Figure 4).

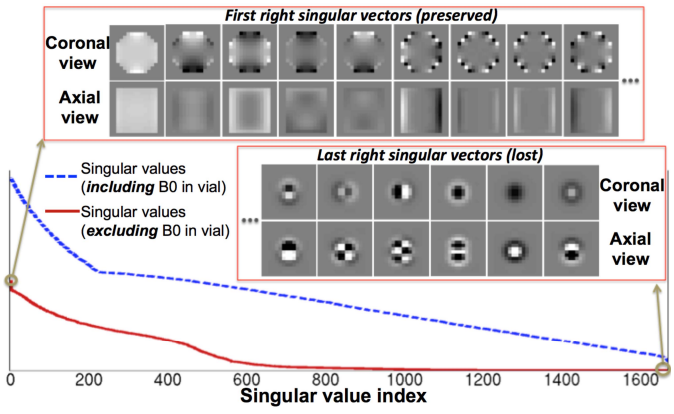

Fig 4: SVD analysis of susceptibility mapping in MR-invisible regions. Smooth susceptibility distributions over the entire MR-invisible region or localized susceptibility features near the MR-visible regions will be preserved in the measured B0 field map (high singular values), but localized susceptibility features away from the MR-visible region will be lost (small singular values).

Discussion: Susceptibility measurement may be feasible in MR-invisible regions. However, susceptibility mapping of spatially-varying susceptibility distributions is inherently challenging. Specifically, localized features away from MR-visible tissues (where B_0 can be measured) are difficult to recover. The proposed SVD analysis may prove useful for characterizing the ability to measure susceptibility in MR-invisible objects.

References: [1]Buch et al, MRM DOI: 10.1002/mrm.25350; [2]Meisamy et al, Radiology 258:767-775, 2011; [3]Wang et al, MRM DOI: 10.1002/mrm.25358.
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