Improving accuracy of susceptibility and oxygen saturation quantification of veins using correcting factor method

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Introduction: Mapping susceptibility from field perturbation data often uses a high pass filter to remove the low spatial frequency phase. The problem of doing this is that the high pass filter will result in a concomitant loss of important local phase information [1] and lead to decreases of susceptibility values inside vessels, especially for large vessels. In addition, as the increase of the filter size, the estimated susceptibility value will be decreased accordingly [2]. For a large vessel such as Superior Sagittal Sinus (SSS), when a 64×64 high pass filter is applied, the susceptibility value will decrease to only around half of the value without using high pass filter. If this susceptibility value is used to estimate oxygen saturation, we will obtain a totally wrong answer. To solve the problem of the underestimated susceptibility values due to using a high pass filter and to improve the accuracy of susceptibility quantification of veins, we propose a new method which uses correcting factor (CF) to automatically adjust the underestimated susceptibility value inside the vein. The underestimated susceptibility values will be completely compensated by the CF. An *in vivo* dataset from a healthy volunteer filtered by a 64×64 high pass filter was used to evaluate the effect of the CF algorithm. After using CF, the susceptibility values inside SSS increased 2.5 times and the oxygen saturation changed to 70% which is consistent with the value from a healthy person in most literatures.

Materials and methods: The steps of the correcting factor algorithm are illustrated in Fig. 1. Step-1: An initial estimate of the susceptibility map (SM), $\chi(r)$, is obtained by applying a regularized version of the inverse filter, $g_{reg}^{-1}(k)$ [3]. Step-2: Geometry of structures of interest i.e., venous vessels, are extracted from $\chi(r)$ and a constant susceptibility value, 0.45ppm, is assigned to the vessels, which is $\chi_{vm}(r)$ (part (b) in Fig. 1). The value of 0.45ppm was used since it is the susceptibility value for a hematocrit (Hct) of 0.45 and an oxygen saturation of 0.70. Step-3: Phase image $\Phi_{vm}(r)$ is obtained by applying a forward filter [4] to $\chi_{vm}(r)$. Then a homodyne high-pass filter [5] of size 64 is applied to $\Phi_{vm}(r)$ to obtain $\Phi_{vm\_HP}(r)$ (part (c) in Fig. 1). Step-4: $\chi_{vm\_HP}(r)$ is acquired by applying $g_{reg}^{-1}(k)$ to $\Phi_{vm\_HP}(r)$ (part (d) in Fig. 1). Step-5: Correcting factor map, *CF*(r), is obtained by dividing $\chi_{vm}(r)$ by $\chi_{vm\_HP}(r)$. *CF*(r) shows how many susceptibility values suppressed by using a high pass filter (part (e) in Fig. 1). Step-6: SM, $\chi'(r)$, with improved susceptibility values inside vessels, is obtained by multiplying $\chi(r)$ by *CF*(r) (part (f) in Fig. 1).

To understand the effect of the high pass filter to the susceptibility value, simulations were performed using standard geometries of cylinder. Phase images of a diameter 14-pixel cylinder, parallel to the main field, was simulated with $\Delta\chi$ of 0.45 ppm at a field value of 3T, as SSS is parallel to the main field. A series of size 8, 16, 32 and 64 high pass filter were applied to the simulated phase images.

To evaluate the efficiency of the CF algorithm, the susceptibility value inside SSS from a 0.5mm isotropic dataset was measured before and after using the correcting factor.

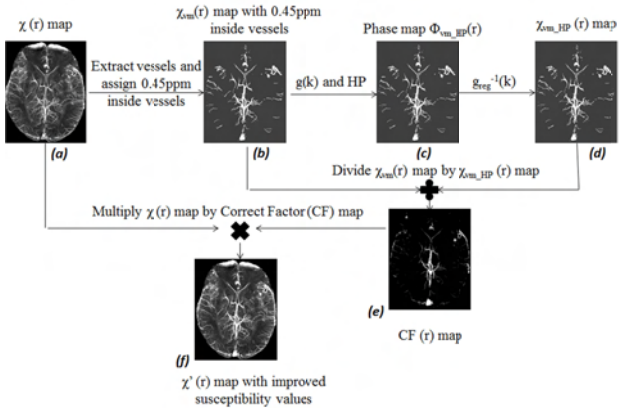

Figure 1: Illustration of the correcting factor algorithm to obtain improved susceptibility maps of veins.

Results:
Figure 2 presents the plot of susceptibility values inside the cylinder after applying different sizes of 8, 16, 32, 64 and 96 high pass filter, respectively. As can be seen, the quantified susceptibility value decreased as the increase of the filter size, especially when filter size is larger than 32, the susceptibility value will decrease dramatically. For the size of 64 or 96 high pass filter, it leads to 40% and 70% errors, respectively, in the quantified susceptibility value with respect to the actual value 0.45ppm. Fig. 3a and 3b show the comparison of MIPped over 32mm SMs before and after using the correcting factor algorithm from a 0.5mm isotropic resolution data with an echo time of 14.3ms and a 64 × 64 high pass filter. As can be seen, vessels in Fig. 3b are much brighter than those in Fig. 3a. Figure 3c is the associated CF map. In Fig. 3c, larger vessels are brighter than smaller vessels. This means larger vessels have a larger CF since a high pass filter has a larger effect to large vessels. We also notice, in Fig. 3b, that vessels have more consistent intensities compared to those in Fig. 3a. Quantitatively speaking, the mean susceptibility value inside SSS is only 0.184±0.058ppm before using the CF method and it changes to 0.464±0.159ppm after using the CF method, which corresponds to oxygen saturation level of 70%. The estimated oxygen saturation level matches the typical range of venous saturation level (65%-75%) for a healthy person.

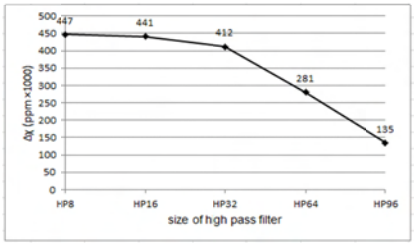

Figure 2: This plot shows the effect of high-pass filtering on the quantified susceptibility values. Results showed here are from filter size 8, 16, 32, 64 and 96 for a diameter of 14 pixels cylinder parallel to the main field. Errors in the quantified susceptibility values increase with the increasing filter size especially when the size is larger than 32.

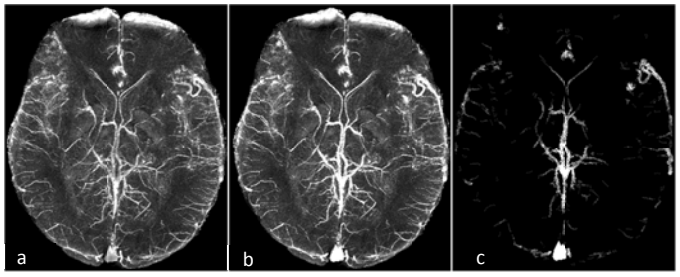

Figure 3: Comparison of MIPped over 32mm SMs a) before and b) after using CF from 0.5mm isotropic resolution data with an echo time of 11.6ms. c) The corresponding correcting factor map.

Discussion and Conclusions:
This unique correcting factor approach proposed here dramatically reduced the errors in the estimated susceptibility values in large vessels due to the use of a high pass filter. High pass filter is the most popular technique to process the data especially in clinic settings. The proposed CF method takes advantage of efficiency of the high pass filter and successfully solves the problem of the underestimated susceptibility value caused by the high pass filter. This approach can be applied not only for veins but also to other structures as well (e.g. basal ganglia structures) to improve the accuracy of susceptibility quantification. For this algorithm, successfully extracting vessel geometric information to produce a vessel map is critical, since this method can only adjust susceptibility values of the vessels inside the vessel map. If a vessel is failed to be extracted, the CF method is not applicable. In summary we present here a new method to improve the accuracy of the estimated susceptibility values. This method can be used for quantitative *in vivo* venous oxygen saturation measurement using SWI data.

References: [1] Haacke et al. J Magn Reson Imaging (2007) 16: 256-264. [2] Haacke et al. J Magn Reson Imaging (2011) 33:1527-1529. [3] Haacke et al. J Magn Reson Imaging (2010) 32:663-676. [4] Neelavalli et al. J Magn Reson Imaging (2009) 29:937-948. [5] Rauscher et al. J Magn Reson Imaging (2008) 26:1145-1151.[6] Spees et al. Magn Reson Med (2001) 45:533-542.