Investigating the effect of image resolution on susceptibility values inside the vessels for venous oxygen saturation quantification

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Introduction: Knowledge of venous oxygen saturation is important to characterize the physiological or pathological state of tissue function in the brain. Deoxygenated blood in veins is less diamagnetic than oxygenated blood, and relative to the surrounding tissue it appears to be paramagnetic, which makes it possible to detect venous oxygen saturation levels using quantitative susceptibility mapping (QSM). However, the susceptibility values inside the vessels are usually underestimated when using QSM [1]. Research in QSM has focused on conquering the ill-poseness of the inverse filter itself, rarely has attention been paid to the effect of image resolution on the accuracy of susceptibility quantification. This is the key to measuring oxygen saturation since partial voluming will dramatically decrease the estimated susceptibility inside the veins especially for small vessels (such as cortical veins) and lead to large errors in oxygen saturation. To understand the effect of image resolution on susceptibility inside different sized vessels, in this work we performed 3D brain model simulations. We compared these predictions using a 7T dataset with high resolution as described below. Additionally, sources of error in oxygen saturation quantification derived by QSM are also investigated.

Materials and Methods: In this study, we use a 3D model of the brain [1] to study how resolution will affect the quantification of oxygen saturation. The model includes vessels, basal ganglia structures, mid-brain structures, grey matter and white matter. The susceptibility ($\Delta\chi$) of all veins was set to 0.45 ppm (SI units). Here, 0.45 ppm represents venous blood when the hematocrit (Hct) = 0.44, $\Delta\chi_{do} = 4\pi \cdot 0.27$ ppm [2] and the oxygen saturation level = 70%, where $\Delta\chi_{do}$ is the susceptibility difference between fully deoxygenated and fully oxygenated blood [3]. $\Delta\chi$ for the remaining structures were assigned according to ref [1]. The phase simulations of the brain model were performed using a forward method [4-7] with Bo=7T and T_E=5ms. A short T_E was chosen to avoid phase aliasing that can affect the estimated susceptibility values. Simulation of the brain model and its induced phase was first performed using a 1024^3 matrix which represents $0.25mm^3$ image resolution. Lower resolution complex images, i.e., with resolutions of 0.25x0.25x0.25mm, 0.25x0.25x0.5mm, 0.25x0.25x1mm, 0.5x0.5x0.5mm, 0.5x0.5x1mm, 0.5x0.5x2mm, 1x1x1mm and 1x1x2mm, were obtained by using k-space cropping. *In vivo* studies were also carried out using a 7T Siemens scanner with a resolution of 0.25x0.25x1mm and T_E=10.3ms. The phase image was modified using a 96x96 high pass filter. The resolution of this data was also modified by interpolation to give 0.25x0.25x0.25mm and 0.25x0.25x0.5mm and then to 0.25x0.25x2mm by k-space cropping. Both the brain model and human data susceptibility maps were generated using a regularized inverse filter [8]. The mean susceptibility value was measured from the vein of Galen (VG), superior saggital sinus vein (SSS), left and right thalamostriate vien (LTV and RTV) and left and right septal vein (LSV and RSV) to evaluate the effect of the change of image resolution on the susceptibility values inside the veins.

Results: Figure 1 illustrates the change of susceptibility value inside larger veins (SSS and VG), medium sized veins (LTV, RTV and LSV) and smaller veins (RSV) from the 3D brain model (Fig. 1a) and the 7T data (Fig. 1b) with different image resolutions. For the 3D brain model, a very short echo time (T_E=5ms) was applied to avoid phase aliasing (which leads to reduced estimates for $\Delta\chi$) and T2* blooming. In the end, the decreased $\Delta\chi$ relative to 450 ppb mainly came from the inverse filter and partial voluming effects due to lower image resolution. As expected, image resolution has a large effect on smaller sized veins, for instance the RSV, due to more severe partial voluming. According to Fig.1a, to keep the same susceptibility value (around 0.4ppm) measured in the 0.25x0.25x0.25mm resolution image, for big veins (SSS), medium veins (LTV, RTV and LSV) and small veins (RSV), the image resolution should be no less than 0.5x0.5x2mm, 0.5x0.5x0.5mm and 0.25x0.25x0.5mm, respectively. For instance, for the RSV, in the 0.5x0.5x2mm resolution image, the estimated susceptibility value is only 0.22ppm (a 50% error). Fig.1b for the *in vivo* data shows the same trends as in Fig.1a. For most vessels, the susceptibility values are the same in the 0.25x0.25x0.25mm and 0.25x0.25x0.5mm images; the value only starts to decrease when the resolution is worse than 0.25x0.25x0.5mm and especially when it is worse than 0.25x0.25x1mm. We also notice that the susceptibility value measured from real data (Fig. 1b) is lower than the value measured from the brain model (Fig.1a). The highly underestimated susceptibility values for the smaller veins may be caused by two reasons; one is that a relatively long T_E (10.3ms) was used in the real data which leads to phase aliasing and blooming effects due to T2* decay and both of these can lead to a larger volume for the vein and hence a decreased susceptibility [8]; the other reason is that no high pass filter was applied to the brain model whereas a 96x96 high pass filter was applied in the real data which removed the local phase information and led to the underestimated susceptibility values [8].

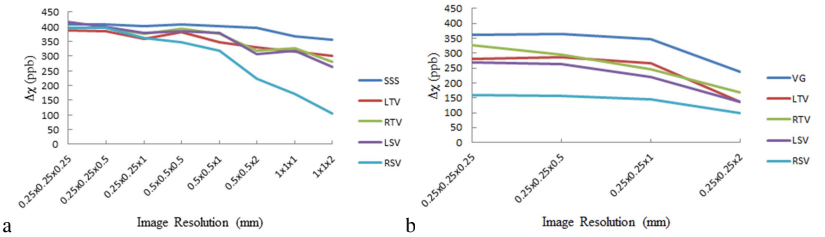

Figure 1: Estimated susceptibility values in different sized vessels in different resolution images from a) a 3D brain model and b) a 7T real dataset. VG: vein of Galen, SSS: superior saggital sinus vein, LTV: left thalamostriate vien, RTV: right thalamostriate vien, LSV: left septal vein and RSV: right septal vein.

Discussion and Conclusions: Image resolution is the major factor in accurately measuring oxygen saturation level with QSM. A deeper understanding of the effect of resolution on the susceptibility in different sized veins can help to decide what kind of resolution is needed to best quantify oxygen saturation in veins of a given size. For instance, if we only focus on large vessels, such as the SSS, a 0.5x0.5x2mm resolution is enough (Fig. 1a) and will save considerable scan time. For a relatively small vessel, such as the RSV, even with a 0.5x0.5x0.5mm resolution, we will expect to see around 30% error in the estimated susceptibility values (Fig. 1a). If phase aliasing exists due to a longer echo time or a large sized high pass filter or both, the error will become even bigger (Fig. 1b). This suggests that a short echo time should be used to collect the data if the main goal is to quantify oxygen saturation; moreover, a large high pass filter should be avoided and it would be more expeditious to use other sophisticated background field removal methods [9] to better preserve the phase information. In summary, the right choice of resolution is the key to quantifying venous oxygen saturation levels successfully when using QSM.

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