Background field removal based on local complex phase unwrapping and spherical mean value property

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Introduction

Quantitative Susceptibility Mapping (QSM) is valuable technique for quantification of iron or calcification content, and venous oxygen saturation (1-4). The quality of QSM relies on the accuracy in background field removal, since the original phase contains the component from the background field which is mainly induced by the air-tissue interfaces. Recently the SHARP method was proposed, which removes the background field based on the spherical mean value property of the harmonic functions (4). Phase unwrapping is generally required, which is usually a time-consuming procedure. Although phase unwrapping could be avoided by using the Laplacian of the field which could be calculated directly from the original phase (5, 6), the Laplacian based method has errors in regions with sharp phase changes, such as the edges of the veins (5, 6). Besides, the Laplacian of the field is equivalent to a spherical filter with radius of 1 pixel, may lead to reduced accuracy in the SHARP processed phase images (6, 7). In this study, we proposed a method which allows for using an optimal kernel size other than 1 pixel in SHARP without explicit phase unwrapping. This helps to reduce the processing time and improve the accuracy in background field removal using SHARP.

Theories and Methods

To remove the background field using SHARP, the difference (***B'***) between the field ***B*** and its local mean value $\boldsymbol{B_m}$ in a spherical VOI has to be calculated. This is a convolution process using a normalized spherical kernel, ***f***: $\boldsymbol{B'=B-B_m=B-B*f}$. Since $\boldsymbol{B=B_{local}+B_b}$, where $\boldsymbol{B_b}$ is the background field, and $\boldsymbol{B_b=B_b*f}$. Thus, $\boldsymbol{B'=B_{local}-B_{local}*f}$. The local field can be calculated from ***B'*** through a deconvolution using the kernel (***δ-f***). In the above calculations, the unwrapped phase ***P*** was used, and $\boldsymbol{B'=P'/(-\gamma B_0 TE)}$. For a given pixel, $\boldsymbol{P'=P-P*f=\Sigma[P(i,j,k)-P_s]/N}$, where $\boldsymbol{P_s}$ denotes for the pixels in the spherical VOI centered at ***P(i,j,k)***. Fundamentally, the difference between the phase of every pixel and the center pixel in the spherical VOI (***P'***) needs to be calculated. Assuming that $\boldsymbol{|P(i,j,k)-P_s|<\pi}$, and there is only one wrap within the spherical region, this phase difference can be calculated through complex division: $\boldsymbol{P(i,j,k)-P_s=arctan(exp(1i*(P-P_s)))}$. This suggests that it is possible to calculate this phase difference ***P'*** using the original phase $\boldsymbol{P_w}$. Since the phase images with wraps $\boldsymbol{P_w=P+2\pi n}$, so $\boldsymbol{\Sigma[P_w(i,j,k)-P_{w,s}]/N}$ equals ***P'***, if $\boldsymbol{n(i,j,k)=n_s(i,j,k)}$, or $\boldsymbol{P'\pm 2\pi m/N}$ when $\boldsymbol{n(i,j,k)=ns(i,j,k)\pm 1}$. $\boldsymbol{n_s(i,j,k)}$ denotes for the number of wraps for a certain pixel inside the spherical region. We only need to determine "***m***", the number of pixels where $\boldsymbol{n(i,j,k)=ns(i,j,k)\pm 1}$. This is done by counting the number of pixels where $\boldsymbol{|P_s(i,j,k)-P(i,j,k)|>\pi}$. Consequently, an initial estimate of ***P'*** could be calculated using the original phase images $\boldsymbol{P_w}$ through convolution and this estimate of ***P'*** will be corrected using ***m***. Then the local field could be recovered from ***P'*** through a deconvolution as it is done in SHARP. The proposed algorithm was tested on a 3D brain model, which has several basal ganglia structures, veins, grey matter, white matter and sinuses, with realistic susceptibility values. The air-tissue interface induced background field was simulated by assigning 9ppm to the sinuses. The field of this 3D brain model was calculated using the fast forward calculation. Phase images were generated at **TE=13ms**. Further tests were carried out on one *in vivo* dataset, which was collected with 0.5 isotropic resolution on a 3T SIEMENS VERIO scanner using 3D gradient echo sequence, with matrix size **512x384x224**, **TE=15ms**. The *in vivo* phase images were first unwrapped using Phun (8), when the traditional SHARP was used; while the proposed algorithm was directly applied on the original phase images with wraps. Same spherical kernel and regularization parameter were used in both the proposed and traditional SHARP. The kernel sizes were chosen to be **4** pixels and **6** pixels for 3D brain model and *in vivo* data respectively; while the regularization parameters were chosen to be **0.01** and **0.05** for the model and *in vivo* data respectively. Susceptibility maps were generated using the phase images processed with the proposed algorithm, for the *in vivo* data only, using the truncated k-space division with a truncation threshold of **0.1**.

Results

As shown in **Fig. 1.d** and **1.e**, the background field is removed very well except for some areas in the frontal regions which have rapid field changes. Besides, there is error associated with superior sagittal sinus, mainly because of the loss of the pixels near the edge. No high-frequency signal is noticeable in the error image (**1.e**). For the *in vivo* dataset, open-ended fringelines caused errors in the unwrapped phase image (**1.g**), and propagated into the SHARP processed phase images (**1.h**). But in the phase image processed using the proposed algorithm does not contain significant artifacts (**1.i**). In addition, the artifacts in the susceptibility map caused by the open-ended fringelines are not significant but still noticeable (**1.j**).

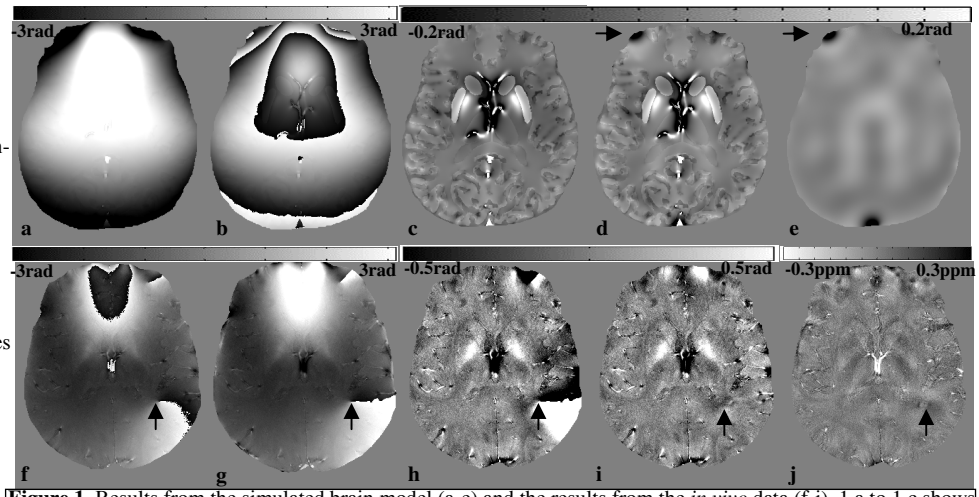

Figure 1. Results from the simulated brain model (a-e) and the results from the *in vivo* data (f-j). 1.a to 1.c shows the simulated phase with background field component (1.a and1.b), and the phase from local field variation(1.c).

Discussion and Conclusion

SHARP will be a very time-efficient for background field removal if the phase unwrapping can be avoided. Most best-path algorithms are time-consuming, and they cannot deal with open-ended fringelines. Formerly the Laplacian based SHARP was proposed to avoid phase unwrapping and to reduce the signal loss on the edge, but the accuracy of the processed phase images is also decreased. Recognizing that most parts of the brain do not have too rapid changed field, the SHARP algorithm could be constructed using original phase. This is based on local complex unwrapping. The proposed algorithm leads to almost the same results as the results generated by SHARP based on best-path phase unwrapping algorithm, except for regions near the edge where the field is changing rapidly and the underlying assumption of the proposed algorithm is violated. The *in vivo* dataset has a matrix size of 512x384x128, and the whole process takes around 2mins in MATLAB on a laptop with 8G of RAM. But the processing time and the requirement for available RAM will also increase as the matrix size increases. Besides, the proposed algorithm deals with the singularities in the phase images as good as the Laplacian based SHARP. Thus, this algorithm provides a time-efficient and robust processing scheme for phase data, and helps to improve the reliability of QSM.

References

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