FAST PARALLEL IMAGE RECONSTRUCTION USING SMACKER FOR FUNCTIONAL MAGNETIC RESONANCE IMAGING

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ABSTRACT

SMACKER is a method of calculating sensitivity maps from *k*-space reconstruction coefficients using only a few lines of inner *k*-space. In this method the problem of sensitivities ending at object boundaries is eliminated, unlike in other established methods. The method allows for the rapid calculation of sensitivity profiles from images, and it is proposed here that the approach can be used in functional MRI to obtain reconstructed images in little time. Functional MRI relying on fast parallel reconstruction techniques naturally lends itself to a method that can generate and use sensitivity maps directly from images.

***Index Terms*—** Parallel MRI, SENSE, GRAPPA, Sensitivity profiles

1. INTRODUCTION

Parallel imaging has been an emerging technique in MRI for many years, and in more recent years it has been widely used in functional MRI (fMRI) to generate images in less time, when compared to using a body radio frequency (RF) coil for both transmission and reception of the MR signal.

Imaging through the use of multiple RF channels allows for the acquisition of information in parallel, which promotes the ability to generate data in less time. Given that the acquisition time is reduced with multi-channel RF arrays, the image reconstruction also needs to be performed faster. To achieve speedup within the reconstructions, RF coil sensitivity profiles are used to assure that the image contrast is relatively uniform over the field-of-view (FOV) and that the information loss using distributed transmit receive coils is minimized. Parallel imaging supported by techniques such as SMASH, SENSE and SPACE-RIP [1-5] have been widely used in the past . These methods use the sensitivity of RF array coil elements as prior knowledge to reconstruct missing information, due to skipped phase encoding steps.

In parallel imaging separate calibration scans can be used to determine the RF coil sensitivity profiles, but these take up extra time, and therefore provide an undesirable time overhead to image acquisition. Self calibration techniques through the acquisition of additional *k*-space information have also been investigated by researchers [6-8]. In particular, GRAPPA is a general implementation of self-calibrating *k*-space theory, in which uncombined images are obtained for each RF coil [6].

Sensitivity map calculation from *k*-space reconstruction coefficients (SMACKER) is based on complex weighting factors similar to that used in GRAPPA. The complex weighting factors are obtained relative to other coils, and therefore they are ratios of relative sensitivities with respect to a reference coil. The calculated relative sensitivities combine with other established parallel imaging techniques to construct a reference image [1-5], which is generalized in [9]. Once the reference images have been obtained, then other RF coil element images are obtained by multiplying the reference image by the relative sensitivities as outlined in [10].

SMACKER provides relative sensitivity profiles with a smooth boundary between objects and image background. This poses an advantage over other methods [1, 3, 11, 12], in which the individual RF coil images are scaled by their sum-of-squares or by a body RF coil image. In SMACKER due to a smooth background, slight object motion during acquisition does not affect the image obtained through the reconstruction. In turn, SMACKER can be used in fMRI to obtain images fast, and without significant motion artifacts, which have been mentioned in [11]. In the following sections a brief outline of SMACKER is provided, and results are illustrated for a particular set of brain images.

2. THEORY

In this section the methodology of SMACKER is briefly outlined and a full detailed description is provided in [13].

Relative sensitivity profiles for RF coil element i with respect to coil element j can be obtained in a simple manner by comparing the fully sampled *k*-space image of coil i and coil j:

$$C_{ij} = \frac{I_i}{I_j} = \frac{C_i \rho}{C_j \rho} = \frac{C_i}{C_j}, \tag{1}$$

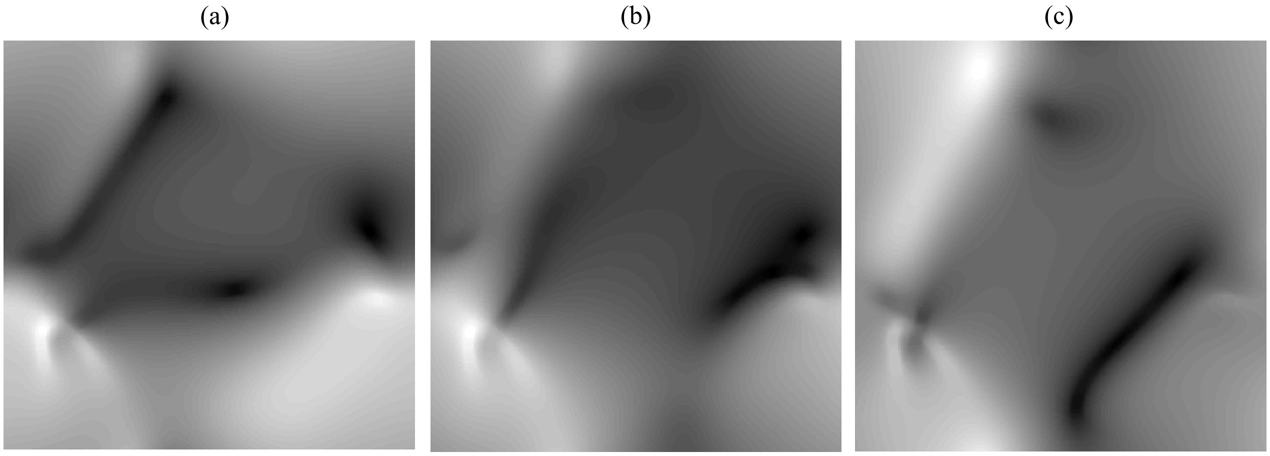

Fig. 1. The relative profiles are constructed using SMACKER with 41 centre reference lines of Fig. 2(d): (a) relative coil profile 2 with respective to coil 1, (b) relative coil profile 3 with respective to coil 1, and (c) relative coil profile 4 with respective to coil 1.

where, C is the sensitivity profile, I is the image and ρ is the relevant spin density. The method of constructing relative sensitivities in (1) is called Simple Full Data Division (SFDD), for which Larkman provided explicit descriptors for constructing reference data using a single coil or a combination of coils [14]. Simple Partial Data Division (SPDD), which provides the ability to use central *k*-space information to construct low resolution images, can also be used to construct the coil sensitivity profiles [15]. SFDD and SPDD provide a simplel way of constructing RF coil sensitivity profiles, but previous work of the authors in [13] show that in the image background, due to low signal-to-noise ratio (SNR), the SFDD and SPDD profiles are largely distorted. As a result, without special background treatment these approaches are not very useful. In SMACKER the RF coil sensitivity profiles are calculated using a few lines of inner *k*-space, eliminating the problem with sensitivities ending at object boundaries.

SMACKER sensitivity profiles are primarily based on the GRAPPA approach [6]. GRAPPA generates uncombined images for each of the RF coil elements, using a block-wise reconstruction technique for the missing *k*-space lines for each RF coil. By letting $S_j\left(k_x,k_y\right)$ be the magnetic resonance signal obtained using RF coil *j*, then the Fourier integral can be written in the form:

$$S_j(k_x,k_y) = \iint C_j(x,y)\rho(x,y)\mathrm{e}^{-\mathrm{i}(xk_x+yk_y)}dxdy. \qquad (2)$$

In discrete form, the signal obtained from RF coil *j* at line $k_y + m\Delta k_y$ offset from the normal acquired data in the *y*-coordinate direction is represented as:

$$S_j(k_x,k_y+m\Delta k_y) = \sum_{l=1}^{L}\sum_{b=0}^{N_b-1} w(j,b,l,m)S_l(k_x,k_y+bA\Delta k_y), \qquad (3)$$

where, A is the acceleration factor, L is the number of individual RF coils and N_b is the number of blocks used in the block-wise reconstruction, in which a block is defined by a single acquired line with $A-1$ missing lines. In (3) $\triangle k_y$ is the increment in k_y and *m* defines the current offset. Equation (3) resolves to L uncombined single coil images with weights $n\left(j,b,l,m\right)$ that can be recombined in a traditional manner using the sum of squares reconstruction.

SMACKER uses *k*-space elements for all coordinate directions (*x*, *y* and diagonal), and not only the *y*-coordinate direction as in GRAPPA represented in (3), to estimate the centre position. To allow for the additional coordinate direction and for a more generalized definition, a more complete form of (3) is written as:

$$S_j(k_x,k_y) = \sum_{l\neq j}\sum_{m,n} w(j,l,m,n)S_l(k_x+m\Delta k_x,k_y+n\Delta k_y) + \sum_{(m,n)\neq(0,0)} w(j,j,m,n)S_j(k_x+m\Delta k_x,k_y+n\Delta k_y), \qquad (4)$$

where, $w\left(j,l,m,n\right)$ are the complex weights and the minimum increments are defined as $\triangle k_x = 2\pi/\mathrm{FOV}_x$ for the *x*-coordinate direction and $\triangle k_y = 2\pi/\mathrm{FOV}_y$ for the *y*-coordinate direction in *k*-space. In (4) $w\left(j,l,m,n\right)$ is not used to estimate missing *k*-space lines as in GRAPPA, but to construct relative coil sensitivity profiles, then the acceleration factor A is not required.

Assuming that (4) holds for an arbitrarily spin density distribution ρ, then a set of linear equation can be derived as follows:

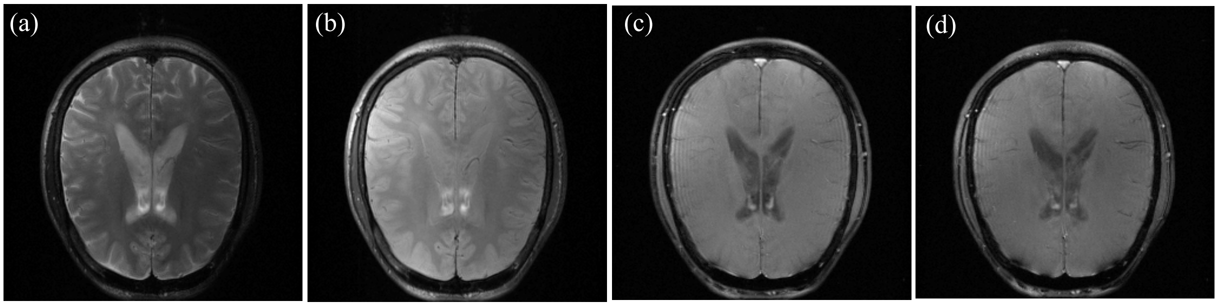

Fig. 2. The original scanned images using full acquisition, for (a) RARE 8, (b) RARE 4, (c) FLASH with TE = 5.5*ms* and (d) FLASH with TE = 10*ms.* Illustration (d) is used to construct relative sensitivity profiles.

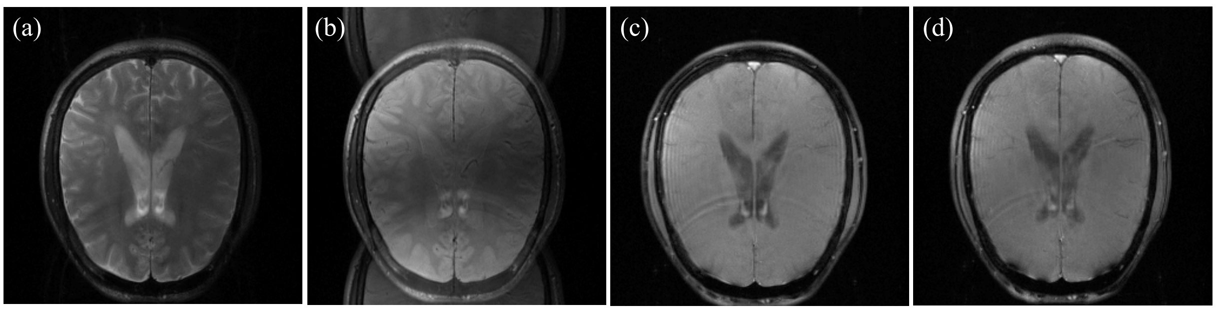

Fig. 3. The respective reconstructed images using GRAPPA with 41 centre reference lines.

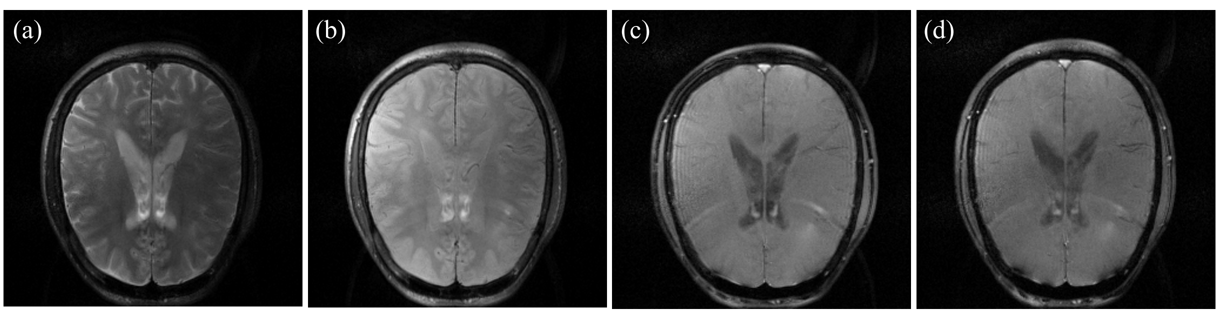

Fig. 4. The respective reconstructed images using the relative profiles from Fig. 1 and rSENSE.

$$\left(1-\sum_{(m,n)\neq(0,0)} w(j,j,m,n)\mathrm{e}^{-\mathrm{i}\left(xm\frac{2\pi}{FOV_x}+yn\frac{2\pi}{FOV_y}\right)}\right)C_j(x,y)- \sum_{l\neq j}\left(\sum_{m,n} w(j,l,m,n)\mathrm{e}^{-\mathrm{i}\left(xm\frac{2\pi}{FOV_x}+yn\frac{2\pi}{FOV_y}\right)}\right)C_l(x,y)=0. \tag{5}$$

Equation (5) is a system of linear equations from which the sensitivities of the RF coil elements can be solved at each point in the image space. The system of (5) is rank deficient, and therefore relative sensitivities have to be calculated to ensure that a unique solution is obtained. Equation (5) can be generalized to 3D to give the following linear system of equations:

$$\left(1-\sum_{(m,n,o)\neq\mathbf{0}} w(j,j,m,n,o)\mathrm{e}^{-\mathrm{i}\left(xm\frac{2\pi}{FOV_x}+yn\frac{2\pi}{FOV_y}+zo\frac{2\pi}{FOV_z}\right)}\right)C_j(x,y,z) -\sum_{l\neq j}\left(\sum_{m,n,o} w(j,l,m,n,o)\mathrm{e}^{-\mathrm{i}\left(xm\frac{2\pi}{FOV_x}+yn\frac{2\pi}{FOV_y}+zo\frac{2\pi}{FOV_z}\right)}\right)C_l(x,y,z)=0$$

for which the solution is obtained by employing an appropriate linear equation solver for the relative coil sensitivity profiles.

3. RESULTS & DISCUSSION

Brain images were acquired on a Bruker S200 (Ettlingen, Germany), which includes an AVANCE spectrometer interfaced to an Oxford 2T whole body magnet. The system contains 4 independent receive channels that enable simultaneous acquisition from the 4 receive coils contained in the Novo Medical (Wilmingtom, USA) dome array head coil. Spin echo (SE) images were acquired with the RARE sequence with the following parameters: TR = 2500*ms*, TE

= 25, FOV = $230mm \times 230mm$, matrix = 256×256, slice thickness = $7mm$, RARE factor either 4 or 8. Gradient echo (GE) images were acquired using the FLASH sequence using identical parameters as in the SE images with a pulse angle of 30°, TR = $100ms$ and TE either $5.5ms$ or $10ms$.

	Fig. 1(a)	Fig. 1(b)	Fig. 1(c)	Fig. 1(b)
GRAPPA	0.1971	1.0039	0.1888	0.1763
SMACKER	0.0956	0.1205	0.1010	0.0968

Table 1. Errors in GRAPPA and SMACKER with respect to the full images.

The work performed here shows that the relative profiles can be constructed based on a primary set of images, which then can be used to construct images of other succeeding sets. This differs from self calibration techniques such as GRAPPA, where the weighting coefficients are repeatedly calculated for each set of images. Hence, providing the ability to acquire and reconstruct images in even less time, while preserving image quality.

Fig. 1 is the illustration of relative coil sensitivities obtained using Fig. 2(d). The relative coil sensitivities illustrated in Fig. 1 are for RF coil element 2, 3 and 4 with respect to coil 1. In Fig. 2 fully scanned images are provided using different sequences. Fig. 3 shows images that were obtained using GRAPPA corresponding to the full images illustrated in Fig. 2, after artificial reduction by a factor of 2. Similarly, the SMACKER images are depicted in Fig. 4, which are constructed with relative sensitivity profiles obtained from Fig. 2(d) and illustrated in Fig. 1. It can be seen through comparison of corresponding images in Figs. 3 and 4 that SMACKER images have smaller image artifacts, when compared to those obtained using GRAPPA, and in particular for the SE sequences, illustrated by Figs. 3(a,b) and Figs. 4(a,b). The results of Figs. 3 and 4 are quantified in Table 1, whereby the table entries were computed using the following figure of merit expression:

$$\sum_{i=1,j=1}^{d_x d_y} \frac{\left|I_O - I_R\right|_{i,j}}{d_x \times d_y}, \tag{6}$$

where, I_0 is the original fully sampled image depicted in Fig. 2, I_R is the reconstruction using an appropriate technique as shown in Figs. 3 and 4, and d_x and d_y are the respective image dimensions, in this case given by the matrix size.

From the calculated values provided in Table 1 for Figs. 1(a) and 1(b) it can be concluded that in the case of SE sequences, the SMACKER approach clearly outperforms GRAPPA. In particular, as the RARE factor is decreased, SMACKER proves to be significantly better than GRAPPA. Not only is this observation confirmed by the table entries, but is also clearly evident by comparing Fig. 3(b) to Fig. 4(b). In the case of GE sequences given as table entries for Figs. 1(c) and 1(d), the differences are not as obvious, but nonetheless, SMACKER still performs to a higher level of accuracy than GRAPPA.

4. CONCLUSION

A method called SMACKER of obtaining relative sensitivity profiles from which images were reconstructed was shown to have a lower level of motion artifact than images using the GRAPPA reconstruction technique. This observation is made with the view that SMACKER is likely to be a better technique to be used in parallel imaging that require fast reconstruction, for example such as in fMRI.

5. REFERENCES

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