VAMPIRE: Variation Minimizing Parallel Imaging Reconstruction

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INTRODUCTION

Over the past several years, a number of parallel imaging (PI) techniques have been developed and used in MRI in order to accelerate data acquisition. The existing approaches can be divided into two groups: those that obtain an image by direct inversion in the image space, such as SENSE [1] and SPACE-RIP [2], and those that attempt to regenerate the missing Fourier space data prior to image reconstruction, such as SMASH [3] and GRAPPA [4]. For both types of methods, in theory, the maximal possible acceleration factor R is limited by the number of available coils. However, practical considerations of SNR or unaliased FOV usually dictate a choice of smaller R.

We propose Variation Minimizing Parallel Imaging Reconstruction (VAMPIRE), a new PI method that works for acceleration factors larger than the number of coils. Such a breakthrough became possible due to an iterative hybrid technique that produces the final image by making alternating updates in the image and Fourier spaces. In the process, VAMPIRE regenerates missing Fourier space data. However, unlike SMASH-type methods, it does not require additional assumptions about specific coil sensitivity maps. VAMPIRE also avoids direct matrix inversions, which are typically employed in SENSE-like techniques, and thus, it is not prone to noise amplification. Moreover, the presence of a regularization parameter in the algorithm allows a certain degree of noise reduction. These advantages come at the expense of increased computational effort. However, in the current implementation, it takes less than 2 minutes to produce a 256x256 image in the Matlab environment on a desktop PC.

THEORY AND METHODS

VAMPIRE utilizes two mathematical tools known as Projections Onto Convex Sets (POCS) and Total Variation (TV) minimization. POCS has been previously used in MRI applications such as image reconstruction from partially sampled Fourier space data [5-6] and reduction of motion artifacts [7]. Recently, a POCSENSE technique was introduced for PI [8]. TV minimization is one of the image processing regularization techniques that only recently found its way into MRI applications [9]. TV is a numerical quantity characterizing how smoothly the intensity of the image is changing. TV of an image increases significantly in the presence of noise or artifacts. This property shapes one of the premises of VAMPIRE: while there are many images satisfying the constraints of undersampled information in the Fourier domain, the artifact-free image has minimal TV among them.

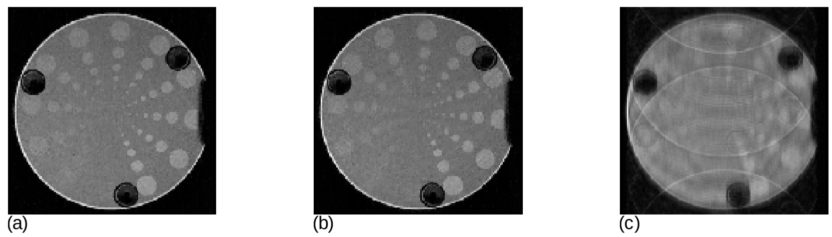

Figure 1. VAMPIRE reconstruction with (a) R=4.7, (b) R=6. (c) Sum-of-squares reconstruction with R=4.7.

The MR signal detected by each RF coil represents samples on some set *K* of the Fourier transform of the true image *f* modulated by the corresponding sensitivity map. These samples usually are contaminated by noise. The VAMPIRE algorithm is designed as follows: given a current estimate of the image, we form an updated estimate, where the update is determined by the gradient of the TV function. Then, we compute the full set of Fourier samples of the updated image for each coil. Among these samples, we correct only the ones from the set *K* if they differ from the given measured values by more than σ, where σ is a parameter estimating the standard deviation of the noise in the given data. This completes the Fourier space update step. Finally, we compute inverse Fourier transforms of all updated datasets and arrive at the next image estimate by taking the square mean of the image estimates for each coil. The iterations are continued until the difference in the TV between two consecutive image estimates is below a prescribed tolerance, or until a certain number of repetitions is reached. The above procedure converges to a fixed point provided that the sum of the squares of the coil sensitivity maps is relatively flat, an assumption normally satisfied in practice.

RESULTS AND DISCUSSION

A four-coil array was used in the cylindrical quality phantom experiments. Figures 1(a-b) demonstrate the results of the VAMPIRE algorithm for variable density Cartesian acquisition with the reduction factors R=4.7 and R=6 in the phase encoding direction with different noise levels. For comparison, Fig.1(c) presents the result of the conventional sum-of-squares reconstruction from the same data as in (a). The regularizing power of TV reduces the noise in the reconstructed images. A series of more than 200 experiments with different noise levels showed that the g-factor for VAMPIRE typically varies between 0.5 and 1, depending on tissue brightness.

CONCLUSIONS

Phantom experiment results suggest that VAMPIRE is a promising PI tool that produces high quality unaliased images for overcritical undersampling without causing noise amplification. For standard acceleration factors R, VAMPIRE suppresses noise and, thus, may be a viable alternative to other PI techniques. VAMPIRE is compatible with variable density Cartesian, radial or random sampling. In the former two cases, VAMPIRE performs well when paired with the sensitivity maps self-calibration technique described in [10]. VAMPIRE is especially well suited for blood flow applications.

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