On The Benefits Of Accelerated Parallel Imaging For fMRI

Jacco A. de Zwart[1], Peter van Gelderen[1], Jeff H. Duyn[1]

[1]*Advanced MRI section, LFMI, NINDS, National Institutes of Health, Bethesda, MD, USA*

INTRODUCTION:

Functional MRI puts a number of specific demands on the MRI imaging sequence and hardware. In general, it requires: high temporal resolution (≤ 2 s); large coverage (whole brain); minimal artifacts; high temporal stability; and low acoustic noise levels. Furthermore, many fMRI applications benefit from high field strength, since this increases contrast-to-noise ratio (CNR).

Echo-planar imaging (EPI) and other single-shot techniques are commonly used in fMRI since they fulfill several of the above demands. Most importantly, they allow fast scanning and are more stable than multi-shot techniques. However, drawbacks include geometrical distortions and T_2*-blurring as well as high acoustic noise levels, effects which increase with field strength. Several of these drawbacks can be alleviated by combining EPI with accelerated parallel imaging (PI).

PI [1-3] was initially developed to increase image acquisition speed for cardiac MRI applications [4,5]. Since PI generally results in a decrease in image signal-to-noise ratio (SNR), the benefits for fMRI are not immediately evident. However, most fMRI experiments are primarily limited by physiological noise (temporal instabilities), not by the image SNR. In that case, the use of PI will result in a relatively small penalty in fMRI sensitivity while allowing reduced artifacts, increased temporal or spatial resolution, reduced acoustic noise and/or increased coverage (more acquired slices per unit time). Furthermore, PI appears critical to yield the full potential of fMRI at high field strength (≥ 3 T), where the reduced T_2* significantly affects EPI performance.

PENALTY ON FMRI SENSITIVITY:

In SENSE MRI [3], the image SNR is reduced by a factor $g\sqrt{R}$ when compared to the corresponding conventional experiment with identical scan parameters (apart from the field-of-view (FOV) in the SENSE direction). This does not necessarily lead to reduced fMRI sensitivity, since the sensitivity (statistical power) of fMRI for the detection of cerebral activation is only partially determined by the image SNR. Blood oxygen-level dependent (BOLD) fMRI experiments are not an absolute measurement of brain activity, but rather use a signal amplitude difference between rest and activated state to map active areas. Temporal stability, expressed here by the temporal standard deviation (σ_t), therefore ultimately determines statistical significance of the activation measured by fMRI. Both the intrinsic (image) noise σ_i and the physiological noise (which is described here by the standard deviation of physiological fluctuations, σ_{ph}) contribute to σ_t. It was assumed that σ_i and σ_{ph} are fully independent and Gaussian noise sources and therefore [6]:

$$\sigma_t = \sqrt{\sigma_{ph}^2 + \sigma_i^2} \qquad [1]$$

In this model, only σ_i is affected by the reduced sampling in accelerated PI, while σ_{ph} remains the same. As was described above, σ_i increases by $g\sqrt{R}$ in a rate-R SENSE experiment and therefore

$$\sigma_{t,PI} = \sqrt{\sigma_{ph}^2 + \sigma_{i,PI}^2} = \sqrt{\sigma_{ph}^2 + \left(g \cdot \sqrt{R} \cdot \sigma_{i,noPI}\right)^2} \qquad [2]$$

where $\sigma_{i,noPI}$ is the intrinsic standard deviation in a conventional fMRI experiment, and $\sigma_{t,PI}$ and $\sigma_{i,PI}$ are the temporal and intrinsic standard deviation in the SENSE experiment with otherwise identical scan parameters [6]. This indicates that the penalty for SENSE use in fMRI depends on the relative contribution of physiological noise to the overall temporal standard deviation:

$$\frac{\sigma_{t,PI}}{\sigma_{t,noPI}} = \sqrt{1 + \left(g^2 \cdot R - 1\right) \cdot \left(\frac{\sigma_{i,noPI}}{\sigma_{t,noPI}}\right)^2} \qquad [3]$$

This shows that the penalty for SENSE use in fMRI might not be as severe as one would expect based on a decrease in image SNR. In an experiment in which temporal signal stability is completely dominated by image SNR (and thus by σ_i), the measured fMRI activation does indeed suffer the full $g\sqrt{R}$ penalty ($\sigma_{t,PI}/\sigma_{t,noPI}=g\sqrt{R}$, see Eq. 3). On the other hand, if physiological noise is the dominant noise source, application of SENSE will not affect the sensitivity of the fMRI experiment at all ($\sigma_{t,PI}/\sigma_{t,noPI}=1$).

ARTIFACT REDUCTION:

Off-resonance effects in combination with the long readout train used in single shot techniques like EPI leads to geometrical distortions [7]. Spins that are off-resonance have a phase offset that increases with TE, leading to a linear phase gradient over k-space in the phase encode direction. This leads to a shift of the corresponding signal in the reconstructed image. This effect scales linearly with field strength. When using PI, the length of the readout can be shortened by a factor R, thus reducing geometrical distortions by a factor of R also.

In areas with reduced homogeneity (e.g. close to cavities), the minimum TE of a single-shot EPI experiment might be longer than optimal (TE ~ T_2*). The resulting phase dispersion will cause signal loss. Hardware limitations, as well as the possibility of inducing peripheral nerve stimulation, might render it unfeasible to increase the acquisition bandwidth as a

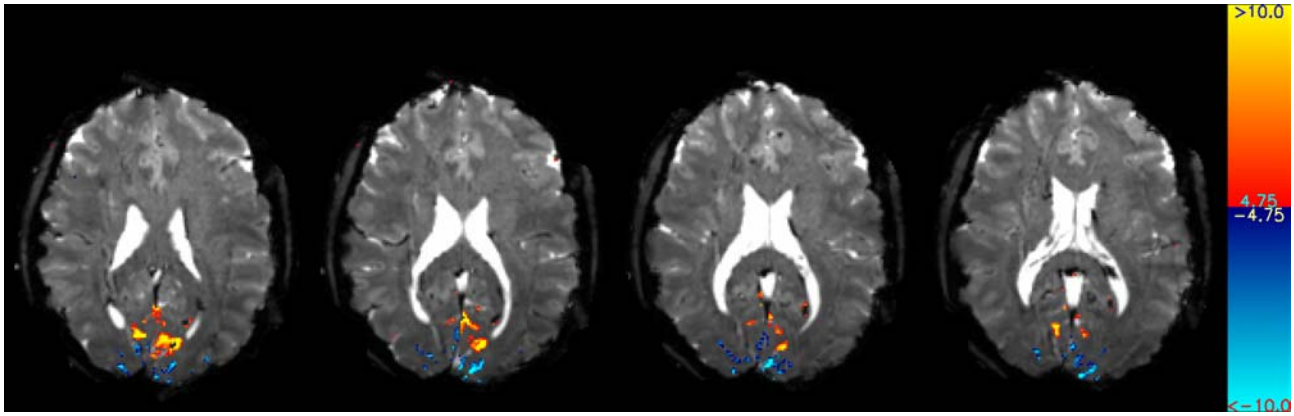

Figure 1: High-resolution SENSE-EPI fMRI data acquired at 3.0 T with a 16-channel head coil [9], connected to an in-house built 16-channel receiver. Single-shot gradient echo fMRI experiment with a nominal voxel size of 1.1×1.1×1.5 mm^3 (211.2×158.4 mm^2 FOV with 1.5 mm slice thickness and 192×144 acquisition matrix). Fourteen slices were acquired with 2 s TR and 48 ms TE using a 5-minute visual stimulus paradigm that stimulates either peripheral or foveal vision in alternating 30-s long blocks.

means to reduce acquisition train length. When PI is used for echo-train length shortening the TE for a given spatial resolution can be reduced.

PI-based EPI is also beneficial for perfusion-based fMRI techniques, since PI allows a shorter TE to be used, which reduces the contribution of the BOLD effect to the perfusion data.

SPATIAL RESOLUTION IMPROVEMENT:

The spatial resolution of EPI is intrinsically limited by T_2 and/or T_2* signal decay effects during the data acquisition window, which result in blurring [7]. This signal decay causes filtering of the acquired k-space [7], leading to widening of the point spread function. This effect is more severe at higher field strength due to the reduced T_2 and T_2*. Using PI to acquire the data allows acquisition of data with an *R*-fold improvement in nominal spatial resolution (in one dimension) for a given readout train length.

ACOUSTIC NOISE REDUCTION:

The readout gradient is the dominant source of gradient acoustic noise in EPI. If the spatial resolution and acquisition window duration are unaltered, the ramp times of the readout gradient can be increased, and the sampling bandwidth reduced, by a factor of *R* in a rate-*R* PI experiment [8]. The factor-*R* reduced sampling bandwidth also leads to a reduction of a factor *R* in readout gradient amplitude, therefore reducing the gradient slew rate by a factor R^2. Since the reduction in the number of samples is compensated by the decreased acquisition bandwidth, the image signal-to-noise ratio (SNR) is not expected to change, except for increases in image noise due to the SENSE *g* factor, which can be smaller than 10 % depending on the number of coils, the coil configuration and the acceleration factor *R* that is used [9].

FUTURE DEVELOPMENTS:

Recently, 7 T scanners have been used for fMRI in humans. PI seems an important tool to achieve the full potential of fMRI at high field to reduce distortion and spatial resolution limitations of EPI. A larger number of coil elements can be used at higher field, and g-factors are smaller, reducing the penalty for PI. Due to increased intrinsic SNR at higher field, optimal voxel size is reduced, requiring higher PI acceleration rates, possibly 2D PI [9].

PI in perfusion-based fMRI [10] appears promising, since it allows a reduced TE for a given spatial resolution, resulting in both increased sensitivity and reduction of the BOLD contribution.

CONCLUSION:

Several of the issues that currently hamper fMRI can be addressed by the use of an fMRI technique based on an accelerated parallel imaging sequence. This paper has addressed several of these issues and the potential use of PI to address that specific problem. These are 1) the reduction of artifacts in single-shot sequences, both geometrical distortions and signal loss due to off-resonance effects, 2) the potential for increases in spatial and/or temporal resolution when employing PI, and 3) the possible use of PI to reduce gradient acoustic noise in order to reduce interaction between the scanner and the fMRI experiment. Although the majority of the PI applications will reduce the intrinsic SNR of MRI, the penalty on fMRI sensitivity could be substantially less.

REFERENCES:

[1] Ra, JB; Rim, CY, Magn Reson Med 1993, 30:142-5
[2] Sodickson, DK; Manning, WJ, Magn Reson Med 1997, 38:591-603
[3] Pruessmann, KP; Weiger, M, et al., Magn Reson Med 1999, 42:952-62
[4] Jakob, PM; Griswold, MA, et al., J Cardiovasc Magn Reson 1999, 1:153-7
[5] Weiger, M; Pruessmann, KP, et al., Magn Reson Med 2000, 43:177-84
[6] de Zwart, JA; van Gelderen, P, et al., Magn Reson Med 2002, 48:1011-20
[7] Farzaneh, F; Riederer, SJ, et al., Magn Reson Med 1990, 14:123-39
[8] de Zwart, JA; van Gelderen, P, et al., Neuroimage 2002, 16:1151-5
[9] de Zwart, JA; Ledden, PJ, et al., Magn Reson Med 2004, 51:22-6
[10] Talagala, SL; Chuang, K-H, et al., 12th ISMRM, 2004; p 717