Assessment of signal variations in EPI, induced by breathing and hardware instabilities

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Introduction: There are manifold reasons for single-shot GRE EPI having become the work-horse for functional MR imaging (fMRI), the most importants being a fast data acquisition, a rather simple trajectory and an intrinsic BOLD contrast, achieved by a long TE, in the order of T2*. As is well known, the latter is not only beneficial: the long readout makes the method more susceptible to geometric distortions, especially in phase encoding direction. Thus, in addition to the desired functional signal variations, undesired, more global ones might be observed, e.g. caused by physiological noise (motion/breathing) or hardware instabilities (warming up effects of shims, etc.). Several prospective or retrospective remedies have been proposed ([1-4,6]), most of them showing effects on global phase variations. To our knowledge, however, no investigation of the typical expected image distortions, which represent an additional source of noise in fMRI activation maps, has been carried out yet. We will therefore give here an assessment of the effects of the mentioned causes on GRE EPI images, based on typical values for the field inhomogeneities, determined in phantom and in-vivo measurements.

Methods: For the sake of simplicity we restrict our assessment to the effects of time varying field inhomogeneities up to first order on a 3T Magnetom Trio (Siemens Medical Solutions, Erlangen, Germany). Since the usual TR used in EPI measurements of 2s lies close to the normal breathing period (5-10s), we chose to determine the field variations with a real-time approach presented by Splitthoff et al. ([6]). The obtained values were then used to assess image distortions, depending on the desired image resolution. In an ideal situation, the terms to be considered (zero, X, Y and Z) are orthogonal and can therefore be dealt with separately. Assuming the slice orientation to be in the X-Y-plane and X to be the readout and Y the phase encoding direction, it can be shown ([5]) w.l.o.g. that the effects can be described as follows:

Zeroth order: This being a global frequency offset it leads to a phase accumulation along the k-space trajectory. In the case of EPI this results in phase jumps in Y-direction at the k-space borders, and a linearly increasing phase along the k-space-centres. The first effect can be compensated by using phase correction scans; the second, however, leads with the Fourier shift theorem to an image shift in Y-direction: $\Delta y = \Delta\omega N T_{esp}$, with $\Delta\omega$ being the deviation in [Hz], N the number of k-space lines and T_{esp} the time between two echoes.

First order: Assuming thin slices, gradients in Z-direction can be seen as slice dependant inhomogeneities of zeroth order; they will thus not be discussed separately. A gradient G_y in Y-direction on the other hand leads to a change of the k-space line distance: the moment acquired by the gradient during T_{esp} adds to the desired moment of 2π ; the associated shearing of the k-space trajectory can be neglected. Since the k-space line distance is inversely proportional to the FOV, a compression or dilation of the image results, which can be described in pixel as: $(1-1/Q_y)N$, with N being the original number of pixel in Y-direction, and $Q_y = 1+\gamma/(2\pi) FOV G_y T_{esp}$. Additionally, the k-space centre line is shifted and acquired at a different time, leading to a linear phase in the resulting image and a possibly suboptimal BOLD contrast. For fMRI measurements a global phase in the image is not relevant, unlike a change in TE, which can be described as $\Delta TE = (1-1/Q_y)T_{acq} + ((Q_y-1)/Q_y)T_0$, with T_{acq} being the true acquisition time and T_0 the difference between TE and T_{acq} . Due to the high bandwidths in read-out direction, the only relevant effect of G_x gradients is an accumulation of moment in X-direction which leads to increasingly non-centred k-space lines. The result is a shearing in the final image of $S_x = N\gamma G_x T_{esp} FOV$ pixel.

Results & Discussion: Using the presented formulas, an approximate assessment in pixel of the effect of the respective distortions can be performed, assuming knowledge of the inhomogeneities. Using the mentioned method ([6]), inhomogeneities were determined separately for hardware instabilities and physiological noise, by carrying out measurements with a duration of 5min, first of a stationary phantom and secondly of three healthy volunteers at normal breathing. To provide a certain load, especially in the hardware instabilities investigation, in each case several axial slices were measured. Only the slice in the iso-centre was used for the determination of the inhomogeneities (thus no Z effects). The order of the measured peak-to-peak variations is listed in Table 1. Based upon these values and assuming FOV=0.25, the distortions to be expected can be calculated using the presented formulas, depending on the desired matrix size NxN, which of course limits T_{esp} . The results for the respectively shortest T_{esp} are shown in Figure 1. It can be seen, that distortions induced by breathing (Figure 1.a) are only in the order of sub-pixels. However, at bigger matrix sizes distortions of about 0.2 pixels over the FOV can be observed in Y-direction, such that influences on fMRI activation could be relevant; with lower bandwidth, i.e. longer T_{esp} , stronger distortions are to be expected. Distortions caused by hardware instabilities change much more slowly; on the other hand, they are much stronger, in the order of pixels. In any case, distortions caused by inhomogeneities higher than zeroth order cannot be corrected for without interpolation; a prospective real-time approach is therefore mandatory. For the given values, changes in TE of maximum 0.25ms were calculated; thus, no significant influence on the BOLD contrast is to be expected.

	0^{th} order	X	Y
Breathing:	1Hz	0.1µT/m	0.2µT/m
Hardware:	25Hz	0µT/m	1µT/m

Table1: Order of the measured peak-to-peak field variations. Hardware effects are over a period of 5min.

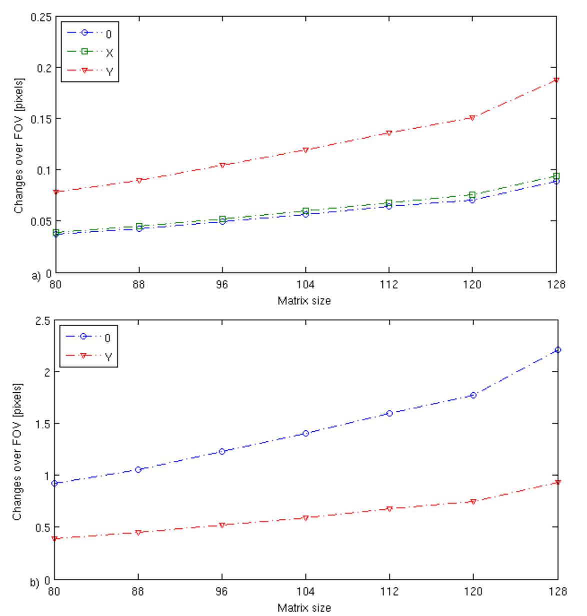

Figure 1: Changes in pixels over a full FOV, calculated based on the values in table 1: a) Breathing, b) hardware instabilities; for b) no changes in X-direction were detected.

References:[1] Pfeuffer et al., MRM 47, 344-353, 2002;[2] Ward et al., MRM 48, 771-780, 2002;[3] van der Kouwe et al., MRM 56, 1019-1032, 2006;[4] van Gelderen et al., MRM 57, 3363-368, 2007;[5] Chen et al. NI 31, 609-622, 2006;[6] Splitthoff et al., ISMRM, Berlin, 2007

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