Image based ghost correction for oblique imaging

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Introduction: Nyquist or FOV/2-ghosting is a common artefact in echo planar imaging (EPI). The sources that lead to ghosting are manifold, but are primarily caused by gradient hardware time delays. Since even and odd echoes in the EPI readout are acquired under positive and negative gradient waveforms, the delays create misalignments between odd and even echoes along the readout direction Δk_{RO}. If the readout gradient is a combination of physical gradients ($G_{RO}=aG_x+bG_y+cG_z$), e.g. as in an oblique imaging plane, and the gradient delays differ between the physical axes, the echo will also be shifted in the phase encoding direction, Δk_{PE} [1]. This doesn't only shift the data, but also introduces some degree of under-sampling in k-space. It has previously been shown that the Δk_{PE}-shift can be resolved using parallel imaging [3] or gradient compensation blips [1,2]. In this work, we have extended our previous image entropy based method [5], to also estimate this Δk_{PE}-shift. This method is independent of any reference scan and does not require any pulse sequence changes. We have compared conventional ghost correction in the k_{RO}-direction with $k_{RO}+k_{PE}$-correction. We also investigated the upper limit of the Δk_{PE}-shift that can be corrected for, before k-space becomes too under-sampled in the phase encoding direction.

1) Initialize Δk_{RO}, Δk_{PE} and Φ_0
2) Generate a sinc-kernel for ramp-sampling correction, including the Δk_{RO}–shift.
3) Apply 2) to odd and even echoes separately together with Φ_0.
4) Generate a sinc-kernel for the Δk_{PE} -shift
5) Apply 4).
6) 2D-DFT to image space
7) Calculate the image entropy and update Δk_{RO}, Δk_{PE} and Φ_0, using Gauss-Newton based minimization.
8) Go to 2).

Fig 1. The different steps involved in the estimation algorithm.

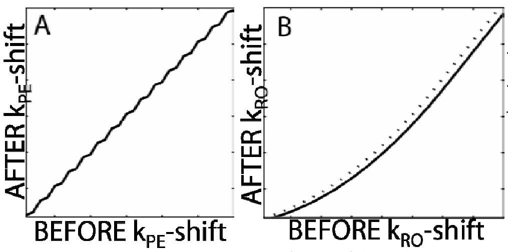

Fig 2. shows the interpolation locations (zoomed) for shifting the odd and even lines along k_{PE} (A) and k_{RO} (B). In A, odd/even lines are shifted up/down. In B the echo is shifted along k_{RO}, simultaneously to being corrected for ramp sampling. (dashed line = non-shifted reference). Onto each of these locations a sinc kernel is added to facilitate a Fourier interpolation.

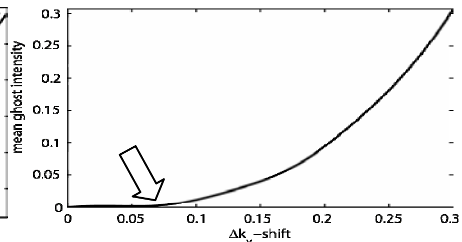

Fig 3. A phantom simulation, where the residual ghost was measured after attempting to correct for the Δk_{PE}-shift. The arrow indicates where the shift makes k-space too under-sampled to be undone.

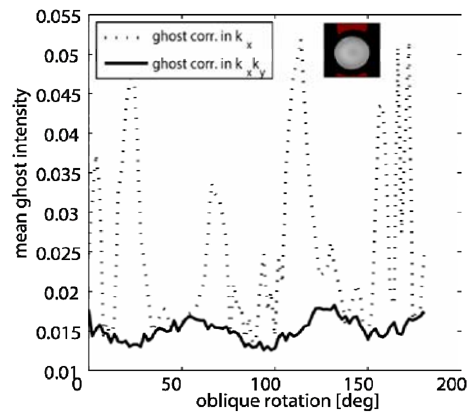

Fig 4. 91 images where acquired with different rotational angle around the z-axis. The residual ghost was measured for ghost correction applied only along the readout dimension as well as applied to both readout and phase encoding direction. Small inlay show ROI for mean ghost intensity calculations.

Method: An iterative algorithm, based on image entropy minimization [4,5], was used to find the correction parameters. This algorithm is further explained in Fig. 1. The corrected k-space was estimated as:

$$S'_{odd}\left(k_x,k_{y,odd}\right)=S_{odd}\left(k_x+\Delta k_x,k_{y,odd}+\Delta k_y\right)e^{i\phi_0},$$
$$S'_{even}\left(k_x,k_{y,even}\right)=S_{even}\left(k_x-\Delta k_x,k_{y,even}-\Delta k_y\right)e^{-i\phi_0}$$

where S_{odd} and S_{even} are odd and even k-space lines and Δk_{PE}, Δk_{RO} and Φ_0 are the three unknown parameters to be determined. Φ_0 is the constant phase between odd and even echoes, Δk_{RO} the shift along the readout direction, and Δk_{PE} the shift along the phase encoding direction. If the correct parameters are estimated, the Δk_{RO}-shift may always be undone. On the contrary, a Δk_{PE}-shift under-samples k-space and cannot be undone if too large, even if one would know the true shift since it would violate the Nyquist criterion. Following the estimation of the three parameters, the Δk_{RO} and Δk_{PE} shifts were corrected via regridding k-space using two sinc-interpolations matrices. For an efficient implementation the Δk_{RO}-shift was included into the ramp-sampling correction matrix and applied prior to the Δk_{PE}-shifting matrix. These resampling matrices are shown in Fig 2.

In order to investigate to what extent a Δk_{PE}-shift can be undone, a phantom simulation was performed on an ideal phantom. Using inverse gridding, different amounts of Δk_{PE}, was synthetically added to the data before being resolved with the same but negative Δk_{PE}-value.

Ghost corrections were also performed on data from a 3T (Signa, GE, Milwaukee) equipped with 40 mT/m gradients (SR=150 T/m/s). Single shot EPI images (128×128, N_a=288) were acquired in 91 incrementing steps between 0 and 180° (0° corresponding to the scanners physical *y*-axis and 90° to the *x*-gradient).

Results: The simulation shows that it is possible to resolve a Δk_{PE}-shift of up to ±0.075 voxels (Fig. 3). Beyond this limit, k-space becomes too under-sampled and methods such as parallel imaging or gradient compensation blips would be needed. However, in our data, the maximum Δk_{PE}-shift was approx. ±0.045 voxels (for angles 22°, 115° and 158°), which is under the critical value found in the simulation. Moreover, Figs. 4 and 5 show that correcting for the Δk_{PE}-shift further reduces the residual ghosting. Note that this is not the case for all oblique angles, but only when the readout is a linear combination of physical gradients with different gradient delays.

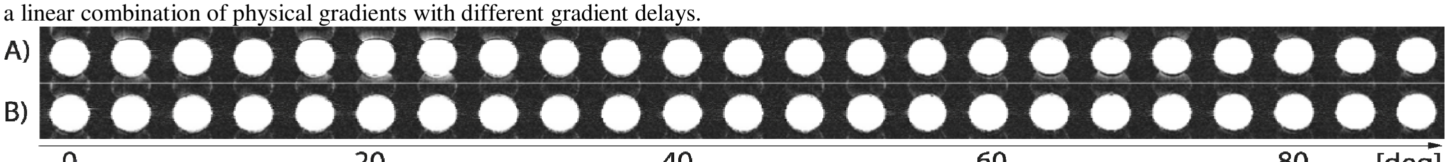

Fig 5. shows the same dataset as fig. 3 (every 2nd image from 0-90 deg.). The x-axis is the rotational angle from 0 (physical y-gradient) to 90 (physical x-gradient). Row A) show images corrected in the k_{RO}-direction, B) show images corrected in both k_{RO} and k_{PE}. The large differences in residual ghost originate from anisotropic gradients (i.e. in this case different time delays on the physical x- and y-axis).

Discussion: We have shown that it is possible to perform an image based ghost correction in two directions. This work applies to oblique image plane orientations in EPI scans and is by far superior to corrections applied in the readout direction only.

References: [1] Reeder S et al. 1999. MRM 41:87-94. [2] Grieve S et al. 2002. MRM. 47:337-343. [3] Winkelmann et al. 2005. MRM 54:1002-1009. [4] Clare S, ISMRM 2003, Toronto. [5] Skare S et al. ISMRM 2006, Seattle.