Iterative Nyquist Ghost Correction for Single and Multi-shot EPI using an Entropy Measure

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Synopsis

An iterative method for reducing the Nyquist ghost in EPI, based on an entropy cost function measure is evaluated. The method works well for both single shot and multi-shot EPI, but would be particularly useful in the multi-shot case where no other method currently exists that does not require either a reference scan, navigators, or user intervention.

Introduction

Nyquist ghosting is one of the most severe artefacts observed in echo planar images. In single shot EPI the ghost image is shifted by half the field of view in the phase encode direction. However in multi-shot (interleaved) EPI, the ghosting pattern is more complex. There are several methods for correcting this artefact based on information gained from reference scans or navigator echoes acquired at the same time as the image [1,2].

Alternatively, there are methods that require no additional information. Buonocore presented an elegant method, firstly for single shot EPI [3], and then extended to multi-shot [4,5] that compares the phase of images reconstructed with 'odd' or 'even' lines of k-space set to zero respectively. This method can be used successfully without user intervention in the single shot case [6], but for multi-shot EPI requires some user definition of eligible image pixels.

An alternative strategy to calculating the phase correction is to use iterative reconstruction. Foxall suggested an approach where phase corrections are applied iteratively until the ghosting is minimised [7]. Critical to any iterative method is the choice of minimisation cost function. The choice of a measure of projection sum works well for single shot EPI, but works much less well for multi-shot EPI, with its attendant complex ghosting patterns.

Atkinson, in his work on reducing motion artefacts from images, including multi-shot EPI, proposed using an entropy-based cost function [8]. This is distinct from reconstructing the image using maximum entropy [9]. The use of this cost function specifically for reducing Nyquist ghost artefact in single and multi-shot echo planar imaging is evaluated here, and compared with several of the methods detailed above.

Methods

To evaluate the proposed method a series of data sets were acquired on a 3.0 Tesla whole body scanner consisting of a Varian Inova console and Magnex SGRAD head gradient coil. Sets of multi-slice EPI images were acquired covering the whole brain of a human volunteer with between 1 and 4 interleaves and a matrix size of 128 x 128 x 64. Slight timing mismatches between gradients and sampling were introduced intentionally in order to provide variable levels of Nyquist ghosting in the data sets.

The iterative entropy minimisation method first splits the raw data, on a slice by slice basis, into two matrices; one containing only echoes acquired under the positive read gradient and one containing only echoes acquired under the negative read gradient. The missing lines in each case are set to zero, and both matrices are 2D Fourier transformed. A linear phase change in the read direction is then applied to the odd echoes image and the two matrices are complex-added and modulus rectified to produce a final image. The level of ghosting in the image is then measured and the last step repeated until the ghosting has been reduced to its minimal value. The entropy cost function that is used is slightly different from [8], since it was found that using a more traditional measure of image entropy [10] worked more successfully. This is defined as $E=-\sum F_q \ln[F_q]$, where F_q is the frequency of occurrence of image pixel values within histogram bin q. The minimisation strategy was based on Powell's method [11] and implemented in C code on a Linux PC.

For comparison, the data sets were also Nyquist ghost corrected using the standard reference scan method of Bruder [1] and with the self reference methods of Buonocore [3,5]. For quantitative evaluation, a whole brain mask was generated using BET [12], and this was shifted by half a field of view to produce a 'ghost only' mask. This is not entirely suitable for evaluating the multi-shot EPI results, but gives an indication of the level of ghosting remaining in the image after correction.

Results

Figure 1 shows an example of severe (uncorrected) Nyquist ghosting from the 4 shot EPI data set, together with the ghost corrected image resulting from the iterative entropy based reconstruction. Figure 2 shows the level of ghost correction for all data sets, using each of the three ghost correction methods. The ghost correction methods appear to give the most significant improvement when applied to single shot data. However, this is misleading, since in the case of multi-shot EPI the ratio of image intensities between brain and ghost areas is biased by significant signal interference introduced into any brain areas with bad ghosting, as can be seen in Figure 1. Reconstruction of the four shot EPI data using the entropy method took 2.5 minutes, significantly longer than for the other two analytical methods.

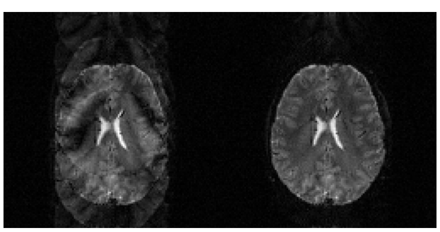

Figure 1. Four shot EPI before and after correction.

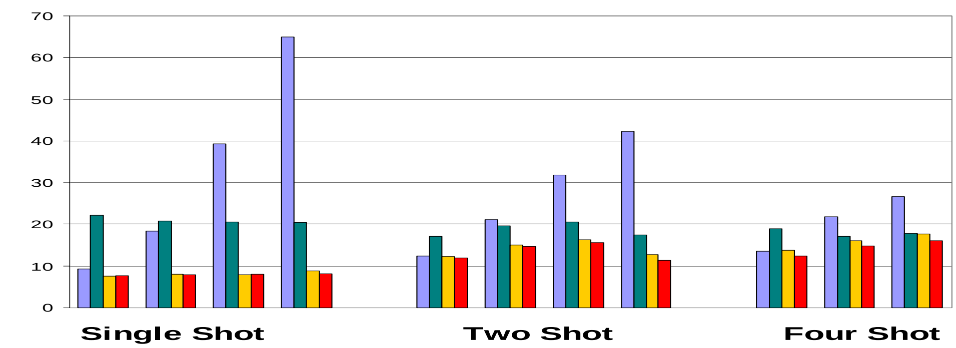

Figure 2. Ghost level (%) for no correction (blue), ref scan (green), self ref (yellow) and iterative (red).

Discussion

The iterative reconstruction using an entropy cost function performs as well as, and in many cases significantly better than the standard reference scan method for Nyquist ghost correction. It performs as equally well as the self reference (Buonocore) method in all cases. Since the iterative method requires no user intervention, its major benefit would come from its use in correcting multi-shot EPI images, where Buonocore's method requires user intervention. Although the reconstruction time is longer than other methods, the level of ghost improvement, and lack of a need for user intervention mitigate. It is possible that the reconstruction time can be reduced by optimising the algorithm, and the rate of increase in computer speed means that the computational intensity of a reconstruction method continues to be less significant.

References [1] Bruder et.al. MRM **23,** 311 (1992) [2] Hu and Le. MRM **36,** 166 (1996) [3] Buonocore and Gao. MRM **38,** 89 (1997) [4] Buonocore and Zhu. MRM **41,** 1199 (1999) [5] Buonocore and Zhu. MRM **45,** 96 (2001) [6] Clare et.al. 6th ISMRM, 2137 (1998) [7] Foxall et.al. MRM **42,** 541 (1999) [8] Atkinson et.al. MRM **41,** 163 (1999) [9] Constable and Henkelman. MRM **14,** 12 (1990) [10] Shannon. Bell System Technical J **27,** 379 (1948) [11] Numerical Recipes in C, CUP. [12] Smith. HBM **17,** 143 (2002)