Doubling EPI resolution by acquiring two k-space lines per readout gradient reversal using TRAIL

A. N. Priest[1,2], E. De Vita[2,3], R. J. Ordidge[3]

[1]Department of Diagnostic and Interventional Radiology, University Hospital Hamburg-Eppendorf, Hamburg, Germany, [2]Department of Medical Physics and Bioengineering, UCL Hospitals NHS Trust, London, United Kingdom, [3]Department of Medical Physics, University College London, London, United Kingdom

Introduction

In single-shot echo-planar imaging (EPI) the length of readout train is restricted by the T2* relaxation time and also by off-resonance effects which lead to image distortion. At high fields, the useful readout duration can be particularly short. Given typical constraints on the readout gradient amplitude and slew-rate, this in turn limits the achievable resolution. Some additional resolution gains can be achieved using parallel imaging.

We propose an additional method to increase the achievable EPI resolution by a factor of two along the phase-encode (PE) direction, by adapting 'Two Reduced Acquisitions Interleaved' (TRAIL) [1]. In TRAIL, two readouts are acquired in rapid succession and the resulting images are interleaved in the spatial domain. It imposes two complementary sub-pixel modulations on the magnetisation – so that, in effect, the two images represent signal from the two different halves of each pixel.

Theory: Pulse Sequence

Fig. 1 shows the TRAIL pulse sequence, containing two sinusoidal EPI readouts. Unlike previous versions of TRAIL [1] the spatial modulation is performed along the readout direction, as determined by the orientation of the 'wrap-up' gradient. In this novel implementation, two peaks appear for each line of readout data, representing two coherences, or (equivalently) the Fourier transform of the sine/cosine wave modulation. The two peaks represent two identical copies of the object k-space. In the previous TRAIL implementation, the readout was shortened so that only one of these peaks was acquired, but in this work both peaks are acquired for each readout gradient lobe. An additional PE gradient blip is inserted between them, so that they can be used to acquire two separate lines of k-space.

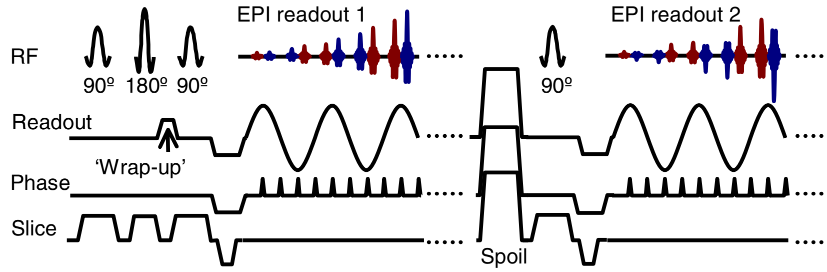

Fig. 1: TRAIL pulse sequence, adapted for interleaving in the readout direction. The two echoes per readout lobe come from two separate coherences (coloured red and blue) and are used to acquire two different lines of k-space.

Each readout is equivalent to a 128×64 acquisition with standard EPI. The data is reformatted to a 64×128 dataset (twice as many k-space lines, of half the length). After reconstruction, the images from the two readouts are spatially interleaved in the readout direction to form a 128×128 image: double the conventional resolution in the PE direction. Additional corrections compensate any signal mismatches between the interleaved images [1].

Theory: N/4 Ghosting and ghost correction

For conventional EPI, the two-fold periodicity of k-space (due to the alternating gradient polarity) leads to N/2 ghosting. For the proposed approach this periodicity is now four-fold, leading to N/4 ghosting (any ghosts are offset from the primary image by ±¼ of the FOV). Most ghosting is corrected using 1D reference scans as for normal EPI. Some additional ghosting may result from differences in the amplitudes of the two coherences contributing to each readout (see above, also red/blue echoes in Fig. 1). The ratio of the coherence amplitudes $a(x,y)$ depends mostly on flip-angle inhomogeneities (as well as weakly on T1) so the ghosting is 2D, and needs 2D ghost correction similar to ref. 2.

As two datasets are acquired, deghosting must be performed for each dataset separately before interleaving. Firstly, a prescan is used to measure $a(x,y)$ from the ratio of two 'single coherence' images. The prescan consists of 2 acquisitions, between which the positions of the two coherences are exchanged, by reversing the sign of the 'wrap-up' gradient. Each 'single coherence' image is formed from the two appropriate half-readout datasets.

To produce a ghost-free image using this prior knowledge of $a(x,y)$, four separate sub-images I_i are reconstructed for the four-fold sections of k-space (each with data from a single coherence and a single readout gradient polarity). Each pixel of the image I_i is a linear combination of four pixels P_j from the desired object image P, at the locations of the image and ghosts. Thus $P_j(x,y) = P(x,y+j.\mathrm{FOV}/4)$ for j = $0...3$. The images I_i are related to the object P by $I_i(x,y) = \Sigma_j\, M_{ij}(x,y).P_j(x,y)$ with → where the a_j represent the values of $a(x,y+j.\mathrm{FOV}/4)$. For each set of linked pixels, the matrix M_{ij} is inverted using singular value decomposition; the ghost-free image pixels are then given by $P_j(x,y) = \Sigma_i\ [M(x,y)]^{-1}_{ij} . I_i(x,y)$.

$$M_{ij} = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ a_1 & ia_2 & -a_3 & -ia_4 \\ a_1 & -a_2 & a_3 & -a_4 \\ 1 & -i & -1 & i \end{pmatrix}$$

Methods

The head of a human volunteer was imaged using a 4.7 T SMIS spectrometer (provided by Philips) equipped with a head gradient set. Conventional EPI (128×64) and TRAIL EPI images (128×128) – using the new method – were acquired. Both sequences had TE 30 ms, FOV 240 mm, slice thickness 3 mm. For reference, a conventional spin echo image was also acquired (TE/TR = 30/2000 ms).

Results

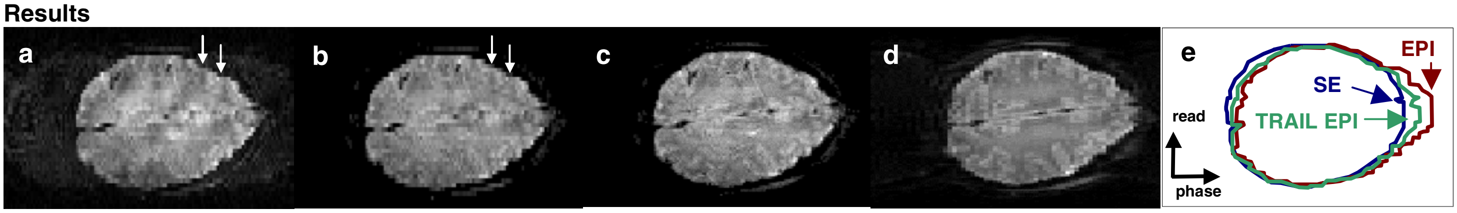

Fig. 2: Before Correction | After Ghost Correction | 128x128 TRAIL EPI | 128x64 standard EPI | Comparison of outlines

The ghost correction procedure (**a**,**b**) removes most of the ghosting – see for example the reduction of interference fringes indicated by white arrows. The final interleaved TRAIL image (**c**) clearly has higher resolution than standard EPI (**d**). TRAIL EPI has only half the distortion levels of conventional EPI as shown by a comparison of the brain outlines from these two images and an (approximately distortion-free) spin echo image (**e**).

Discussion and Conclusions

The new version of TRAIL doubles EPI resolution, at the cost of approximately doubling the total acquisition time (from ~50 ms to ~100 ms) since two successive readouts are used. However, there is no increase in the individual readout lengths and thus no increase in T2* decay over the readout. Distortion is reduced by a factor 2 because the effective PE bandwidth is doubled. Compared to a notional 128×128 acquisition with standard EPI, the SNR penalty for halving the readout length using TRAIL is 1/√2, the same as for increased gradient power or parallel imaging (g = 1).

Acknowledgement We thank the Wellcome Trust (London) and the Florindon Foundation (Zürich) for funding.

References [1] Priest AN et al. Magn Reson Med 51: 1212–1222 (2004). [2] Chen NK, Wyrwicz AM. Magn Reson Med 51: 1247–1253 (2004).