Simultaneous slice excitation and reconstruction for single shot EPI.

R. G. Nunes[1], J. V. Hajnal[1], X. Golay[2], D. J. Larkman[1]

[1]Imaging Sciences Department, MRC Clinical Sciences Centre, Hammersmith Hospital, Imperial College London, London, United Kingdom, [2]MRI Facility, Singapore Bioimaging Consortium, Singapore, Singapore

Introduction and Background: Partially Parallel Imaging (PPI) is highly effective for reducing acquisition time in multi shot MRI because the speed up factor equals the reduction in the number of shots required to construct a non aliased image. For single shot EPI reduction in the number of phase encodes has a lesser impact on scan time due to the relative length of the preparation phases and the readout. Typically scan time is only decreased by 20-30% with a speedup factor of 2. Image artefacts are reduced due to the reduced length of the readout window. Where time is critical a better strategy for single shot imaging is to excite multiple slices simultaneously. This, combined with unfolding using PPI, has been demonstrated before[1]. The method provides a direct speedup factor (factor 2 for two slices etc) and carries with it the additional benefit of not suffering from the $\sqrt{r}$ (r=speedup factor) penalty in SNR that is associated with other PPI methods. However, the method does not perform well with standard enveloping array coils when transverse slice geometries are used because of a lack of variation in coil sensitivity in the through slice (z) direction. PPI reconstruction of closely spaced slices results in prohibitively high g-factors. Attempts have been made to tackle this problem: CAIPIRINHA[2] uses shot by shot modulation of the RF pulse to synthesise shifts in plane of one slice by half a field of view (fov) to improve PPI unfolding performance. RF encoded [4] and hardware [3] solutions have also been proposed, however the former are not suitable for single shot imaging (EPI) and the latter are largely unpractical. We propose a different method to introduce an arbitrary shift between two simultaneously excited single shot EPI slices, allowing them to be separated by PPI with acceptable g-factors.

Theory and Methods: Simultaneous slice excitation pulses were produced by modulating the single slice time domain RF pulse by cos(ωt) which by the the Fourier convolution theorem produces two slices excited at +/-ω, where ω determines the slice separation. If PPI is applied to multislice excited data directly, then in the transverse geometry, for small slice spacing the g-factor is prohibitive because of the similarity of the coil sensitivities at the locations of the superimposed pixels. Since the coils have much greater differential sensitivity in plane than through plane, we seek to introduce a differential in plane shift between the two excited slices. This is achieved during readout by creating a k-space phase ramp in the direction of desired shift using a scheme proposed for FLASH imaging [3] that was modified for single shot EPI. To produce the phase ramp an additional set of blip gradients is required in the through slice direction with the same timing as the in plane phase encode blips. These introduce an accrual of phase throughout the readout producing a shift which is proportional to the magnitude of the through slice field at the location of the slice. Slices further from isocentre experience greater fields and therefore greater shifts. The differential shift between two slices a fixed distance apart is constant regardless of their proximity to isocentre. Such simultaneously excited slices can be separated using standard PPI algorithms by modifying the input and reference data to conform to the standard field of view reduction formalism usually considered in PPI. This approach is similar to that described in the context of fat artefact removal [4]. In a fully sampled image, the signal intensity S_1 in a pixel where there is a superposition of signals x_1 in slice1 and x_2 in slice2, imaged with coil j can be written as $S_j=C_{j1}x_1+C_{j2}x_2$, where C_{j1} represents the sensitivity of the coil at slice 1 and C_{j2} the sensitivity at slice 2. This equation is the SENSE equation and with multiple coils the problem can be solved. The in plane difference in position between the locations of x_1 and x_2 is not necessarily half a field of view as in traditional SENSE with factor two pixel degeneracy. It can be chosen at will according to the selected differential shift. The data can be made to fit the usual formalism by constructing reference data from standard coil sensitivity data for each slice position shifted by the known differential shift. Reconstruction uses a standard SENSE algorithm.

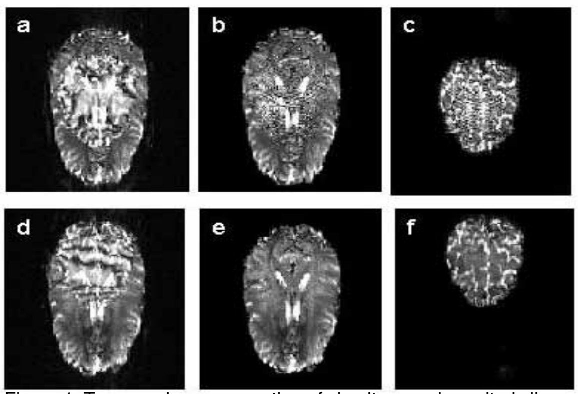

Figure 1. Top row shows separation of simultaneously excited slices (b and c) without proposed shift. Results are unusable due to high g-factor noise. e and f show results of proposed method.

Methods: The principle was tested by simulation and experiment. The data presented is a full practical implementation. At present this has been tested on phantoms and 3 healthy volunteer subjects. Acquisition: 240mm FoV, 4mm slice thickness, 4mm gap, TE/shot duration 196/54, 128x128 matrix. The multi-slice excitation has a slice separation of 32mm and was the same duration as the single slice excitation. For testing purposes a 5 slice acquisition was used resulting in 9 unique slice locations with one slice acquired twice with each part of the RF pulse for comparison. Data reconstruction was performed using a standard SENSE reconstruction algorithm in the manner described. All data were acquired on a Philips 3T Intera.

Results: Figure 1a) shows an acquisition where two slices were excited without additional blips in the slice direction and figure 1d) shows the differential effect of these blip gradients. It is important to note that as the shifts required to control the g-factor are relatively small (32 pixels in this case) the blips are small in area, introducing negligible slice dephasing. Comparison of the regions of the image where the slices do not overlap demonstrate this. Figure 1b and c show the results separated using SENSE, The peak g-factor is 37.2 the mean g-factor is 7.4. These images are not interpretable.. Figure 1 e and f show the same slices excited with the slice blips on and separated using SENSE with modified reference data . The reconstructions are faithful to the anatomy and have peak g-factor 1.8 mean g-factor 1.2 resulting in fully diagnostic images.

Discussion: For many applications time per acquired slice is critical. For example in the recently published method for model free quantitative arterial spin labelling (qASL) [5], coverage of the brain is limited by the lifetime of the tagging pre-pulse, dictated by the T1 of the blood. A typical exam with a total scan time limited to 10-12mins only achieves coverage of 4 slices, which with 6mm slice thickness and a 2mm gap samples only a 32mm slab of the brain. By using the method presented here, the volume of brain measured in the example above would double. As the two slices would have been excited simultaneously (double the number of spins) there would be no $\sqrt{r}$ term in the PPI SNR equation. This is vital for SNR limited applications like qASL. Although in plane shifts serve to reduce the g-factor, introducing these shift can cause through slice de-phasing. Use of a pre-winder gradient ensures that the centre of k-space is fully refocused, but some spatial frequency dependent de-phasing may be seen introducing blurring in the phase encode direction. The greater the slice separation the smaller the blip gradient needed and the less this artefact manifests. As can be seen in the examples successful separation of even closely space slices can be achieved with little loss of image quality. In conclusion we have demonstrated by simulation, in phantoms and in vivo that this methodology provides a flexible framework for PPI based separation of signals in simultaneously excited slices. The method can also be applied with slice shifts in the frequency encode direction, potentially allowing both separation of simultaneously excited slices and reduction in echo train length in the phase encode direction using PPI unfolding in two orthogonal directions.

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