Navigated Multi-Shot EPI Diffusion Imaging of the Spine

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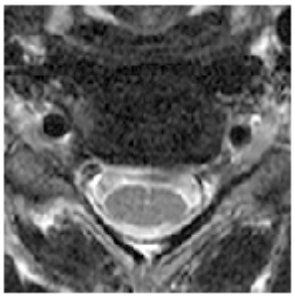
Introduction High resolution diffusion tensor imaging of the spine has clinical potential in the assessment of axonal injury following trauma, demyelination in multiple sclerosis, spinal cord stenosis and ischaemia. In animal models diffusion imaging has demonstrated injury to white matter tracts that have no evidence of abnormality on conventional MRI [1] and rodent studies have shown an association between motor recovery and altered diffusion values [2]. In humans, single-shot EPI imaging suffers from susceptibility-induced distortions and limited resolution. Potential improvements using parallel imaging are limited because the coil geometry would require phase encoding in the head-foot direction. Line scan imaging is time consuming, suffers a signal to noise loss and is usually applied only to sagittal images with a rectangular field of view (FOV) [3]. Multi-shot EPI potentially offers reduced distortions, high resolution and no geometry constraints if motion artefacts can be corrected.

Motion during the diffusion sensitisation period results in image-domain phase changes that differ from shot to shot and uncorrected, lead to ghosts in multi-shot diffusion imaging. The effect of motion can be monitored by 2D navigators and the phase changes observed are complex and spatially varying. Simple rigid-body corrections are unlikely to be effective, furthermore the spinal cord occupies a small part of the FOV and brighter structures such as fat may dominate other regions of the signal, all of which suggests the correction should be based on 2D images. We have explored the feasibility of a multi-shot EPI method that uses 2D navigator data to achieve correction for localised motion to produce high-resolution diffusion images of the spine.

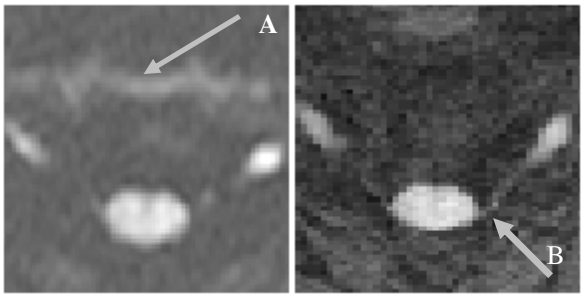
Method The diffusion weighted image, s_0 is found by solving, $s_j = \sum_t (F^H A_t F c_j p_t)\, s_0 = \mathbf{g} s_0$ where p_t is the motion-induced phase error measured by the navigator, c_j is the sensitivity of coil j, F and its complex transpose F^H denote Fourier transforms from image to k-space and vice-versa, A_t represents the sampling of k-space at shot t and s_j is the artefacted image from coil j. The equation can be interpreted as image multiplications and Fast Fourier Transforms, or equivalently as multiplication by large matrices giving the matrix $\mathbf{g}$. Conjugate gradient and LSQR based solutions [4,5] require the user to supply matrix-vector products $\mathbf{gu}$ and $\mathbf{g}^H\mathbf{v}$. By considering both the matrix interpretation and equivalent image operations, we were able to efficiently compute these matrix-vector products.

Two healthy volunteers were imaged on a Philips 3T scanner using a 6 channel spine array coil. A single-shot scan was acquired with parameters: b= 500, 6 diffusion directions, FOV 150mm, matrix 89x128, 7 slices, 0.4mm slice gap, true pixel size 1.3/1.7/4.0mm, water fat shift 46 pixels, phase encode AP, scan time 1 min 47s. An interleaved multi-shot scan was acquired with similar parameters except: true pixel size 0.85/0.85/4.0mm, water fat shift 9.5 pixels, matrix 176x176, scan time 13 mins 43s. Each shot was followed immediately by a 180° RF pulse and a navigator that scanned the central 11 lines of k-space. A high resolution, non-diffusion weighted scan was also acquired for anatomical reference.

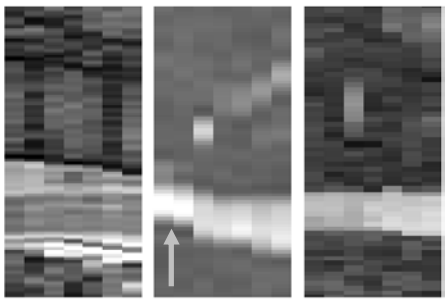
Results and Conclusions Data from one volunteer is presented below, similar findings were observed for the other volunteer.



Anatomic reference, slice 6.



Isotropic diffusion weighted images. Left single-shot showing artefact (A) and distorted cord, right multi-shot with nerve root more clearly visible (B).



Sagittal reformat of all slices. Note upwards distortion in single-shot (arrowed).

The figure demonstrates that the multi-shot technique can produce images without intrusive artefact and with sufficient resolution to visualise small detail such as the nerve root not seen in the single-shot image. A sagittal reformat highlights the reduced distortions of the spinal cord in the multi-shot data and correctly preserves the anatomy. The reconstruction assumes the navigator captures all the significant motion-induced phase information. Given this, multi-shot EPI diffusion sequences have the potential to provide high-resolution diffusion weighted images with reduced distortions.

References: [1] Ford JC et al, Mag Reson Med 31:488-494. [2] Schwartz ED et al, Exp Neurol 184:570-589. [3] Bammer R. et al. AJNR 24:5-12. [4] Liu C. et al. ISMRM 2005 p. 509. [5] Batchelor PG. et al. Mag. Res. Med. 2005;54:1273-1280.

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