Addressing a Systematic Vibration Artefact in Diffusion-weighted MR Images

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Introduction: The large gradient lobes employed in diffusion-weighted imaging are known to cause vibrations of the patient table. These vibrations can affect the diffusion-weighted signal, as demonstrated by changes in the measured apparent diffusion coefficient in a phantom with and without mechanical contact to the patient table [1]. Here we identify an artefact in-vivo that is caused by the gradient-induced table vibrations which can lead to severe disruption of the quantitative diffusion measures derived in diffusion tensor imaging (DTI). It is not clear to what extent other systems may be affected, but the same artefact has been observed in multiple sites using common protocols. We suggest a method to improve the analysis of data corrupted in this manner, as well as suggesting how to adjust the sequence parameters to avoid the acquisition of corrupted data.

The Artefact: Figure 1a shows an example of a diffusion-weighted image affected by the vibration artefact. Imaging was performed on a clinical 3T system using a typical protocol: 2 mm isotropic resolution EPI, 192x192 mm FOV, 65 slices, TE/TR = 94 ms/9300 ms, *b* = 1000 s/mm^2 in the left-right direction (using the twice-refocused spin-echo (TRSE) to reduce eddy-current related distortions [2]) and ¾ partial Fourier imaging with phase encoding in the anterior-posterior (AP) direction. Typically a large region of the occipital lobe, often close to the mid-line, demonstrates marked signal loss when the *x*-component (i.e. left-right) of the diffusion-gradient direction is large. We see clear artefact in most subjects scanned using this protocol, although the exact location of the signal-loss is variable.

The artefact arises due to the presence of mechanical shear-waves oscillating in the left-right direction which propagate through the brain when the head is in strong mechanical contact with the patient-table. Motion in the diffusion-encoding direction that occurs during the diffusion-encoding gradients will lead to phase offsets. If neighbouring voxels move different amounts this will lead to a phase ramp in the image, which in turn leads to a displacement of the k-space centre. Fig. 1b clearly shows the strong phase ramps present in the occipital region of the affected slice, and the corresponding k-space image (Fig. 1c) demonstrates the defocusing of the signal echo. The use of a ¾ partial Fourier acquisition means that the phase ramp need only be $\pi/2$ per voxel in the AP direction before the signal echo is not acquired and the signal drops dramatically.

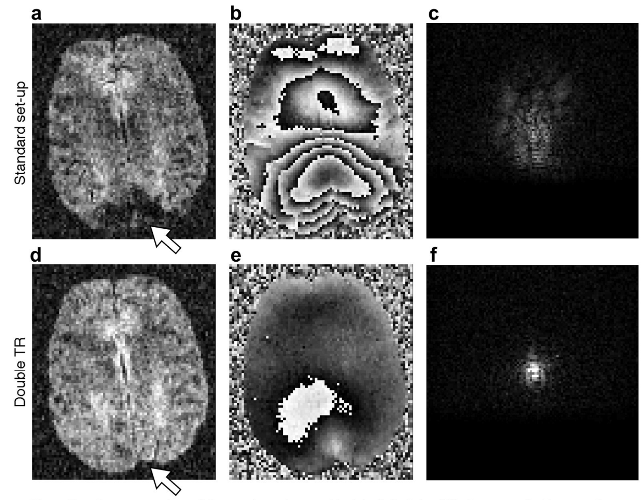

Fig. 1. Top: Demonstration of the artefact observed in (a) a left-right diffusion-encoded image, along with (b) the corresponding image phase and (c) k-space. Bottom: The same acquisition with double the normal TR.

Figure 2 shows how the signal in an area affected by the artefact varies with the *x*-component of the diffusion-gradient direction during 2 averages of a 60-direction acquisition. Also shown for comparison is the signal in an area selected to approximate a pure left-right running white-matter tract (in the splenium). Whereas the signal in the splenium decreases continuously, within the area of the artefact the signal remains constant until the *x*-component of the diffusion-gradient direction reaches ~0.75, whereupon the signal decreases sharply. The directional dependence of the artefact naturally leads to errors in the diffusion-tensor fitting process, with areas of artefact being falsely interpreted as having a high fractional-anisotropy (FA) corresponding to a tract in the left-right direction. This artefactually high FA can be observed in Fig. 3.

The artefact can also hinder clinical diffusion-weighted imaging if the area of suspected pathology lies within the region affected by the artefact.

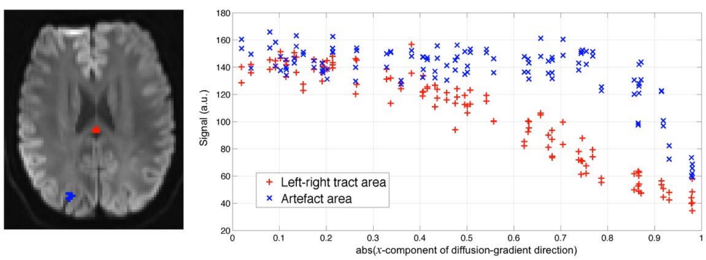

Fig. 2. Variation in signal vs. magnitude of *x*-component of diffusion-gradient direction for an area with a left-right tract (red +) compared with an area affected by the vibration artefact (blue x).

Correcting for the Artefact: Whilst the acquisition of uncorrupted data is preferable, inevitably there are many datasets that were acquired prior to the recognition and characterisation of the artefact. We have found that the reliability of measures such as FA can be vastly improved by including an empirically-derived approximation to the artefact curve shown in Fig. 2 as a co-regressor in the diffusion-tensor fit. The improvement in the tensor fit is demonstrated in Fig. 3, where the large region of erroneous red is almost completely corrected.

Avoiding the Artefact: Based on our experimental observations, we have identified several aspects of the protocol that affect the artefact. The system vibrations we observe appear to behave similarly to previous measurements using a laser interferometer [3], with a resonance ~20-25 Hz and a decay constant of ~200 ms. The vibrations do not peak until after the diffusion gradients which cause them, meaning that a single measurement is not affected, but when measurements are repeated (for example, over several slices) the vibrations from the *previous* diffusion-weighting gradients are still present at the time of the current diffusion weighting. Extending the time between consecutive acquisitions to allow the vibrations to decay reduces the artefact, as can be seen in the bottom row of Fig. 1, where the TR was doubled. Doubling the TR, however, also means doubling the overall acquisition time, which is not acceptable for routine use.

The simplest approach to acquire data unaffected by the artefact is to use a full k-space acquisition. The phase ramps in the images will still remain, but will need to be twice as strong to cause signal drop-out. The primary motivation for using partial k-space acquisition is to reduce the TE. To achieve a short TE with full k-space, parallel acceleration (e.g. GRAPPA x2) can be used. This will lead to a slightly reduced SNR, but this is partially compensated by the increase in SNR efficiency due to the shorter TR. Artefact-free images were successfully acquired on our system with identical parameters to the above acquisition, but full k-space, GRAPPA x2, TE = 93 ms and TR = 8200 ms. Removing any subject restraints (padding) that directly contact the side of the head reduces, but does not remove, the artefact. This is expected, as the vibrations causing the problem are in the left-right direction, so tighter mechanical coupling in this direction between the head and the vibrating structure leads to larger effects. Ultimately the artefact may be avoided entirely by consideration of these low-frequency vibrations in the hardware design – an approach which manufacturers are beginning to pursue.

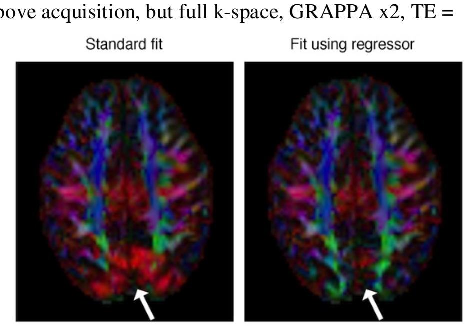

Fig. 3. FA maps with colour-coding for the direction of the first eigenvector from the fitted diffusion-tensor with (right) and without (left) the artefact co-regressor in the tensor fit.

Discussion: Vibrations are typically strong on all systems when high *b*-value diffusion-weighting is performed, so some degree of phase variation across the image should be expected. Whilst this may not in all cases lead to the gross drop-out artefact we observe here, strong phase variations have been shown to lead to errors in partial k-space reconstruction methods [4]. Regions of rapidly changing phase can also affect algorithms that combine data from multiple coils, as they may rely on approximating the high-resolution phase from low resolution data. We are currently also investigating the possibility that the gradient-induced may be utilised as a mechanical driver for MR elastography experiments.

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[3] J Hiltunen et al, NeuroImage 32 (1) 93-103 (2006); [4] MD Robson and DA Porter, MRI 23 (9) 899-905 (2005)