Detection and correction of spikes in fMRI data

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Introduction

One commonly recurring experimental problem in MRI is the presence of impulsive noise superimposed on received time domain data. These impulses are often referred to as *spikes*. They are usually caused by small electrical discharges (i.e. sparks) which emit radio frequency power (partly) within the bandwidth of the scanner receiving system. Small sparks can occur when electrical contacts are made or broken (for example in switches) or can arise from instrumental problems including loose connections and insulation breakdown. Spikes are a particular problem for functional Magnetic Resonance Imaging (fMRI) experiments where additional electrical stimulus or monitoring equipment which may cause spikes is often present in the scanner room and where noise caused by spikes may mask the relatively small signal differences caused by neuronal activation. To put this latter point into perspective: a typical functional activation of 1% average signal change between conditions is equivalent in magnitude to one out of 100 volumes suffering a single spike of energy similar to the NMR signal – a common occurrence for spike interference. Clearly it is desirable to eliminate spikes at source (for example by fitting suppressor filters to contacts) but from time to time fMRI data are contaminated with this form of interference. We have developed a procedure to reliably detect and correct spike-affected data. The detection procedure is computationally suitable for online monitoring allowing for immediate identification of spike interference during scanning. The correction procedure is straightforward and sufficiently robust to cope with moderate levels of spike interference.

Methods

Detection: One characteristic aspect of a spike is its very rapid onset (< 10 microseconds). This rapid transient contains signal energy over a wide frequency band. The duration of the spike depends on its source but is often found to be of order or less than the time to acquire one line of k-space during an EPI readout (i.e. < 1000 microseconds). In summary, a spike is expected to produce a brief burst of wide bandwidth noise. In contrast the NMR signal from the object is band-limited according to the extent of the FOV filled by the object in the frequency encoded direction. In EPI scanning, the FOV in the frequency encoded direction can be extended arbitrarily by ADC over-sampling without affecting the basic pulse sequence or reducing image quality. In fact over-sampling is commonly performed in ramp sampled EPI in order to ensure adequate sampling during the entire readout (1). We choose to exploit this and detect spikes using the following procedure. The time domain data are Fourier transformed along the frequency encoded direction (i.e. into projection or p-space). The signal arising from the object's projections is limited in extent in the frequency encoded direction. Any energy beyond the object's projection in each line of p-space will be due to noise – either thermal or spike related, making additional adjustments for physiological noise unnecessary (2). This is illustrated in Figure 1.

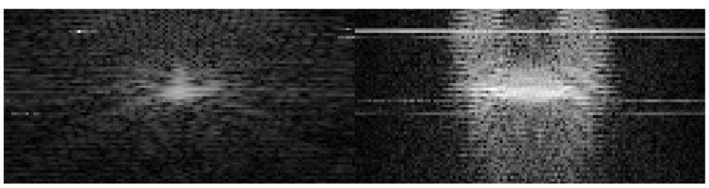

Figure 1. EPI data affected by several spikes: k-space (left) and p-space representations (right). Frequency encoding was in the left-right direction. Note how both the high intensity spike and several lower intensity ones are clearly apparent in the periphery of the p-space projections and extend well beyond the object.

Under the null hypothesis that no spike has occurred, noise in the periphery of each p-space line will be thermal in origin, uncorrelated, and so the expected signal energy will follow a Chi-Square distribution independent of the object being imaged. Any outliers from this distribution represent statistically significant evidence for the occurrence of a spike. Thus we can set a threshold to determine in which p-space (and therefore k-space) lines spikes have occurred.

Correction: There are several options for dealing with data in which spikes have been detected. If the spikes are detected on-line, scanning may be interrupted in order to rectify an instrumental problem. If spikes are discovered retrospectively but are extremely infrequent the volumes in which spikes occurred may be omitted, replaced by adjacent volume(s) or otherwise accounted for in the statistical analysis. If spikes occur more frequently (e.g. of order one spike per volume of data) then the loss in experimental degrees of freedom inherent in these approaches leads to a significant reduction in sensitivity to functional activation. In these cases we can choose to replace only the corrupted k-space lines from adjacent, uncorrupted time points. This will not usually affect image intensity because only few spikes will occur in the centre of k-space and so functional activation detection is not significantly impaired. Adequate phase correction is necessary to prevent slight movement from one scan to the next introducing sufficient phase discontinuities to disrupt the reconstructed image. We apply a simple correction for linear within-slice displacements based on the examination of the phase differences between uncorrupted lines and fitting for linear phase variation across k-space. The method was tested on data acquired at 3 T (64x64 matrix, 2-fold over-sampling in the frequency encoded direction, 32 slices, 3 mm isotropic resolution, TR/TE=2080/30 ms) using an auditory stimulation paradigm in which the electrostatic headphones worn by the subject were producing intermittent spikes.

Results

The uncorrected data were degraded by the occurrence of spikes (rate approximately 2 spikes per volume). This prevented any meaningful detection of functional activation. The corrected data contained no visible spike artifacts, allowing for fMRI analysis.

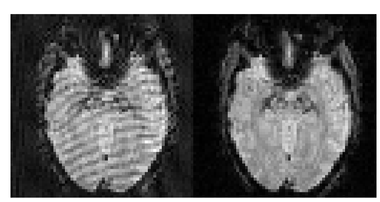

Figure 2 showing a representative EPI slice before and after spike correction.

Discussion

This work allows for the restoration of EPI time series that have been corrupted by spike interference. Detection of spikes is based on the oversampled k-space data allowing for robust assessment of the thermal noise and detection of spike artifacts independently from physiological noise or the shape and size of the imaged object. Only k-space lines in which spikes have occurred are actually modified. Even for a spike rate of one spike per slice, only 1 out of 64 k-space lines has to be corrected, resulting in a total loss in experimental degrees of freedom of only 2 %, which may sensibly be neglected in subsequent statistical analyses.

Reference

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2. X. Zhang, P.F. Van De Moortele, J. Pfeuffer, X. Hu. Elimination of k-space spikes in fMRI data. Magn Reson Imaging 19: 1037-41 (2001).