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Integrating temporal information with a non-rigid method of motion correction for functional magnetic resonance images

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Abstract

Existing approaches to the problem of subject motion artefacts in FMRI data have applied rigid-body registration techniques to what is a non-rigid problem. We propose a model, which can account for the non-linear characteristics of movement effects, known to result from the acquisition methods used to form these images. The model also facilitates the proper application of temporal corrections, which are needed to compensate for acquisition delays. Results of an implementation based on this model reveal that it is possible to correct these effects, leading to accurate realignment and timing correction.

Keywords: FMRI; Image registration; Non-rigid motion; Motion correction; Slice-timing correction

1. Introduction

Functional Magnetic Resonance Imaging (FMRI) is a relatively recent development of Magnetic Resonance Imaging (MRI) and is a non-invasive technique, which can be used to form images of neural activation. The technique can answer questions about the way in which the brain works and can also characterise deficiencies due to illness or injury. The modality is based on measurements of the magnetic behaviour associated with blood flow change due to the metabolic activity, which can be observed using an MRI scanner. Images are acquired using a multi-slice Echo Planar Imaging (EPI) protocol which raster scans k-space. While this achieves the necessary acquisition speeds for individual slices which are grouped along the z-axis to form volumes (typically a volume must be acquired every 3 s so that the temporal dynamics of the haemodynamic response can be captured), the signal-to-noise ratio (SNR) suffers and as a consequence image resolution must be lowered. This makes it much harder to reliably detect activation and dynamic behaviour in a subject's brain. Also, because this detection is based on the statistical comparison of many scans of the same sections of the brain, the situation is further confounded by the adverse effect of subject motion at even very low levels of a few millimetres or less. This situation is exacerbated by the fact that clinical patients will generally move far more than co-operative volunteers while in the scanner, Echo Volumetric Imaging is the full extension of EPI to 3D, which means that the full volumetric image is acquired in a single shot. It is extremely difficult to carry out in practice and it results in a very low-resolution image (currently, about $32 \times 32 \times 16$ voxels) with large levels of distortion due to an even lower SNR than is typical of multi-slice EPI.

Given that SNR considerations limit FMRI to stacked-slice acquisitions in practice, the problem of temporal offsets within a volume due to the successive acquisition of slices remains a significant confound to motion correction. Previous attempts to correct FMRI data for artefacts introduced during acquisition have considered spatial realignment and slice-timing correction as two distinct and separate stages in the processing chain [1,5,16]. We discuss the problems inherent in such an approach in Section 2, and go on to propose a new method, which we have called Temporally Integrated Geometric EPI Re-alignment (TIGER). We present the initial results from an implementation based on this model and conclude by describing a more sophisticated realisation based on this model, which may be applied to real FMRI studies.

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2. Existing approaches to motion correction in FMRI

While the need for slice-timing is acknowledged widely, these corrections are not always performed in practice on FMRI data. Applying the two corrections separately is convenient, not least because it facilitates the use of existing tools such as MCFLIRT [7] and SPM [4] for rigid-body motion correction along with separate temporal interpolation of each voxel time-course to re-shift slice-timings. There are fundamental errors in the assumptions underlying this distinction, however, regardless of the order in which the two steps are performed. Clearly, if no subject motion has occurred, it is sufficient simply to apply slice-timing correction as a series of temporal interpolations over each voxel time-course in turn, where the amount of shift is proportional to the temporal offset associated with the slice containing the voxel being considered. However, a complete lack of subject motion is unlikely to occur in real data, so the interaction between motion and acquisition delays must be modelled in order to correct fully for the resulting artefacts in the data.

Assuming that motion correction is carried out before any temporal corrections, data which may not correspond to acquisition at a consistent point in time will be co-registered. If slice-timing correction is applied after the initial realignment, the corrected images will contain data from several discrete sample times within individual slices. This is because, in the general case of through-plane motion, spatial registration will realign the data so that intensity values from individual slices in scanner space are distributed across several slice locations in the corrected data. This is illustrated in Fig. 1.

Specifically, if rigid-body realignment is performed, subsequent slice-timing will make the incorrect assumption that data within individual slices will have been acquired at the same time-point. In this situation, it is necessary to keep a record of the slice in which the data were originally acquired, and then apply the appropriate timing correction, a step which is usually omitted.

It might, therefore, seem obvious that temporal re-sampling should be carried out before motion correction. An obstacle to such a re-sampling is that in order to carry out slice-timing correction by temporal interpolation of a particular voxel, the time-course of that voxel must be known. If the subject has moved, there is no guarantee that a voxel in object space will be in constant alignment with a voxel in scanner coordinates. This creates a cyclic problem, where motion correction is needed in order to determine slice-timing before motion correction. Recognising this inter-dependency is by no means original; but prior to this work there have been no attempts to utilise knowledge about the acquisition sequence in order to correct the situation.

The situation is worse when considering a voxel on an intensity boundary (for example, on the interface between two tissue types or on the perimeter of an activating region), since in such a case the voxel described by a particular set of scanner coordinates may rapidly switch between two different intensity regions in object space, thus creating a physically implausible (uncorrected) time-course on which to base temporal interpolation.

In general, if a rigid-body model is assumed, the motion correction stage will also ignore the fact that there may not be a parallel correspondence between the slices from different volumes if motion has occurred during or between activations (i.e. it is no longer correct to assume that the relative movement between slices is consistent across different volumes), such as the example in Fig. 2. Thus, a rigid-body spatial realignment will inevitably attempt to compute pair-wise voxel comparisons on data, which originates from different spatial locations in the subject's brain. It is also possible that the slices will remain unaligned, even when the volumetric optimisation has reached a minimum. In conclusion, movement throughout a scan will lead to different displacements in individual slices. This is ignored by volumetric corrections, which assume a rigid-body transformation over the entire volume.

These observations show that the separate application of slice-timing and motion correction cannot accurately account for motion artefacts in FMRI. For this reason, we propose an integrated approach to these two corrections that is able to cope with the potential spatial non-linearities in the data. If the subject has moved during acquisition of that volume, a quite likely possibility, as previously noted, is that there will be redundancy at some locations yet sparseness and/or voids at

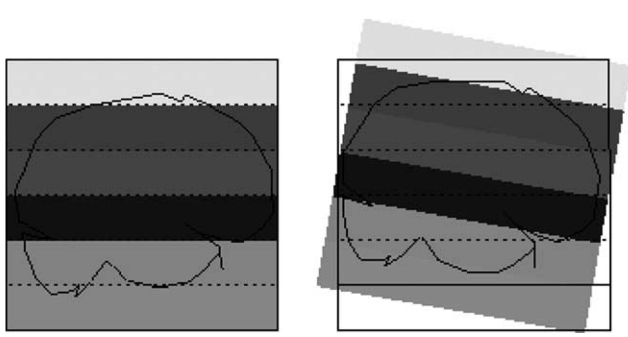

Fig. 1. In this figure the shaded bars, fixed to the same reference frame as the brain, indicate the acquisition timings associated within each slice. Even in the case of rigid-body motion, spatial realignment (in this case correcting a simple pitch of the head) will lead to a breakdown in the correlation between slice location used to determine slice-timing correction (marked with dotted lines) and associated acquisition timings (shaded bars).

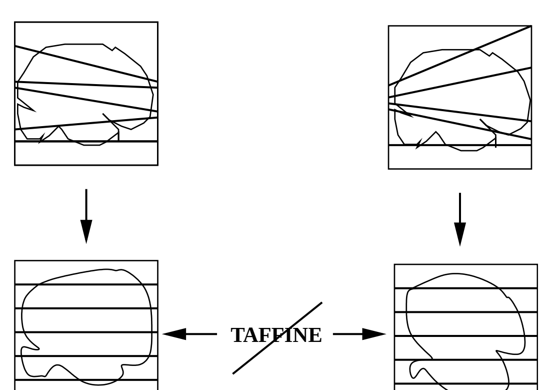

Fig. 2. Local distribution of slices within different volumes may force the motion correction problem to require a non-rigid solution.