Correction of Motion Artefacts in Magnetic Resonance Imaging

Final Report for Advanced Research Fellowship GR/A01381 funding David Atkinson

Background and Summary

Magnetic Resonance Imaging (MRI) can provide high quality images exhibiting good soft tissue contrast and without the use of potentially harmful ionising radiation. The process of MR image formation is inherently slow compared to many physiological processes and this can lead to image artefacts such as a blurring and ghosting. The aim of the project was to correct for motion artefacts.

MR data is acquired in the Fourier, or k-space domain. Following acquisition, a Fourier Transform reconstructs the MR image. Multiple receiver coils can be used to receive data simultaneously from different spatial locations - so called 'partially parallel imaging' (PPI). With PPI, acquisitions can be shortened by skipping the collection of some lines of k-space and the coil information is used to enable the image reconstruction. Diffusion weighted MR imaging (DWI) is sensitive to the molecular diffusion of water. When diffusion is restricted, such as in tracts of fibres within the brain, the signal depends on the diffusion direction. Diffusion tensor imaging (DTI) calculates the diffusion tensor from six or more DW images. Fibre tracts can be found by ‘tractography’ algorithms which follow the directions of the principal eigenvectors of the tensors.

This Fellowship started in October 2000 at Guy’s Hospital, KCL. In January 2005 I transferred with other members of the group to University College London. At the outset of the Fellowship, it was known how affine motion affected k-space and during the Fellowship we developed a novel method for handling the irregular sampling caused by rotational motion and went on to show how to correct for general, non-rigid motion. Diffusion tensor imaging was not widely available at the start of the Fellowship, but is now a package on most scanners. During the Fellowship we showed the optimal directional sampling scheme, we provided quantitative means to assess fibre tracts, we suggested solving the diffusion equation (rather than using tractography) to analyse connectivity, and we demonstrated a method that can give higher resolution DTI data with reduced distortions. This became particularly relevant because during the five years higher field strength scanners have become available for which the distortion problems are more significant.

The use of PPI for acquisition speed-up was known but not widely available commercially at the start of the Fellowship. Now virtually all scanners are equipped with multi-channel receive capacity and we showed how this extra information can be used not just for acquisition speed-up, but for the reduction of artefacts caused by motion and other factors.

The original objectives were to publish novel algorithms to improve the quality of MR images corrupted by motion. Validation on volunteers, patients and ratings by radiologists was envisaged. The actual research resulted in a wider range of algorithms being published than originally anticipated. Their more speculative nature meant that principally volunteers were imaged. Artefacts arising from sources other than motion were also corrected.

Key Advances

Motion Artefact Correction

Inconsistencies in the object during acquisition, such as motion or flowing blood, lead to blurring and ghosting in the final image. The effect of affine motion upon k-space is known but anything other than corrections for translations requires a regridding of the data which itself can introduce artefacts. For head imaging, rotational motion is common and we developed a novel method for reconstructing this irregularly sampled data that resulted in less regridding artefacts. This was published in the leading journal Magnetic Resonance in Medicine (MRM) [1], presented at a workshop of the International Society for Magnetic Resonance in Medicine (ISMRM) [2] and at a UK meeting [3].

For many parts of the body, the motion may have a component that cannot be described by affine motion. During the Fellowship, I applied for and was awarded EPSRC grant (GR/S30184) that employed Dr Philip Batchelor. Part of this work resulted in the development of a framework for correcting general, non-rigid motion. For the first time, it is now possible to correct for known motion in two or three dimensions and the motion is not restricted to rigid-body or even to affine transformations. The framework can also include useful information from multiple receiver coils. The method is applicable to most image domain artefacts and a further application to diffusion weighted imaging is described later. This work was published in MRM [4] and presented at a UK conference [5], at ‘ISMRM’ (the leading international conference in MR) [6], at the European version [7] and the Zurich parallel imaging workshop [8].

Respiratory motion: cardiac and liver imaging

Notice of the Fellowship award allowed me to take a five month sabbatical in the group of Prof. Alison Noble, Engineering Science, Oxford University. Whilst there, and during the early stages of my Fellowship, we showed how the tracking of a marker attached to the chest could be used to monitor respiration and correct 3D cardiac ultrasound images for the effects of patient respiration. This lead to a journal publication [9]. Subsequently at Guy’s, we used MRI to study in more detail the motion and deformation of the heart during respiration leading to journal [10] and conference [11, 12] publications. The position in the respiratory cycle can be monitored by a pencil beam navigator and we examined how this information might be more accurately applied
Multiple coils for artefact reduction

The speed-up that can be achieved using partially parallel imaging is usually not fast enough to overcome artefacts caused by physiological effects. In collaboration with colleagues at The Hammersmith Hospital, we examined methods to use the spatial information from multiple coils to correct for artefacts rather than the more traditional application of speeding-up scans. Our first approach used coil information to predict one line of k-space data from that previously acquired. The predicted line was compared with that actually acquired and differences consistent with motion were detected and corrected (termed ‘SMASH Navigators’ and published in MRM [16], at ISMRM [17] and ESMRMB [18]). The line-by-line approach could suffer cumulative errors and we developed a more general method in which the source of the artefact was parameterised and varied in an optimisation scheme. The optimisation aimed to make all the data from all the coils consistent. The technique was demonstrated for artefacts caused by motion and by flowing blood in abdominal imaging. An MRM journal article [19], ISMRM conference presentations [20, 21] and presentation at the MICCAI conference [22] resulted. Fig. 1 shows an example. Our work on parallel imaging and artefact reduction has lead to an invited book chapter [23] and invitations to publish in Topics in MRI [24] and NMR in Biomedicine [25].

Diffusion Tensor MRI: acquisition and analysis

At the start of the Fellowship, the choice of measurement directions for diffusion tensor imaging was the subject of discussion. We showed that icosahedral-based schemes are optimal in terms of noise propagation. Remarkably, we also showed theoretically that when using an icosahedral scheme, the condition number of a matrix used to determine the tensor components, is the same as using an infinite number of directions, i.e. from that point of view you cannot do better than icosahedral schemes. A publication in MRM [31] as well as presentations at SIAM [32], ISMRM [33, 34] and an ISMRM workshop [35] resulted.

Many sites use diffusion tensor imaging and ‘tractography’ algorithms to infer the directions of fibres within the brain. This produces nice visualizations but little quantitative information. We examined the use of measures such as curvature, torsion and link (a measure of how two curves twist around each other) to quantify the shapes of fibre tracts. The latter two measures were a novel application of geometry to DTI data and published in MRM [36] and at conferences [37, 38, 39]. We also proposed to

Multi-shot Diffusion Imaging

In Diffusion Weighted imaging, pulsatile motion of the brain during the application of the diffusion sensitisation gradients causes non-linear phases in the image domain. To achieve images with high resolution or reduced distortions, multi-shot acquisitions must be used. The motion-induced phase changes differ from

shot to shot causing huge image artefacts if uncorrected. Using the Philips pulse programming environment, we inserted a 2D navigator after each shot. This navigator is just a low resolution image that provides a measure of the phase errors. These provide a measurement of the artefact cause that we could use in our new general framework [4] described above. Fig. 2 shows the reduced distortions we can achieve. This work has been presented at ESMRMB conference [26] and submitted to MRM [27]. I regard this as the single most important outcome of the Fellowship - it combines the theoretical work with a practical implementation of pulse programming and has the potential to show new insights into brain and spine anatomy and disease processes.

In PPI, multi-coil allow image reconstruction after lines of k-space have been skipped during the acquisition. In multi-shot diffusion imaging, the effect of motion is to create gaps in k-space and we showed that by receiving on multiple coils, the resulting image can be improved, particularly when the number of data averages is low. This was presented in the UK [28], at the Zurich workshop on parallel imaging [29] and at ISMRM [30].

Figure 1: Removal of flow artefacts.

Figure 2: Diffusion weighted images showing state of the art single shot image (left) and multi-shot sequence reconstructed using our new method (right) with artefacts arrowed.
solve the diffusion equation directly to determine connectivity, rather than try to follow fibre tracts (presented at the prestigious IPMI conference [40] and ISMRM [41]).

Given that we have tensor image data, tools to perform image processing type operations are important. In collaboration with Dr Moakher of Ecole Nationale d’Ingénieurs de Tunis, we showed new ways of performing interpolations between tensors, provided a new measure of tensor anisotropy and showed how to take the means of tensors. This was presented at ISMRM 2004 [42], at a Dagstuhl workshop [43] (which has also led to an invited book chapter [44]) and published in MRM [45].

Use of Prior Knowledge

Comparison of acquired data with the k-space from a previous scan can reveal changes consistent with motion. We presented this at ISMRM [46] and with QinetiQ filed a patent [47] on these ideas.

For most MR image reconstructions, no information from other scans is used to help in the image formation. In the case of images reconstructed from multiple coils, when the acquisition speed-up is large, there is noise amplification if the coil spatial profiles are not ideal. By using a reference image, which may be of different resolution or contrast, we can overcome some of this noise amplification potentially leading to enhanced acquisition speed-up, this is accepted for publication in MRM [48].

Other cardiac work

Collaborations with Dr V. Muthurangu at Guy’s Hospital on the assessment of pulmonary compliance resulted in journal [49] and conference presentations [50] of work that could lead to non-invasive (and thus safer) patient monitoring. My input was in the development of an optimisation scheme to determine physiological parameters from the MR data. I also collaborated with Dr Miquel at the same site on the non-invasive measure of left ventricular pressure leading to an ISMRM presentation [51].

Determining the left ventricular shape and changes from ultrasound is important, especially given the ease of use of ultrasound scanners and their lower cost compared to MRI. I collaborated with colleagues at Oxford on comparison of ultrasound and MR measures of the left ventricle, resulting in a publication in IEEE Trans Med Imag [52].

Research Plan Review

Although not originally planned, a PhD student was recruited to work on the use of prior anatomical information. The output and attendance of this student fell far below expectations and after numerous meetings and warnings we took the decision to terminate his studentship. When the Fellowship started, routine clinical scans at Guy’s were no longer collecting respiratory ordered data and I decided to omit the proposed post-processing of this type of data and concentrate on the more speculative parts of the work plan earlier than originally anticipated.

Research took productive directions that were unplanned due to the establishment of various collaborations. While attending a Philips pulse programming course I met Dr Sebastian Kozerke and he subsequently came to work in our group for one year. The collaboration with him and his colleagues led to papers on correcting respiratory motion during cardiac imaging [15, 13, 14]. I continued some of the work started during my Oxford sabbatical, resulting in journal publications [9, 52]. Within the cardiac group at Guy’s, collaborations resulted in publications on measuring pulmonary compliance [50, 49] and left ventricular pressure [51]. A very productive collaboration was established with The Hammersmith Hospital group and their expertise in parallel imaging. The application for an EPSRC First Grant (GR/S30184) that employed Dr Philip Batchelor was not originally planned but led to a large number of publications. Furthermore, Dr Batchelor and I maintained our links with the group at Gt Ormond Street, Institute of Child Health leading to publications of novel ideas related to diffusion tensor imaging.

Research Impact and Benefits to Society

The reference list at the end of this report is testament to the large number of publications and conference presentations that have resulted from this Fellowship.

The application of optimisation techniques to the measure of pulmonary arterial compliance and resistance [49, 50] has the potential for major improvements in patient care as it could lead to the non-invasive assessment of patients.

Our work on the noise propagation and directional sampling schemes in diffusion tensor imaging demonstrated and explained the optimal sampling schemes [35, 33, 31, 34], this has put the acquisition on a stronger scientific footing.

The potential benefits to healthcare of correcting for a wider class of motions (now including non-rigid) are better diagnosis and reduced cost and risk in the scanning of patients, especially young children. The reduced distortions in DTI now allow fibre directions to be plotted on top of high resolution (non diffusion) anatomic scans. This could lead to a better understanding of disease mechanisms and brain anatomy. The ability to quantify fibre tracts is essential if DTI is to move beyond a visualization tool towards something that enables comparisons between patient groups. The framework developed for handling tensor data is important because it allows data sets to be combined to reduce noise, provides a new measure of anisotropy and enables interpolation which is useful for aligning images from different individuals and in generating detailed fibre pathways.

In the case of flow artefacts, our work on the use of information from multiple coils to reduce artefacts [19] requires knowledge of the position of the artery causing the artefact and researchers at Philips Medical Systems have developed a complementary technique that can locate the source. Together there is the potential for benefiting patient care through better quality images and improved diagnosis.

Public Awareness Activities

I am co-investigator on a Partnerships for Public Awareness grant (EPSRC GR/S83197). This use examples from our research and
medical imaging to enhance the National Curriculum for pupils at GCSE level. The aim is to develop classroom teaching material that uses medical imaging to make Science, Maths and ICT more relevant and exciting. This grant is still active and we have applied to EPSRC for further funding to work with the examining bodies to improve the National Curriculum.

I would be willing to assist EPSRC in relevant future promotional activity, thought our current Public Awareness Activities can be very time consuming.

References


