Image Reconstruction 2009: Motion Correction.
David J Larkman. (david.larkman@imperial.ac.uk)

Introduction

The aim of this document and the accompanying lecture is to provide a very brief overview of motion correction schemes in MRI. The references given should be seen as starting points for the interested reader. It is by no means a comprehensive review.

Motion during data acquisition has been a persistent problem in MRI from its earliest days. Two basic strategies are available to cope with motion: Image fast so that motion is "frozen out", motion can then be ignored, or acknowledge motion exists within the acquisition and minimize and/or correct it. Both leave us with reconstruction problems, many rapid acquisition strategies focus on single slice speed (EPI, TSE for example). These may be fast enough to freeze out motion within a slice acquisition but motion on the longer timescale of multislice acquisitions is still problematic resulting in poor 3D data. Several registration based strategies have recently been developed to tackle this particular problem[1, 2]. The focus of this session will be on tackling motion within multi shot acquisitions and strategies to correct or compensate for it. We usually refer to this as inter-shot motion. The assumption usually taken is that each shot is rapid enough such that intra-shot motion is frozen out.

Although this course is about image reconstruction most of the methods I will discuss cannot be separated from the details of the acquisition strategies, many depend on modified acquisitions to work.

Acquisition Strategies

There are a number of exclusively acquisition based strategies to minimize the effects of motion which have been very successful, some are specific to periodic motion (cardiac and respiratory related motion) such as gating or triggering where an external transducer monitors a signal which is correlated to the motion of interest and this information is used to control when the scanner acquires each shot. The aim being to acquire all shots under as similar conditions as possible[3, 4]. K-space ordering techniques such as respiratory ordered phase encoding[5] can also be used where periodic motion is present and they increase efficiency but generally leave blurring in the images. Other methods do not require periodic motion, for example gradient moment nulling[6] can successfully compensate for first order motion (constant velocity) by careful design of the gradient activity during the pulse, this is widely used and is effective but clearly is limited as most motion has some element of higher order motion which can only be compensated at significant expense to echo time and hence signal and contrast. Other strategies available are multiple averaging, which weights coherent (stationary) signal greater than incoherent motion artifact at the expense of scan time. For respiratory artifact fat suppression (or water selection) can be effective where artifact come predominantly from the chest wall and of course if the acquisition is short enough then Breatholding is effective[7].

Whilst all these methods have great value they are limited or impose limits on the acquisition often extending the scan time. With motion such as sporadic bulk motion (patient twitching) or the patients position drifting throughout the scan they provide little help. If we are to reach the high spatial (and temporal) resolution that high field MR promises then accurate correction of motion corrupted data is essential.

Effects of motion on Data

It is usual to consider the effects on k-space of motion as this is the domain in which time evolves during the acquisition, this often means the motion usually can be described with the minimum number of parameters in this domain. To do this we need to understand how motion affects k-space. Rigid body motion can readily be corrected by applying phase shifts to the measured k-space[8]. In general In plane translations in the image domain result in linear phase ramps in k-space and In plane rotations in the image domain result in rotations in k-space[9]. Rotations can cause significant reconstruction problems as the Nyquist criteria can be locally violated if rotations are large, any rotational component will result in a regridding stage in the reconstruction. Out of plane motion is more problematic for multislice imaging but is generally considered to result in global signal loss in k-space[10]. If 3D Fourier encoding is used then the in-plane relations hold through plane also. More complex motions (e.g. non rigid motion) have no simple k-space description and as such are usually tackled partially or wholly in the image domain, some models for linear expansion have been developed[11]. Complex bulk motion results in phase errors with a spatial variation that is more complex than linear phase ramps. If these phase errors can be measured on a shot by shot basis then correction can be attempted by normalizing image phase between shots.

Motion Correction

We can break down the challenge of motion correction in MR into two parts. We need to accurately identify the true nature of the motion and to apply an appropriate correction. These two parts can be considered separately (in non iterative methods) or together (as is the case in iterative corrections).

Non iterative methods

In this family of methods a measurement of the motion is made and then a correction applied directly assuming that the measurement is accurate. Many of these methods rely on the "navigator" concept. Navigators are repeated measurements of the same object where any changes in the resultant measurements are assumed to be due to motion and from these differences a motion correction is determined (using the known effects of motion on the data). Navigators can also be used to gate and trigger acquisitions (as is often the case with pencil beam navigators to monitor the motion of the diagphram) but we are primarily interested in those applications which impact on the image reconstruction. The simplest type of navigator echo is a 1D navigator echo[8]. Here an additional echo is acquired for every imaging shot. The navigator echo has no phase encoding and so is identical every shot whereas the imaging echos(s) increment phase encoding steps as is usual in imaging. A comparison between the navigator echos for each shot will reveal phase structure if motion has occurred. This phase structure can then be removed from the imaging echos and the data is corrected assuming simple motion models. A 1 D navigator cannot provide information about motion orthogonal to the readout (or through plane) and so this correction is limited. However this concept can be extended to 2D (or 3D) Navigators with two (or three) orthogonal navigator echos[12] or extended further to fully sample a 2D space (spiral or Cartesian readouts)[13]. The advantage of fully sampling the navigator space is that complex spatially varying phase structure can be identified and corrected, this is increasingly being used and developed by researchers in multi shot diffusion weighted imaging where motion is a major problem[14, 15]. Recent developments have shown that a full forward model based treatment of the reconstruction of such data provides a natural framework for such corrections[14] (note: these new methods can involve iterative inversion tools due to the large size of the problem but it is not always a requirement that the motion model is refined during these iterations and so I include them in this section).

The navigator concept has been extended with a class of acquisitions known as "self-navigating" sequences, here the navigation information comes from the imaging data itself, the simplest (and most limited) being a radial acquisition where each shot samples the centre of k-space, if the subject moves then the central point in kspace is modified and by corrected each shot with a global term which makes all the central points is k-space identical then a level of motion robustness can be achieved, the inherent oversampling of the centre of k-space also adds motion robustbness[16] (spiral methods also have some motion robustness for this reason [17]). Radial data correction is limited as any motion orthogonal to the readout direction is not captured – this limitation lead to the development of "propeller" style acquisitions [18] where blades (typically single shot TSE or EPI) are acquired and then rotated to fill k-space. The shared information between shots is now a central 2D region of k-space and so more complex motion can be corrected in the same way as the 2D navigators previously mentioned. A self navigated Cartesian sampled scheme has also been proposed which uses Parallel Imaging to provide the navigation information. Array coil information is used to predict a line of k-space data based on the adjacent line using SMASH[19]. The prediction and actual measurement are compared and subsequent navigator corrections made to make them more similar.

Iterative Methods

Whilst the direct (non iterative) methods have the advantage of simplicity and in many cases a high degree of success they rely largely on inefficient data acquisition schemes. The navigator approach requires an excess of information to be available from which the details of the motion are extracted. Another approach can be taken which does not assume knowledge of the motion but requires a metric (cost function) which can assess when an image is motion corrupted and when it is not. If such a metric is available then repeated estimated motion models can be trialed and tested against the cost function until the cost function is minimized (and hence an artifact free image reconstructed). In general such methods can be efficient in acquisition (often requiring no modification of standard imaging sequences) but the price is that reconstruction becomes computationally intensive.

The key to success of these methods is twofold. First to limit the number of free parameters to be solved for to ensure convergence, usually by imposing a model of the motion (as we have discussed in the non iterative methods) and secondly to have a cost function which has a well behaved approach to a global minimum. A relatively simple cost function is a measure of the energy outside the object (assuming that the object is fully bound by the fov)[11] the nature of the acquisition plays an important role in determining the nature of the background energy present and hence can affect choice of cost function for example in interleaved multi shot acquisitions motion generates n/shot ghosting and hence high coherent signal energy outside the object. Correction of multi shot acquisitions pose an interesting reconstruction question relating to when during the reconstruction the correction should be applied this has recently been generally formulated[20] allowing potentially correction of a wide range of complex motion types

Examples of some other cost functions which relay on the object content rather than background energy are entropy based methods[21], POCS approaches [22] and coil based consistency[23]. The use of array coils to provide information about the consistency of the final reconstruction is a new but potentially powerful tool which uses the different views of the object that local coils generate to perform consistency checks on the reconstruction.

Outlook

Increasingly it is combinations of the approaches outlined above which show most promise. For example the use of 2D navigator echoes with a general formulation of motion correction[14] or the use of respiratory sensors to help parameterize a motion model based correction [24] have both been demonstrated recently. It is only with recent advances in compute power and the adoption of advanced numerical methods by the MR community that the intensive iterative methods where complex motion models can be solved are starting to reach reconstruction times that could see them on commercial scanners in the next few years.

Many of the non iterative methods are already available on commercial scanners, methods such as PROPELLOR are now available from multiple vendors and I expect that the more complex iterative methods will follow provided the currently long reconstruction times can be addressed, the recent use of graphics card processors to perform rapid large scale calculations give one avenue towards significantly speeding these up.

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