

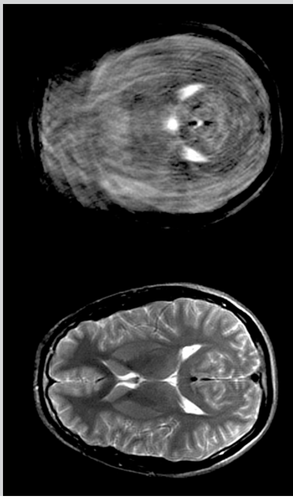

MRI Hot Topics
Motion Correction for MR Imaging

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Motion Correction for MR Imaging

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Motion Artifacts in a Clinical Setting

Patient motion is probably the most common cause of artifacts in today's MR imaging. This can range from physiological motion, such as respiratory or cardiac movement, to physical movement by the patient. Physical movement may be due to voluntary movements or involuntary movements as in Parkinsonism. Physiologic motion can be controlled by gating or in the sequence design, so it is really the physical patient movement that creates the largest concern and will be addressed here.

The reality is that patients are often in pain and may or may not be cooperative. Many times, the patient for whom the results are most needed is also the patient who can be the least cooperative. Beyond that, the longer a patient spends in the scanner the more likely they are to become restless, agitated, or nervous, which again leads to motion in the images.

Patient Motion and the Clinical Exam

Since most exams in the chest and abdomen are dominated by physiologic motion, the goal of most motion correction algorithms is to produce ideal images in the head or extremities. In the clinic a typical head examination consists of T1, T2 Turbo Spin Echo (TSE), Dark-Fluid (FLAIR) inversion recovery (IR), and possibly a diffusion scan (EPI or TSE). Practical imaging times for these exams at 1.5T are about 3 minutes, 2 minutes, 3 minutes, and 1 minute, respectively. Notice that the sequences with the longest scan times are also those where the most motion artifact can occur, simply because the patient has more time to move. So the diffusion scans, and to a lesser extent the T2 TSE sequences, are not as susceptible to patient motion since they are also the fastest.

But motion is still a very real problem that requires an efficient solution. Images that are corrupted by motion artifacts can be rendered unreadable. Many sick patients are unable to cooperate long enough to be imaged without artifacts. Some are simply unable to complete an exam and must have the scan repeated, be called back for another appointment, or be scanned with another, less ideal, modality. Integrated Parallel Acquisition Techniques (iPAT) significantly reduce scan times and are useful, but in a few cases strategies for motion control are needed. In the setting of the MR department, fast, effective motion control provides better care, serves more patients (which increases revenue), and makes scanning more efficient by eliminating repeat scanning (which could potentially increase profit).

Current Strategies for Motion Control

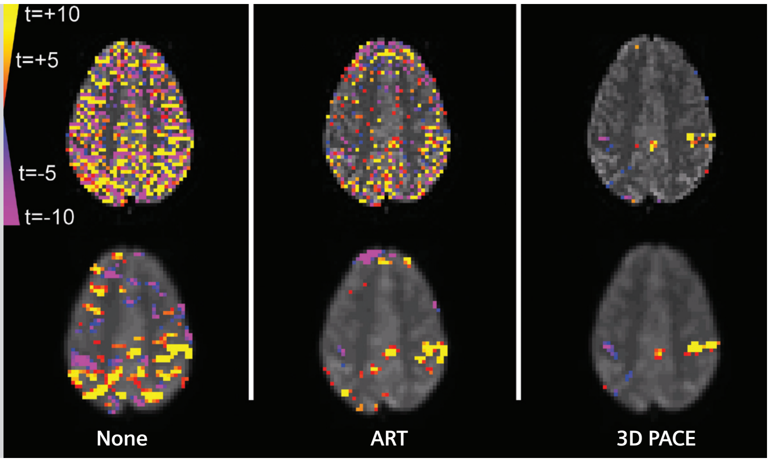
Today, the most common strategy for handling motion artifacts is to use retrospective motion correction. These post-processing approaches use a variety of algorithmic, iterative approaches applied in the image domain as well as in k-space.[1] While they can be effective and are certainly applicable to any acquired image, once the data is corrupted by motion, you cannot recover ideal data. A better strategy, as seen in some of the newer techniques and research, is to perform the motion control during the acquisition, or "inline", so that the data is never corrupted.

Navigators

The fastest "inline" method of controlling motion is the "navigator" technique, 1D-PACE (Prospective Acquisition Correction) to Siemens.[2] This technique only adds about 30 ms to your scan and is typically used for controlling physiologic motion, such as respiratory motion in cardiac or abdominal exams. It works by acquiring a single line of data from a pencil-shaped volume that crosses the boundary of the diaphragm. This single line of data allows the scanner, in real time, to know the exact position of the diaphragm and trigger a scan only when the diaphragm is at the appropriate position. So misalignment is eliminated by only acquiring data when the anatomy is in a specific location.

Siemens provides an enhancement to the traditional navigator technique that makes it more robust and adds quality and reliability. The 2D-PACE technique acquires a low resolution gradient echo image in approximately 100 ms. A low flip angle is used to

Figure 2: Finger tapping fMRI: trained stimulus-correlated 1.5° rotation head motion.



ensure that the magnetization is only minimally effected maintaining final image homogeneity. Instead of a pencil beam, a box is positioned by the user and a 2D evaluation of the diaphragm position is used. The 2D-image provides much more information making the technique broadly applicable. This lead to the emergence of excellent quality "free breathing" or "multi-breath-hold" studies like 3D TSE MRCP. (See Figure 1.)

Figure 1: T2 TSE 3D Restore; PAT 2; 2D PACE; 1 mm x 1 mm x 1.5 mm; Body Matrix, Spine Matrix.

It's not hard to see, however, that navigator techniques provide little help in the brain where bulk motion of the entire imaged volume is the problem. Additionally, since this motion is not periodic and there is no guarantee that the head will ever move back to the original position, the user is left with only post-processing techniques.

3D Strategies

Other methods have been developed specifically to deal with this unpredictable bulk motion that is seen in head examinations. Often rigid body registration techniques are used as a post-processing strategy. While from an ideal perspective, these should be more than sufficient, practical issues such as partial volume effects and through-plane signal changes can create tremendous problems if all of the motion control is left until after the acquisition is complete.

An alternative strategy is to use each acquired volume to estimate any motion that may have occurred using a similar rigid body technique. Each volume is compared with the previous volume to calculate motion in six dimensions (3 translations and 3 rotational axes). Then, in real time, the system uses this information to adjust the acquisition parameters (the imaged volume) so that the brain stays in the same position in the image, no matter where the head has moved. Siemens is the only vendor to have implemented this strategy. It is called 3D-PACE and is used with functional MRI exams.[3] 3D-PACE prospectively adjusts gradient commands according to 6-dimensional head motion providing accurate fMRI results. (See Figure 2.)

Emerging Strategies

In recent years there have been a number of new methods proposed for motion control, though few have caught on. Two methods of note are PROPELLER and octant or cloverleaf navigators.

A technique termed "periodically rotated overlapping parallel lines with enhanced reconstruction" (PROPELLER) was introduced by Pipe in 1999.[4] Originally developed but not implemented on a Siemens MR scanner, over the last 5 years this method has received quite a bit of attention and has proven itself to be useful for motion correction in some cases. The PROPELLER technique collects data in concentric rectangular strips rotated about the k-space origin. (See Figure 3.) The central region of k-space is sampled for every strip, which (a) allows one to correct spatial inconsistencies

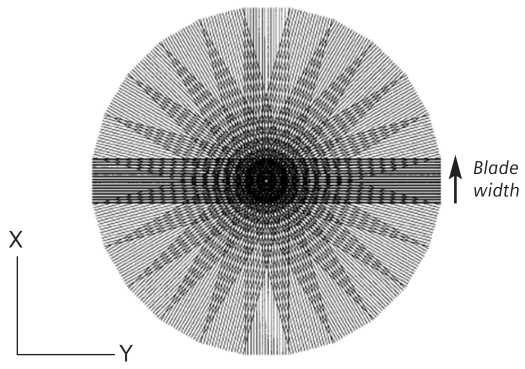
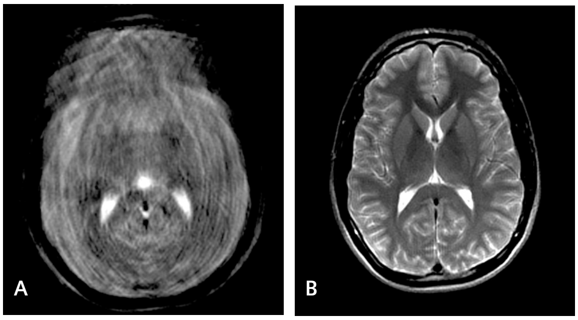


Figure 3: PROPELLER.

in position, rotation, and phase between strips, (b) allows one to reject data based on a correlation measure indicating through-plane motion, and (c) further decreases motion artifacts through an averaging effect for low spatial frequencies. However, while PROPELLER does acquire data differently, all of the motion correction occurs as a post-processing technique that attempts to correct corrupted data instead of inline correction to start with the best data.

In PROPELLER, you can acquire any 2D T2-weighted turbo spin echo (TSE) scan[4] or a diffusion weighted multi-shot TSE scan.[5] (See Figures 4A–4B.) These are



Figures 4A–4B: Head with axial rotation in plane. Figure 4A head without propeller; Standard TSE. Figure 4B head with propeller; motion corrected.

important images to be able to acquire without image artifacts, however, this falls far short of being able to provide a full clinical exam, with both T1 and IR, on an uncooperative patient. Additionally, the PROPELLER technique does not provide through-plane motion correction.[4,6] So while a patient can rotate their head "in-plane", through-plane motion is accounted for by eliminating data. It is rather unrealistic to think that a real patient would only move their head in the imaging plane.

The results, however, have been positive. In a number of studies, radiologists have preferred to view PROPELLER images over conventional T2-weighted TSE or EPI-DWI scans.[6-8] One drawback, recently noted, was that EPI-DWI is superior to PROPELLER for quantitative analysis (i.e. FA mapping) due to artifactual high-signal bands in the PROPELLER images.[9]

A concern for PROPELLER is total time required. In today's clinical workflow, the goal is to decrease the amount of time needed to perform an examination, from patient set-up to scanning, etc. PROPELLER, however, increases the time it takes to perform a scan. Specifically, it adds a factor of pi/2 to the acquisition due to the oversampling of the center of k-space.[4] To its credit, this does increase SNR due to increased k-space sampling. Additionally, the series of corrections that are applied to the 2D slices in PROPELLER to account for translational, rotation, and phase changes that may occur during acquisition each add to the reconstruction time. The intense post-processing of the PROPELLER technique adds about 2 to 3 minutes of additional reconstruction time per scan.[6]

In all, while PROPELLER can reduce apparent motion artifacts that appear in T2 and diffusion weighted TSE exams, it fails to seamlessly fit into today's clinical workflow and is outperformed by traditional EPI techniques for quantitative diffusion analysis.

Another new method for controlling motion is the octant or cloverleaf navigator approach. Developed by Dale and Van Der Kouwe in 2004, cloverleaf navigators are an improved k-space trajectory and associated mapping procedure that allows rapid, inline correction or rotations and translations with minimal additional acquisition time.[10, 11]

The cloverleaf trajectory covers each of the principal axes and three arcs, which connect each of the three axis pairs. A complete navigator set takes only 2.2 ms inside of each TR to be played out. The inherent 3D nature of the navigator makes it appropriate for both 2D and 3D acquisitions and it could be added to almost any imaging sequence. This provides distinct advantages since it can be used for any contrast, any acquisition method, and could be applied to an entire study for an uncooperative patient.

The navigator correction system works in concert with a map of k-space in the vicinity of the navigator acquired in a short preliminary mapping sequence of 15 s. By playing out the navigator in each TR, a linear mapping between the acquired navigator and the preliminary map allows the angle of rotation to be determined with a simple matrix multiplication. The changes due to translational and rotational motion are then fed back to the MR system that applies gradient corrections during the acquisition. This technique carries with it the advantage of finding and correcting motion during the acquisition, as opposed to using post-processing.

A very new and promising technique, cloverleaf navigators have shown great promise for inline control of motion without the drawback of additional scan and reconstruction time. It is hoped that this will provide a robust method for motion control, applicable to today's demanding clinical environment, but to date this technique is unproven clinically.

Conclusion

A series of motion correction techniques have been proposed over the years. There is common understanding that the underlying goal is to provide MRI to everyone who needs a scan. While many believe this is best achieved through motion control, there are still a number of retrospective correction algorithms available. The new techniques, while promising, have their drawbacks, as well. The hope is that through further refinement and innovation, a robust method (or combination of methods) will provide perfect motion control for all patients.

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