Physics Tutorial 4: Image Distortions

Originally Written by James Meakin and Alex Gardener
Last Modified: Mark Chiew, Robert Frost, Nadine Graedel, Alan Stone, Tom Okell, Oct 2014

The purpose of this tutorial is to provide an understanding of how B0 field inhomogeneity causes distortion in EPI images, and how acquisition parameters can be chosen to acquire higher quality data. Questions without any asterisks are those that should be attempted by everyone, whereas more challenging questions are marked with one (*) or two (**) asterisks, and should be considered optional. Take these opportunities to think about these questions, and then discuss your answers with your tutor.

At the end of the tutorial period, you will receive a "take-home tutor", which is an annotated version of this tutorial guide that will help you complete the tutorial at home if you don't manage to make it all the way through with your tutor, or if you missed the tutorial session.

Attendance will be taken by the tutors, and marks will be given by participation. If you would like additional feedback or clarification on the tutorial material, you are welcome to submit your questions or comments to Weblearn, and a tutor will provide written feedback for you. Those unable to attend the tutorial must submit answers to all unstarred questions to receive credit for the tutorial.

Part 0 – Getting Started

0.1 Starting MATLAB

Download and unzip the file containing the tutorial resources from Weblearn, or if you have access to the FMRIB internal network, copy them into your current directory from here:

~mchiew/GradCourse/4_Image_Distortions

Start MATLAB, and make sure you're inside the tutorial directory (i.e., the folder containing all the tutorial files).

Note to jalapeno00 users*:* please start with the -nojvm option, "matlab -nojvm"; *this should reduce server CPU load if lots of people are trying to use jalapeno00 simultaneously*

Part 1 – Distortion Simulator

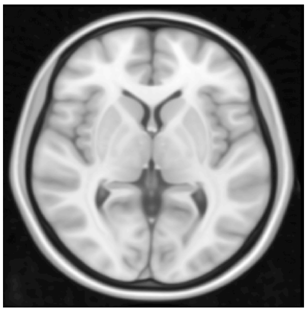

Figure 1

`simDistortion()` is a simplified simulator for the acquisition of echo-planar imaging (EPI) data. This simulation uses a slice of the MNI 0.5mm template (Fig. 1) as source data, and simulated the effects of magnetic field offsets at different spatial locations.

1.1 Chemical Shift

One of the most fundamental relationships in MRI is the correspondence between magnetic field strength and resonance frequency. There are two ways we can measure signals with the *wrong* resonance frequency:

- The magnetic field is not what it should be
- The resonance frequency is wrong because the signals are coming from non-water protons

The former case is often called *magnetic field inhomogeneity* (covered later in this tutorial), whereas the latter is called *chemical shift*. Fat molecules, for instance, contain protons just like water, but their resonance frequencies are slightly shifted (by 3.5 parts-per-million) relative to water protons. However, when signals are measured, it is difficult to distinguish between water that is in the right place, and fat that is in the wrong place, which results in chemical shift artefacts.

Question 1.1.1
Why do off-resonance spins shift in the Phase-Encode direction in EPI? Why isn't there (much of) a shift in the readout direction? Why does this not occur in the simple GRE image?

The separation between the fat and water resonance frequencies changes with the strength of the main magnetic field.

Question 1.1.2
How does changing field strength change the shift of the fat? How does the fat shift at 7T compare to 3T or 1.5T?

One solution to fat-related chemical shift artefacts is the use of fat saturation ("fat sat"), which destroys the magnetisation of protons in fat by applying an RF pulse at the fat resonance frequency.
Consider the following analogy:

- Imagine a race (scan) between neighbourhood cats (water), but to which unwanted dogs (fat) show up to participate. If you blow a normal whistle (RF excitation), all the animals start running and the dogs end up disrupting the race. Instead, if you first blow a whistle that only dogs can hear (fat-selective RF excitation), the dogs go off and they run first. Only after the dogs are gone (fat saturated), do you blow the regular whistle and run the race with cats only (water only image, no fat).

Question 1.1.3**
Can you think of other ways of suppressing fat signals from your images?

1.2 Distortions

In the last section, the simulated system assumed perfect shimming (perfectly homogeneous magnetic field). In reality, shimming a brain is difficult due to its shape and the presence of air-tissue boundaries. The simulation can additionally model the effects sinus cavities have on the magnetic field.

Recall from the lectures how the direction of distortion changes with the phase encode direction:

- in orientation or angle of the phase encode direction, e.g. anterior/posterior or left/right
- in order of traversal of k-space, e.g. bottom to top (blip up) or top to bottom (blip down)

Question 1.2.1
In this example, why would it be preferable to use blip-up rather than blip-down? What is a possible advantage to interleaving the blip-up and blip-down acquisitions?

Question 1.2.2
Why do you think that Posterior-Anterior is the favoured PE direction, over Left-Right? Can you think of a case when we'd want to use a left-right PE?

The level of distortion that any given field inhomogeneity will produce will depend on the **bandwidth** or **bandwidth-per-pixel** in any given direction. The parameter that is set on the (Siemens) scanner is the bandwidth-per-pixel in the readout direction. This value specifies the range of frequencies present in one pixel, and is equal to the total bandwidth across the field-of-view divided by the number of pixels in the readout direction:

$$BW\text{-}per\text{-}px = \frac{BW}{N_{READ}}$$

The time to acquire a single line of k-space is also given by 1/bandwidth-per-pixel:

$$\frac{1}{BW\text{-}per\text{-}px} = \frac{N_{READ}}{BW} = N_{READ}\Delta \mathrm{t}$$

In EPI, the magnetisation is 'recycled' by acquiring multiple phase encode lines after a single RF excitation. The time between phase encode lines is therefore limited by the time to acquire a single line of k-space plus the time it takes to switch the gradient from positive to negative. This is referred to as the phase encode spacing.

Question 1.2.3*
For a 64x64 matrix our system is capable of producing a maximum readout bandwidth of 7500 Hz/pixel. On our system what is the minimum phase encode spacing? At which readout bandwidth (to the nearest 500 Hz/px) does this occur? What is the disadvantage of using higher bandwidths (think of at least two)?

Another way to reduce the spacing between phase encode lines is to use parallel imaging. In parallel imaging, phase encode lines are skipped and coil sensitivity information is used to fill in the missing lines. Skipping lines greatly decreases the phase encode spacing, since multiple lines are effectively "acquired" in the time it takes to measure one.
One implementation of parallel imaging is called GRAPPA (stands for Generalized Autocalibrating Partially Parallel Acquisitions), and on Siemens scanners it is often referred to by the terms PAT or iPAT.

Question 1.2.4*
Consider acquiring data using a 32 channel receive coil (a receive coil consisting of 32 individual radiofrequency coils). What is the theoretical maximum acceleration factor you could achieve with 32 coils (assuming best-case scenario)? Why do you think this cannot be attained in practice?

Question 1.2.5
What happens to the distortions and the noise as the GRAPPA factor is increased?

What is a sensible maximum GRAPPA factor for this simulation?

Extra Information – The cost of parallel imaging

When parallel imaging is used to accelerate the acquisition of an image by a factor R, the noise in the image is expected to increase by a factor of g*sqrt(R), which can significantly impact the SNR of the image.

Two different factors contribute to this noise increase:

1. Unfavorable coil geometries can lead to spatially varying noise amplification factors, called "geometry-factors" or g-factors for short. The g-factor depends on the acceleration factor and the configuration of the receive coils, and can range from 1 (ideal, no amplification) to >1 (noise amplification).
2. When N/R lines of k-space are acquired instead of the full N, this reduces the total readout time by a factor of R, and recall that SNR is proportional to the sqrt(readout time). This is a fundamental relationship, and no degree of coil rearrangement can reduce the impact of this factor. Note however, that this reduction is relative to a fully-sampled acquisition with the same coil, so if measurement quality were improved significantly in a new coil, the relative loss in SNR due to acceleration may be well accommodated by an overall increase in the absolute SNR levels provided by the coil.

1.3 Dropout

From the lectures, recall that field inhomogeneity causes dropout in all gradient-echo sequences, but that distortions primarily occur in EPI (due to extended readout durations). However, distortions and dropout are linked as they are caused by the same effect, B_0 inhomogeneity. It may be useful to think of distortion relating to *inter-voxel* field inhomogeneities, and dropout relating to *intra-voxel* field inhomogeneities.

Question 1.3.1

Why does changing the TE affect the dropout? What about slice thickness? What will this do to signal levels? How does changing the TE or the slice thickness affect the distortions in EPI?

Question 1.3.2**

Introducing spin-echoes almost completely reduces the effect of signal dropout. Explain why this is the case.