3-D Gradient Shimming
3-D Gradient Shimming on imaging and micro-imaging systems

Technical Overview

Introduction

Advantage statement
The GE3DSHIM method is a 3-D gradient shimming procedure developed for Agilent spectrometers equipped with imaging gradients. It is a fast and automated procedure for shimming a region within a sample region. Multiple iterations are possible using all or groups of shim coils. A particular advantage of this method for imaging and micro-imaging applications is the ability to specify an arbitrary region of interest using the image planning tools available in VnmrJ software.

A homogeneous field is critical for many imaging applications, such as localized spectroscopy and echoplanar imaging. The traditional shimming methods of monitoring the NMR signal and manually adjusting the shim currents are tedious and generally not practical for most imaging applications. A more elegant procedure is based on field mapping using imaging techniques. A 3-D field map is measured and the shim currents needed to minimize this field is determined using an analytical procedure.
The Pulse Sequence

The shimming procedure described in this article is based on a 3-D gradient echo sequence (GE3DSHIM), (Figure 1). Two images at echo times, TE1 and TE2, are collected and the field maps calculated [1,2]. The field information is encoded into the images during the echo time difference, TE2 – TE1, and results in a phase change in the images. The frequency (which is proportional to the field) is then determined from the rate of change of phase,

\[ F = \frac{(P2 - P1)}{(TE2 - TE1)} \]  

(1)

The phase (P) is obtained from the real, R, and imaginary, I, components of the complex image data,

\[ P = \arctan(I/R) \]  

(2)

Figure 1. The pulse sequence used in 3-D gradient shimming.
The Shimming Procedure

The first part of the shimming procedure requires the shim coils to be calibrated. A small current is applied to a shim coil and a 3-D field map, Fs, is measured. The field map measured will include the shim field as well as the residual field in the magnet. A reference field map, Fr, is measured and subtracted from Fs to obtain the field produced by the shim coil alone. This procedure is repeated for each shim and a set of shim field maps are generated.

When shimming a sample, a 3-D field map of the sample is obtained. Using the shim field maps, an analytical routine is used to calculate the shim currents needed to minimize the residual field. The shims are set and the procedure repeated, if necessary, to further improve the field homogeneity. Typically, 1–4 iterations may be needed for optimizing the shims. One of the advantages of the 3-D gradient shimming is that an arbitrary region in the image can be specified for shimming.

Experimental Results

The experiments were done using a 98 mm bore, 9.4 T (400 MHz) magnet equipped with 100 G/cm, 45 mm (id), RRI gradients and Oxford 28 channel shim coils. A 25 mm NMR tube containing water was used to demonstrate the 3-D gradient shimming method. The sagittal image corresponding to the sample is shown in Figure 2.

Figure 2. Sagittal, gradient echo image of the test sample in a 25 mm RF coil.

The shimmaps for first, second, third and fourth order shims were collected from the same sample using a field of view of 45 mm along the z direction and 25 mm along the x and y directions. (By visually inspecting the shimmaps, it was found that the x4 and y4 shim coils were not present and were omitted in the analysis.)

Figure 3 shows the spectra taken after all the shims were set to zero. Figures 4 and 5 correspond to spectra taken after the first and second iterations, respectively. The shim analysis was done on the whole sample and appeared to converge after just two iterations using first to fourth order shims.
The 3-D gradient shimming was also done using first, second and third order shims for comparison. The line analysis using the `res` command gave linewidths, at 50%/0.55%/0.11% of the peak height, 45/594/1455 Hz after the first iteration and 27/582/1419 Hz after the second iteration. Repeating the shimming routine did not improve the linewidth any further.

Figure 3. NMR spectrum from a water sample in a 25 mm tube taken with all the shims set to zero.

Figure 4. NMR spectrum after the 3-D gradient shimming using first to fourth order shims.

Figure 5. NMR spectrum after two shim iterations.
Advantages

3-D gradient shimming is a versatile and fast procedure that can be fully automated. Shimming generally requires about one to four iterations and each iteration takes about one minute. The procedure generates a 3-D field map so an arbitrary region can be specified for shimming and optimized. For example, a user can specify a voxel region for localized spectroscopy and a slab region for multislice imaging. The image planning tools used in VnmrJ provide a convenient way to specify the shim regions.

Any number of shim coils can be optimized when using 3-D gradient shimming. This is particularly advantageous with typical samples used in imaging because they often exhibit complex magnetic susceptibility-related field gradients requiring third and fourth order shims.

Practical Considerations

Typical samples used in imaging are heterogeneous and show broad lines that are difficult to shimm. The variations in magnetic susceptibility gradients within the sample tend to cause large, local field gradients within the sample. The latter causes poor SNR due to T2* related signal loss and uncertainty in the field and phase measurement represented by Equation 1. Reducing the echo times, TE1 and TE2, helps to minimize these problems. Uncertainty in the field measurement arises when the phase change in Equation 1 exceeds ± 180 degrees and is referred to as phase-wrapping. The Agilent GE3DASHIM routines use a phase-unwarping procedure to overcome this problem.

When dealing with water and fat signals in tissue samples, for example, the phase measurement will be unreliable because of the chemical shift differences between the two components. In the latter case, fat suppression must be employed to minimize the fat component. It is also essential that the sample remain stationary during the experiments. In the case of preclinical studies, special monitoring equipment must be used to trigger the spectrometer at a specific time during the cardiac/respiratory cycle so that motion effects are avoided.

Results and Discussion

Shimming is a challenging problem when dealing with typical imaging samples. The success of localized spectroscopy and echo planar imaging requires highly homogeneous fields within the region of interest. The GE3DASHIM routine implemented on Agilent imaging and micro-imaging systems provides a fast, convenient and automated way to shimm complex samples. The VnmrJ software provides user-friendly graphical tools for specifying the voxel and slice regions for planning and shimming.

References
