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Communication

Gradient hysteresis in MRI and NMR experiments

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Abstract

In this paper, we describe a gradient hysteresis effect that can modulate the current in gradient coils during MRI and NMR experiments. A simple pulse sequence is presented for the purpose of evaluating the resulting changes in the accumulated phase. Additionally, the nature of the gradient pulse shape changes is described. These experiments will be of interest to MRI and NMR scientists who are developing pulse sequences requiring precision gradient performance or who are currently seeking the source of unexplained NMR artifacts.

Keywords: NMR; MRI; Gradient; Gradient hysteresis; Artifacts

1. Introduction

Precise gradient performance is critical for many magnetic resonance imaging and spectroscopy experiments. Deviation of gradient fields from the pulse sequence prescription frequently results in artifacts in acquired data. These artifacts lead to errors in data interpretation and may unnecessarily restrict the application of pulse sequences. Consequently, research into high performance gradients has been the topic of much investigation, particularly in magnetic resonance imaging.

Deviations from the prescribed gradient field will most obviously occur if the prescribed current through the gradient coils is unfaithfully delivered. It is conceivable that such errors may be introduced at any point along the chain of electronics required to produce and amplify the prescribed signal. While some of these effects may be empirically corrected after system fabrication and assembly, it may be tedious or impossible to develop corrections for non-linear effects that also accommodate flexible and complicated pulse sequence designs.

We describe in this communication a non-linear gradient hysteresis effect. We first discovered the effect on our system during development of a fast spin-echo (FSE) imaging sequence [1] for use with multiple mouse magnetic resonance imaging (MMMRI) [2,3]; however, many other systems and sequences are likely to be similarly effected. Fig. 1 shows a brain image in a live mouse with significant artifact levels that destroy any fine detail in the image. Progressive decomposition of the FSE sequence into simpler components revealed that the artifacts were related to errors in encoding and rewinding during phase encode acquisitions. After some effort, the phase errors were found to be consistently dependent on the amplitude and polarity of preceding gradient pulses, even when those pulses occurred prior to the spin excitation and as long as seconds to hours previously. As these effects did not exhibit any identifiable lifetime—as would be the case with eddy currents for instance, we designate this effect as gradient hysteresis.

In this communication, we present a simple NMR method to measure the phase error resulting from gradient hysteresis. The method can be used by experimenters for onsite testing of gradient power supplies in the aim of quality assurance, but is intended primarily for the purpose of aiding scientists in identifying this particular source of artifact and evaluating its effect on particular sequences.

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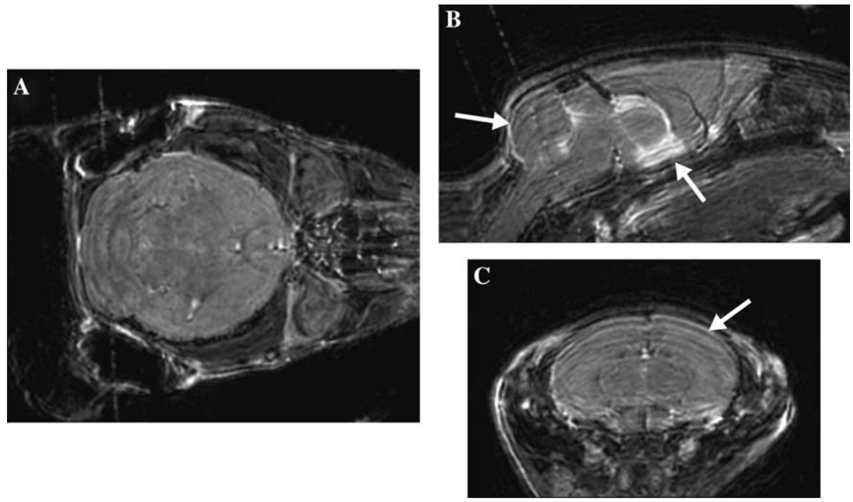

Fig. 1. Three-dimensional fast spin-echo images of a mouse brain with artifacts due to gradient hysteresis. The imaging field-of-view was offset from gradient isocenter 25 mm horizontally and 43 mm vertically with the gradient read-out direction set nose-to-tail. Image parameters were: TE/TR = 12/900 ms, $TE_{eff} = 36$ ms, ETL = 8, two averages, $40 \times 24 \times 24$ mm field-of-view and matrix size $400 \times 240 \times 240$. Scan duration was 2 h 40 min. The artifact appears as split structures (arrows) and obscures fine detail.

2. Materials and methods

Hollow polyethylene balls with 10 mm outer diameter were prepared for use as NMR samples. Each ball was filled with water using a syringe with a 27 gauge needle. Prior to running the sequence, the plastic ball phantom was placed 43 mm off-axis in the direction of the gradient to be tested.

Fig. 2 provides a diagram of the pulse sequence used to examine gradient hysteresis. In its simplest form, the sequence consists of three parts: a preparatory gradient pulse, a gradient test block and signal acquisition. The delay after the gradient preparation pulse should be long enough to allow for any eddy currents from the preparation pulse to completely decay; this is easy to assess empirically by holding all parameters fixed and increasing the delay until a constant free induction decay (FID) phase is observed. An excitation pulse is then used to rotate longitudinal magnetization into the transverse plane. This is followed by a gradient test block prescribed to have zero area. A bipolar pair of trapezoidal pulses, as shown, is representative of the phase-encoding and rewinding pair in an FSE sequence. This bipolar pulse shape is relevant to many MRI and NMR sequences, but if different sequences or gradient shapes are of interest then alternate gradient shapes could be used. Finally, an acquisition block acquires the transverse magnetization signal. A simple acquisition of the free induction decay (FID) is appropriate if the sample is small and shimmed to a narrow linewidth. Alternatively, if susceptibility effects complicate interpretation of the data, the acquisition block could be adjusted to contain a refocusing pulse followed by acquisition of a spin echo. For the NMR phase data in this paper, gradient pulses were 2.87 ms in total length with ramp times of 870 μs. Ramp times were held constant so that the ramp rate varied with gradient amplitude.

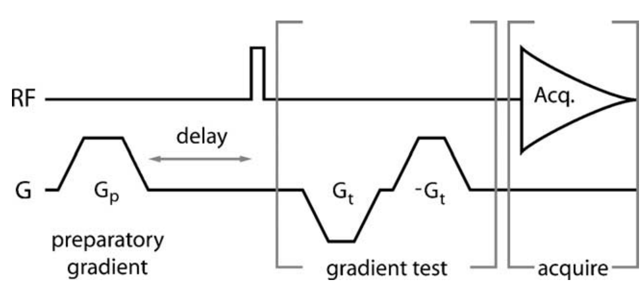

Fig. 2. A sequence to test for gradient hysteresis. A large gradient pulse G_p serves to prepare a particular state of hysteresis and is followed by a delay to allow for complete eddy current decay. An excitation pulse then produces transverse magnetization. A pair of equal and opposite test gradients with amplitude G_t serve as the readout. The remainder of the decaying signal is subsequently acquired. Alternatively, a spin-echo acquisition can be used by inserting a refocusing pulse and a delay.

As a supplement to the NMR experiment, the actual magnetic field induced by the gradients at the sample was measured with a small pick up coil (placed at about 65 mm from gradient isocenter). The coil consisted of 16 turns of 24 AWG magnet wire (Belden Electronics Division, Richmond, IN) with a 9.75 mm inner diameter and was oriented parallel to B_0. Voltages induced in the coil by gradient pulses (3.0 ms total duration) were recorded and stored on an Agilent infiniium oscilloscope (Agilent Technologies Canada, Mississauga, ON, Canada). Several different preparation pulses were used prior to the data acquisition with the intention of assessing gradient hysteresis effects on gradient ramp shape.

Experiments were performed on a Varian INOVA console (Varian NMR Instruments, Palo Alto, CA). The gradient set (Tesla Engineering, Storrington, Sussex, UK) had 29 cm inner bore diameter, 120 mT/m maximum amplitude, and 870 μs rise time. Two gradient amplifiers models were used during these experiments (QDCM

380/135/220-LN, MTS Automation, Horsham, PA and subsequently model 266, Copley Controls, Canton, MA). Both these amplifiers use a Danfysik Ultrastab 866 current probe (Danfysik, Jyllinge, Denmark).

3. Results

An example of the data produced by these experiments is shown in Fig. 3. Bipolar test pulses of +60 and −60 mT/m were used, where the amplitude G_t refers to the first gradient pulse. The preparatory pulse before each acquisition was sequentially varied in amplitude G_p from −60 to +60 mT/m. The phase of the acquired FID signal was recorded and plotted in Fig. 3. In a precisely executed gradient, the phase in this experiment should be zero. However, while the observed phase is close to zero when the preparation pulse is of opposite polarity to the first pulse of the bipolar pair, it changes rapidly and non-linearly when the preparation pulse is of the same polarity. Large phase differences are clearly present as a function of preparation pulse amplitude. These differences are larger than 2π radians in some cases. For the 60 mT/m bipolar test pulses used here, the error corresponds to an imbalance of 0.6% between the bipolar pair. We further observed that the general phase behavior did not vary significantly with either gradient duration or ramp rate. Additionally, the effect was observed equally on all three gradient channels. Consequently, it appears to be an amplitude dependent effect unrelated to gradient coil geometry.

Adjustment of the delay following the preparation pulse is not observed to have any effect on the phase behavior of the signal. We found that a delay of 2.0 s was more than sufficient to completely ensure eddy current decay. Beyond this time, the hysteresis "memory" lasts indefinitely until the next gradient pulse. Increasing the delay to tens of minutes results in the exact same phase shifts. In fact, the delay can be made sufficiently long that the gradient amplifiers, the DC power supply and the step-down transformer providing AC power to the amplifier cabinet can all be turned off and then on again; the phase of the next acquisition is still found to be identical. Thus, the phase anomaly from the preparatory gradient has no measurable lifetime and persists in the absence of power to any of the amplifier circuitry.

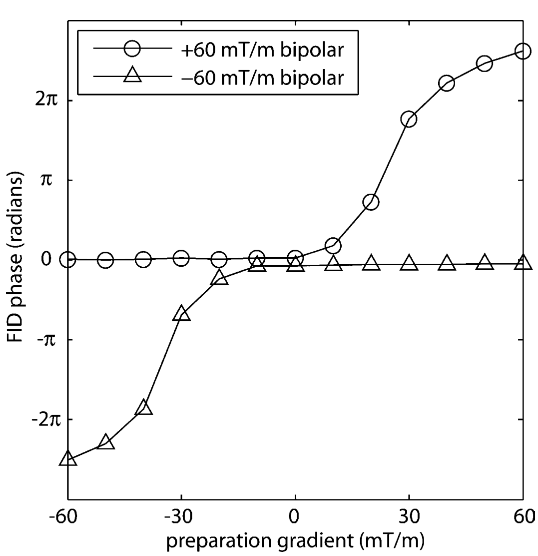

Fig. 3. Induced phase error as a function of preparatory gradient strength G_p. The preparatory gradient was linearly varied from −60 to +60 mT/m with bipolar test gradients of +60 mT/m (circles) and −60 mT/m (triangles) (where the stated amplitude is that of the first gradient pulse in the bipolar pair).

In Fig. 4, the voltages induced in the pick up coil from a single 120 mT/m gradient pulse of 3 ms total duration are plotted for two different preparation pulse amplitudes. The pick up coil is sensitive to dB/dt and hence measures the derivative of the gradient waveform. Thus, the traces in Fig. 4 are not bipolar gradients, but represent the rising and falling edges of a single gradient. In Fig. 4A, the gradient is preceded by a −120 mT/m preparation pulse. Significant abnormalities in the attack ramp of the gradient (represented by the first lobe in the voltage plot) are observed. Use of a +120 mT/m preparation pulse, as shown in Fig. 4B, produces an improved gradient waveform. Integration of these waveforms gives a picture of the shape of the gradient pulse shape. In Fig. 4C, integrated curves from the pick up coil data are windowed to show the attack ramp. The nature of the ramp abnormality can be clearly appreciated when the −120 and +120 mT/m preparation pulse data are overlaid. The most significant region of deviation, between about 20 and 50 mT/m, corresponds to the region of most rapid phase change in Fig. 3. Furthermore, the abnormality in the pick up coil data shown in Fig. 4A had similar properties as the phase data in Fig. 3: it appeared independent of the delay time after the preparation gradient; it could be corrected with polarity reversal of either the preparation pulse or the bipolar pulse; and began to be less apparent at smaller gradient amplitudes (though could not be reliably observed at amplitudes less than about 30 mT/m).

Replacement of the original MTS gradient amplifiers with the Copley amplifiers that do not exhibit significant hysteresis resolved the phase problem exhibited in Fig. 3. Acquisition of a FSE image identical to that shown in Fig. 1 with these amplifiers is shown in Fig. 5. Significant improvement in the image quality is evident and fine image details are recovered.

4. Discussion

As a result of the long hysteresis "memory," interpretation of the data in Fig. 3 is complicated. The "zero" amplitude preparatory pulse plotted in Fig. 3 cannot actually be interpreted as an unaffected reference; instead, the hysteresis state in this case is determined by gradient pulse(s) from the previous TR. Furthermore, it is important to note that the second pulse in the bipolar gradient pair is always effected by hysteresis established by the first pulse. Hence

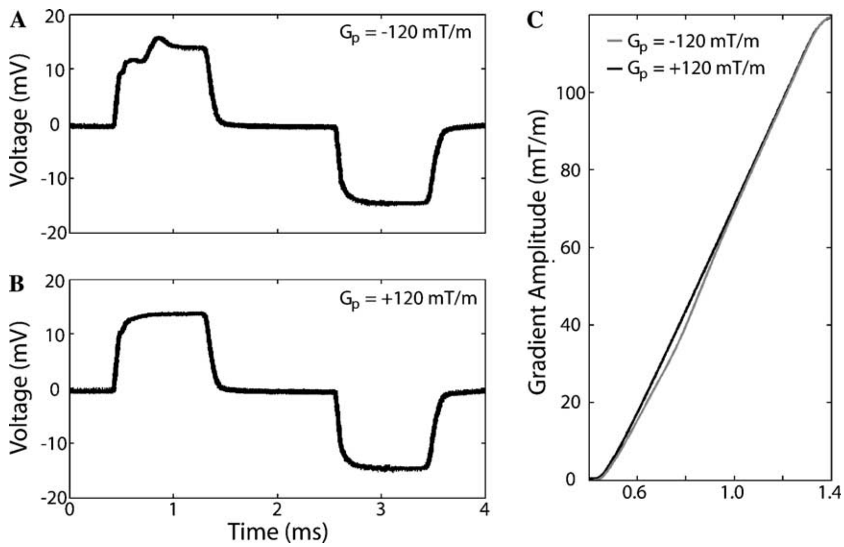

Fig. 4. Gradient ramp assessment using a pick up coil. The voltage recorded from a pick up coil placed ~65 mm away from gradient isocenter was recorded. The pick up coil is sensitive to $\mathrm{d}G/\mathrm{d}t$, so the two lobes in (A and B) represent a single gradient pulse with amplitude +120 mT/m. A preparation pulse of −120 mT/m prior to the gradient pulse shown in (A) reveals abnormalities during the attack ramp of the trapezoidal gradient. (B) A +120 mT/m preparation pulse does not show the same effect. Integration of these waveforms is shown in (C), where the modification to the gradient ramp shape can be clearly seen in the overlay of the −120 and +120 mT/m curves.

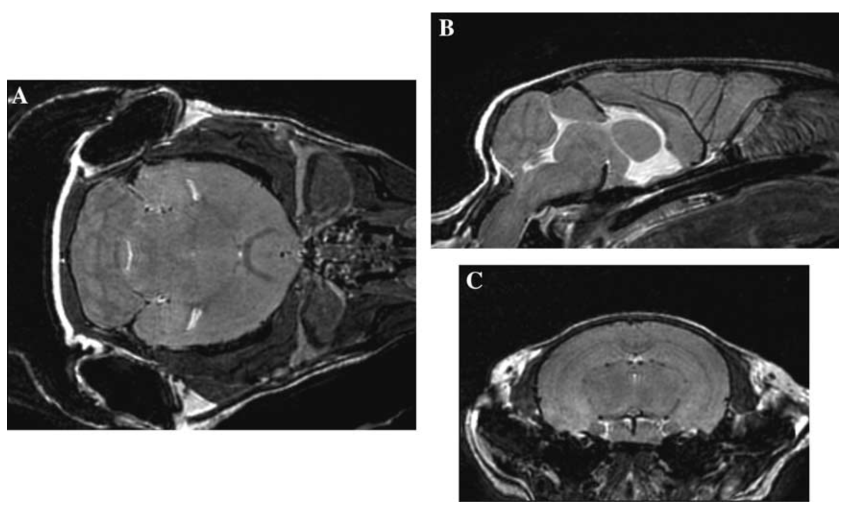

Fig. 5. Fast spin-echo images with gradient amplifiers that do not exhibit a strong hysteresis effect. The acquisition parameters are identical to Fig. 1.

the observed phase is an indication of the difference between hysteresis effects on the first pulse and on the second pulse (as imposed by the preparatory pulse and the first pulse, respectively). For this reason, the improved gradient shape seen in Fig. 4B—from a preparation pulse of the same polarity—corresponds to nonzero phase accumulation in Fig. 3. In spite of these challenges, this method allows for good quantification of the maximal real phase error. As shown here, this can be prohibitively large.

Some pulse sequences will be more sensitive to hysteresis effects than others. A simple spin echo or gradient echo requiring only incremental changes from one TR period to the next is not likely to show large artifacts in the final image. Additionally, in some sequences it may be possible to correct hysteresis effects by insertion of a large gradient pulse at the very end or very beginning of each TR period. This pulse would work in direct analogy to the preparation pulse used in the pulse sequence described here. It could be kept constant or varied according to the events of the coming TR period as required. Unfortunately these methods will inevitably extend the minimum TR and are not compatible with rapid sequences.

Pulse sequences that require repeated gradient rephasing and then recovery of transverse magnetization are likely to be most sensitive to hysteresis effects. As an example, a fast spin-echo sequence requires phase encoding and rewinding gradients for each echo with significant amplitude variation from one echo to the next. Furthermore, artifacts are complicated by interfering signals from different refocusing pathways with inconsistent gradient histories. Other sequences that may likewise show sensitivity to hysteresis effects include interleaved sequences or steady-state sequences that recover transverse signal. Sequence sensitivity may also be exacerbated by particular applications. In our case, for instance, we are imaging with a small field-of-view for samples well away from gradient isocenter. This geometric configuration is bound to be more prone to many sorts of gradient artifacts, including hysteresis.

In particular, our FSE experiment was sensitive to hysteresis induced abnormalities in gradient shape during the gradient attack ramp. The sequence we present here is designed specifically to measure this sort of error. Another common means of reporting hysteresis is instead as a difference in the zero gradient level following large positive and negative gradient pulses. This could be achieved in our experiment by setting the bipolar pulses to zero and observing differences in phase evolution from a continuous FID. We estimate in the MTS amplifiers that the residual gradient level was between 0.01 and 0.02 mT/m (or at most about 0.02%). However, this figure must be treated with caution since the gradient shape abnormalities induced during the transition between hysteresis levels may produce more important phase errors than the residual gradient itself.

Several sources could be responsible for the gradient hysteresis we observe in these experiments. It is possible that hysteresis in ferromagnetic materials is responsible for the gradient behavior. Such materials are used in several components of gradient power supply electronics, including transformers and current monitors among others. Forms of "electronic hysteresis" have also been observed. For example, Performance Controls (formerly MTS) confirms that they have observed a hysteresis effect resulting from improper grounding between the current sensor and the control circuit of the amplifier. Correction of the grounding resolved the problem in current designs (personal communication). Identification and elimination of all hysteresis sources is a significant engineering challenge. It is not unexpected then that the problem is not unique to our laboratory. In our discussions, we have learned from several manufacturers of gradient amplifiers and MRI systems that they have also encountered similar hysteresis problems and have made design modifications to limit them. Even so, many systems are still likely to show some level of hysteresis. The purpose of this communication is to provide broader awareness to MRI and NMR scientists.

5. Conclusions

In summary, a simple NMR pulse sequence to test and quantify gradient hysteresis in MRI and NMR systems has been demonstrated. These effects have been shown to produce significant artifacts in data acquisition, as presented here in a FSE imaging sequence. Artifact resolution can be achieved by elimination of the hysteresis effects or in some cases by insertion of additional gradients. Scientists seeking to identify sources of abnormal phase accumulation may wish to test their own systems for gradient hysteresis effects.

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