Calibration of a 50 T/m Z-Gradient Coil for Quantitative Diffusion Microimaging

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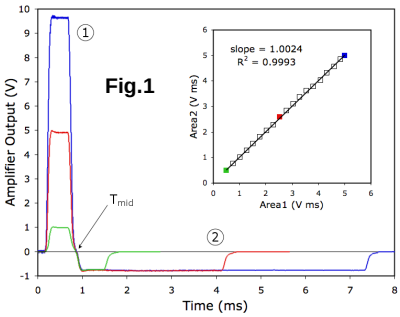
Introduction

Quantitative spin diffusion microimaging could be used to probe variations in cellular microstructure of tissues such as spinal cord[1-4], and the length scale probed hinges on the achievable gradient amplitude. A custom-built high-amplitude (50 T/m) z-gradient coil with integrated solenoidal RF coil has been described that was combined with the x- and y-gradients (1 T/m) of a vertical-bore 400 MHz NMR microimaging system[5]. To reliably use such a system, accurate calibration of the gradient coil is required over its complete range of operation. Here we describe a novel method to calibrate very high amplitude gradient pulses, and demonstrate its capabilities with high *b*-value ADC measurements and diffusion-weighted microimaging of a fixed mouse spinal cord.



Materials and Methods

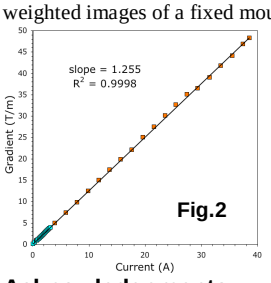
Quantitative spin diffusion measurements require accurate gradient pulse calibration, yet standard calibration methods often rely on the assumption that the gradient coil behaves linearly at very high amplitudes. Here we accomplished a direct calibration in two steps: 1) a spin echo experiment with a bipolar read-out gradient pair, measuring the resulting line width of a 1.1 mm i.d. water-filled capillary, and 2) a spin echo experiment with a bipolar phase-encode gradient pair, using the ^{1}H signal from polyethylene glycol (PEG) dissolved in D_2O in a 2.4 mm i.d. tube. The first step was limited to 4 T/m by our system's largest receive bandwidth (200 kHz). The second step provided calibration up to 50 T/m, aided by the strong signal of PEG (8kD PEG at 12.5 w% dilution) due to its slow diffusion.

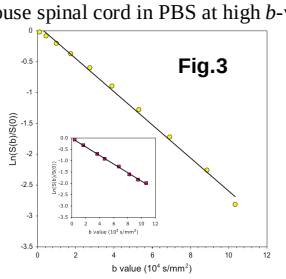
In step 1), the line width of the capillary was plotted (19 pts.) versus current applied (as measured by an oscilloscope) to determine the gradient gain according to $\Delta\nu = (\gamma/2\pi)G\Delta z$, yielding a slope =1.253 T/m/A (R^2 = 0.9998), with G_{max}=50.12 T/m at 40 A. This agreed well with a Biot-Savart law estimation of the z-gradient coil gain =1.26 T/m/A. In step 2), after a 90°-180° RF pair, a short gradient pulse (*G1*) of unknown high-amplitude (>4 T/m) was followed by a longer gradient pulse (*G2*) of known weaker amplitude (<4 T/m) (Fig.1). The *k*-values (cm^{-1}) for *G1* and *G2* are $k1 = 4\gamma(x)Area1$ and $k2 = 4\gamma(1.253)Area2$, respectively. The factor 4 is needed to convert the pulse areas into T-s and *x* is the undetermined gain for *G1*. The *G2* amplitude and duration were varied to obtain the largest PEG signal for a given *G1* amplitude. At maximum signal, the spin phase accumulated from *G1* is refocused by *G2*, i.e., $k1 = k2$. This means that $x = 1.253(Area2/Area1)$, and the pulse area ratio becomes a correction factor for gradient amplitudes higher than 4 T/m.

The experiments were carried out on a custom z-gradient coil (50 T/m) interfaced to a commercial 9.4 T vertical-bore (89 mm) NMR microimaging system (Bruker Avance DMX400 with Micro2.5 tri-axial gradients and BAFPA40 amplifiers)[5]. The *G1* duration was kept constant at 0.4ms, while the *G2* duration ranged from 0.568ms to 6.41ms for the different *G1* amplitudes (19 pts.). *TR/TE* varied from 1s/12ms to 2.5s/20ms to accommodate longer *G2* durations. The gradient waveforms were captured from the amplifier using LabView software, and numerically integrated to obtain pulse areas. T_{mid} was defined as the boundary between *G1* and *G2*.

Results

We found the area ratio to be very close to 1 over the entire range studied (Fig.1 inset), demonstrating highly linear behavior of this gradient coil. Combining the data of steps 1) (■) and 2) (■) resulted in a final calibration curve slope =1.255 T/m/A (R^2 = 0.9998) (Fig.2). As an initial application of these calibrations, we measured the ADC of water (●) and PEG in D_2O (●) by PGSE to be 1.9x10^{-3} mm^2/s and 2.7x10^{-5} mm^2/s, employing *b*-values as high as 10^5 s/mm^2 (Fig.3). Also, we show diffusion-weighted images of a fixed mouse spinal cord in PBS at high *b*-values, demonstrating microimaging capability of this gradient coil system (Fig.4).





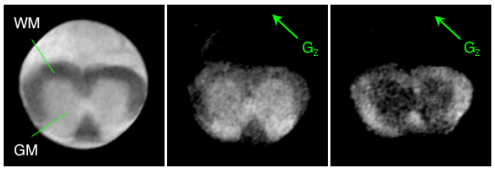


Fig.4 Diffusion-weighted images of a fixed mouse spinal cord in PBS: (left) reference, G_Z = 0; (middle) G_Z = 14.81 T/m; (right) G_Z = 29.63 T/m. PGSE: *TR/TE* = 5s/11.5 ms, Δ = 6.2 ms, δ = 0.24 ms, 3x3 mm^2 *FOV*, 128x64 matrix, voxel size = 23x47x1000 µm^3.

Acknowledgements

This research was supported by NIH grants EB001427 and NS41380.

References

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