A low-cost, mechanically simple apparatus for measuring eddy currents

Kyle M Gilbert[1], L Martyn Klassen[1], and Ravi S Menon[1]
[1]*Robarts Research Institute, The University of Western Ontario, London, Ontario, Canada*

Introduction. The fidelity of gradient waveforms in MRI pulse sequences is imperative to acquiring images with minimal distortion artefacts. Gradient waveforms can become non-ideal when eddy currents are created in nearby conducting structures; however, eddy currents can be characterized and compensated for by measuring the spatial and temporal field response following a gradient impulse. This can be accomplished using a grid of radiofrequency (RF) coils (1-3). The RF coils must adhere to strict performance requirements: they must achieve a high sensitivity and SNR, have minimal susceptibility field gradients between the sample and surrounding material interfaces, and be highly decoupled from each other. In this study, an apparatus is presented that accomplishes these tasks with a low-cost, mechanically simple solution (fig. 1).

Methods. Six solenoid coils were positioned inside a 15.2-cm-diameter spherical phantom and were equidistant (5 cm) from the phantom's isocentre. Solenoids consisted of four turns of 24-gauge copper wire with an enamel coating. Solenoids had an inner/outer diameter of 1.6/2.0 mm and were 2.2 mm long. A continuous twisted pair of wires ran from the coil to ~2.5 cm outside the phantom, where they were soldered to a coaxial cable that led to preamplifiers located outside the magnet. Coils were not tuned, matched, or balanced to attain the highest isolation between coils. The spherical phantom was filled with a 2-M saline solution doped with 3-g/l $CuSO_4$.

All data was collected on a human 7-T MRI system equipped with a head gradient insert. The SNR achieved by each coil was measured on a FID following a 90° non-selective excitation. The sensitivity, temporal resolution, and dynamic field resolution were calculated from this data using the method presented by De Zanche *et al*. (3). A 2D-FLASH image with 200-µm isotropic resolution was acquired to determine the spatial extent of the coil sensitivity. Line widths were measured from FID data without B_0 shimming. S_{12} between loaded coils was measured on the bench and on the scanner. The spatial and temporal variation of eddy currents was measured after applying gradient impulses along each gradient axis.

Results. As determined from two-dimensional FLASH images, the coils were sensitive to a cylindrical region ~1.7 mm in diameter and 3.5 mm long. The SNR following a 90° excitation pulse was 193 for a 1-MHz bandwidth, which corresponds to a sensitivity of $1.9 \times 10^5\ bw^{1/2}$. With this sensitivity, the system can achieve a temporal resolution of 1.4×10^{-11} T s (at 1 MHz) and a dynamic field resolution of 19 fT/$bw^{3/2}$. A field resolution of 1 µT is attained for a 140-kHz bandwidth. The intrinsic susceptibility matching of the materials, due to the unique design of the coil system, resulted in sufficiently narrow spectral line widths (mean: 19 Hz) and long signal lifetimes (>100 ms). This corresponds to a range in T_2^* of 25 – 35 ms; this compares to the measured T_2 value of 86 ms.

In preliminary designs, coils were tuned to 298.2 MHz, matched to 50 Ω and balanced at their input with a lattice balun; however, even with these small-diameter coils, significant coupling was present (S_{12}: approximately -30 dB). The highest isolation occurred when not tuning, matching, or balancing the coil, and increasing the salinity of the phantom to 2 M. The final S_{12} measured on the bench had a mean of -60 dB. When measured on the scanner, the signal on the transmitting channel was 33 – 50 dB higher than the received signal on non-transmitting channels.

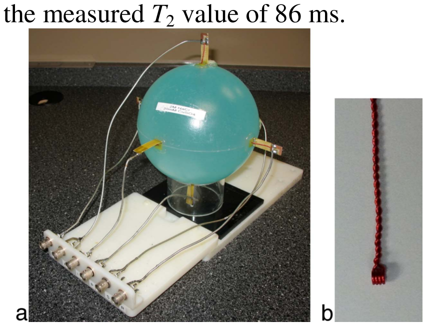

Figure 1. (a) A photograph of the eddy-current measuring apparatus. **(b)** A zoomed-in view of one of the solenoids that was immersed in the phantom.

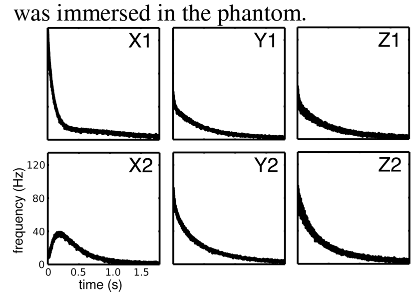

Figure 2. A typical time course of eddy currents for concatenated FIDs acquired at 10-ms intervals, for a total acquisition time of 1.8 s, after an impulse gradient was applied along the *x*-axis.

Discussion. The high mean SNR and sensitivity demonstrated that not tuning and matching the coils (to increase coil decoupling) proved to be non-detrimental to the performance. The SNR remained high because of the small coil size and maximum filling factor. The SNR and sensitivity was sufficient to accurately measure the phase incurred by eddy currents (fig. 2). The only material interface in the coil system is that between water and enameled copper wire, which have nearly identical magnetic susceptibilities; therefore, the reduction in T_2^* due to susceptibility-induced field gradients is minimized. The difference between T_2^* and the measured T_2 is most likely caused by the inhomogeneity of the static field over the sensitive volume of the coils. Since the coils are immersed in the phantom, the sample volume is essentially 'non-localized'. However, the sensitive region of the coils was sufficiently localized to produce a mean line width of 19 Hz. The coupling between coils, as measured on the scanner, was moderately higher than that measured on the bench, most likely due to coupling between receiver channels along the cables that connect the coils to the preamplifiers. The decoupling was sufficient to maintain the fidelity in temporal eddy-current measurements while simultaneously exciting all coils.

Conclusion. The apparatus described presents a low-cost, simple-to-fabricate coil system for measuring eddy currents. The performance of the apparatus was evaluated based on the metrics required to accurately characterize and compensate eddy currents. The apparatus can be expanded to include more coils to characterize and compensate higher order eddy currents.

References. [1] Tountcheva *et al.* Proc. 20th ISMRM 2012: p. 701. [2] Barmet *et al.* MRM 2009;62(1):269-276. [3] De Zanche *et al*. MRM 2008;60(1):176-186.