Measurement of Short Time Constant Eddy Currents with Zero TE Imaging

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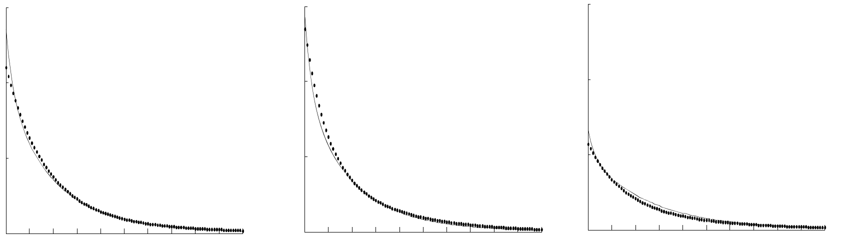
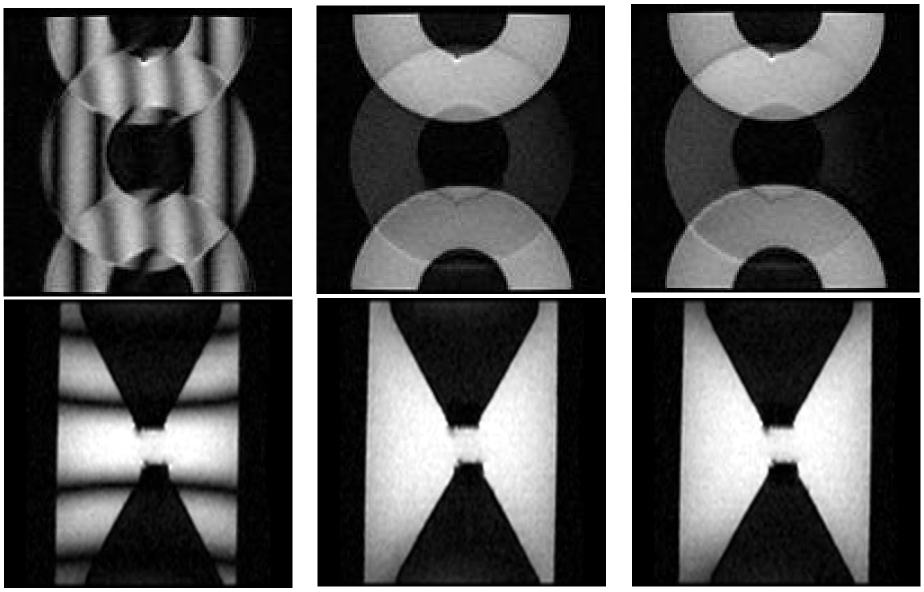
Target Audience: Scientists and clinicians interested in understanding and improving the measurement and correction of eddy currents in commercial MRI scanners.

Purpose: Eddy currents (ECs) caused by time-varying imaging gradients create additional unwanted magnetic fields that have a response characterized by $\sum_i \alpha_i e^{-t/\tau_i}$ where τ_i can vary from tens of microseconds to several seconds. Usually only the low spatial dependence of ECs is measured, for example the constant (B0) and linear components. These spatial components can be characterized from the FIDs of a few small samples at different locations, for example with a special fixture that contains six samples[1]. Recently we developed a method to characterize ECs with multiple spatial orders and a medium time range 2 msec < τ < 2 seconds by scanning a sphere[2]. Here we propose to extend this idea to characterize spatially linear ECs with τ < 2 msec. The previous image-based method for characterizing ECs used conventional slice, phase and frequency encoding, and was not appropriate for very short τ because the echo time was too long. Instead, for short τ measurement we propose using a 3D Ultrashort TE (UTE) pulse sequence capable of TEs as low as 10 usec. The goal is to eventually eliminate all special hardware typically used now.

Methods: A 30 cm diameter sphere was scanned with a single channel transmit/receive coil using a commercial 1.5T scanner (GE Healthcare, Waukesha, WI). A 3D UTE pulse sequence was preceded by a 0.5 G/cm eddy-current-generating gradient (ECGG). The delay between the ECGG and UTE readout Δt was varied in eight steps of 24 usec to sample the ECs at different delays. During the UTE readout, the EC gradient accumulates a phase that is measured in the images. A low readout bandwidth of +/- 2kHz was used which has two advantages: image phase for all short time constants of interest is fully accumulated within a few k-space samples, and the UTE readout gradient itself causes negligible additional ECs that would confound the measurement. Here only the linear component is characterized, allowing a very low resolution acquisition (32x32x32). Measurements were made with the ECGG on x, y and z axes plus an additional phase reference without an ECGG. Total acquisition time is less than four minutes. For a single exponential, an x ECGG with amplitude G, ramp t_r and plateau t_p causes an image phase of approximately $\phi = x\alpha G\gamma\tau^2/t_r e^{-\Delta t/\tau}(1-e^{-t_r/\tau})(1-e^{-(t_r+t_p)/\tau})$. The phase of the reference was removed and thresholding used to exclude areas of low or zero image signal. The phase was then fit to spatial variation up through quadratic and the amplitudes of the linear terms fit to sums of two decaying exponentials to determine values of α and τ. Data were processed using MATLAB (The Mathworks, Natick, MA). The results were compared to fit results from a 6-channel fixture that used three decaying exponentials. Axial imaging tests were done on a fat/water phantom with an EPI pulse sequence with a spectral-spatial RF pulse to compare Nyquist ghosting (a) without EC correction and (b) with EC correction from UTE and (c) from a fixture. Both L/R and A/P frequency encoding directions were used to test x and y EC correction. The images were also coronally reformatted to examine banding and signal uniformity with the spectral-spatial pulse as a test of z EC correction. The banding arises because off-center slices require the frequency offset waveform to accurately match the shape of the time-varying spectral-spatial gradient waveform, which is distorted by ECs.



Results: The figures to the right show a comparison of EC decay curves measured by UTE and a 6-channel fixture (left to right x, y and z). The solid line is the fixture, dots are UTE. Horizontal axes are 0-1000 usec. Vertical axes are 0-15% of ECGG. Below, EPI images show the same comparison. The top row shows (left to right) no EC correction, UTE EC correction and fixture EC correction for an off-center slice with frequency L/R. The EPI phase correction was disabled to highlight the effects of ECs since the ghosting is greatly reduced with phase correction enabled. Similar results were obtained for frequency A/P. The bottom row shows reformats of the top row for (left to right) no EC correction, UTE EC correction and fixture EC correction. For the reformat comparison, the phase correction was enabled to remove additional banding from Nyquist ghosts for clarity.



Discussion: The axial images show comparable Nyquist ghosting between the two methods of EC correction. Likewise in the reformats, UTE EC correction shows results comparable to the fixture. A comparison of the decay curves for all three axes shows a small discrepancy between the fixture and UTE EC measurements that needs further investigation.

Conclusion: A 3D UTE pulse sequence can give equivalent results to a small sample fixture for short time constant EC measurement at 1.5T. More work is needed to extend these results to 3T.

References: 1. Ganin A, et al. US Patent 6,211,675, 2001. 2. Xu et al. Proc ISMRM 2011, p. 4564.