A 64 channel receive-only field camera for eddy current and trajectory calibration

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Synopsis: 64ch receive-only field camera has been built to study the spatial and temporal evolution of the magnetic field in the presence of eddy currents and gradient trajectories. The field camera consists of 64 small solenoids in a 4 x 4 x 4 grid, each with a small (0.9mm diameter) water sample in a capillary plugged with susceptibility matched material. The camera was validated with field maps acquired after inducing eddy currents on the x-, y-, z-gradients at different time delays. The eddy currents frequency offsets have been mapped out as a function of position and time delay for each x-, y-, z-gradients allowing determination of the eddy current gradients and gradient cross term's time constants and amplitudes for either pre-emphasis adjustment or inclusion in image reconstruction methods. .

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Introduction:

Magnetic Field Monitoring (MFM) has become a common practice for studying the dynamics of the static magnetic field especially for the reconstruction of sequences more vulnerable to eddy current effects such as Diffusion-weighted imaging and EPI (1,3). While a reduced set of probes can capture considerable information, the availability of highly parallel receive systems (64- and 128-ch clinical scanners) allows the use of a large 3D grid of probes, and is needed to quickly measure the zero, first and second order spatial terms of an eddy current. In this work, we construct and validate a 64-channel field camera to study eddy currents induced by the high maximum amplitude gradients (G_{max}= 300mT/m) of a diffusion dedicated scanner constructed for the Human Connectome Project. Since eddy current fields scale with the gradient strength full characterization of the eddy current spatial and temporal dynamics is needed to avoid image distortion. The goal of the camera is to *i*) improve the base-line compensation of eddy currents, and *ii*) map the residuals of each gradient direction in a high angular resolution diffusion acquisition to correct image blurring and geometric distortions.

Materials and Methods: The field camera uses an array of 64 six-turn solenoids (24 AWG copper wire) oriented perpendicular to B_0 (axis of the solenoid in the x direction) in a 4 x 4 x 4 spatial array (spacing = 4.5cm). The coils are tightly wound around a glass Pyrex® capillary of internal diameter 0.9mm filled with water sample of about 3 mm length (Figure 2a). One of the main challenges in building magnetic field probes is the susceptibility mismatch between water sample, coil windings and air, which tends to cause line broadening and quick signal decay, thus limiting its use for field monitoring. To achieve best susceptibility matching the water sample in the capillary was plugged with Fluorinert™ (FC70) which has a magnetic susceptibility close to copper and water (1, 2). FC70 was chosen because it is well matched magnetically to water, is hydrogen free, and is insoluble in water and therefore forms a "plug" to contain the water sample. The probes are positioned using 3D printed probe holders as shown in Fig.1. The field camera consists of 4 *xz*-plane 'trays', each housing 16 probes. The probe circuitry (tuning the solenoid to 123.25MHz and providing a symmetric match to the 50 Ohm coax) is about 3 cm away from the probe and uses a minimal amount of copper in order to avoid inducing any additional eddy currents. A 6 cm coaxial cable connects the probe head to the preamp circuit board. An additional phase shifter forms a quarter wavelength cable length between preamplifier (Siemens Healthcare, Erlangen, Germany) input and coil. A PIN diode after this phase shifter provides the active detuning by creating a high impedance within the probe to block induced currents from the transmit pulse providing high isolation from the body coil during transmit. The S_{12} between probes was -45dB so no additional decoupling between the probes was needed. The probe array was characterized on novel 3T system MAGNETOM Skyra CONNECTOM (Siemens Healthcare, Erlangen, Germany) using a standard FID sequence, 500us hard-pulse 90^o excitation followed by a 100 μs pause and then digitization of the FID. Other acquisition parameters are: TR=1500ms, TA=512 ms, TE=0.35ms, bandwidth 1000Hz. The FID was recorded in the absence of a readout gradient after applying a gradient for 1s. The long gradient ensures that only the eddy current from the falling ramp is measured. The timing between the falling gradient edge and the FID was varied. FID's were compared between positive and negative gradients to remove frequency shifts from an imperfect B_0 shim. Time delays between the gradient falling edge and acquisition ranged from 20ms to 1500ms with a step of 20ms. Eddy currents were obtained using $\varphi_{eddy}(t) = 1/2(\varphi_1(t) - \varphi_2(t))$ where $\varphi_1(t)$ and $\varphi_2(t)$ are the phases corresponding to negative and positive gradients waveforms and $\varphi_{eddy}(t)$ is the phase accumulated due to eddy currents(4).

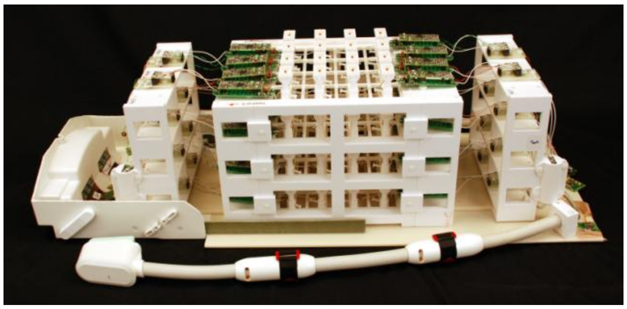

Fig.1: Field Camera

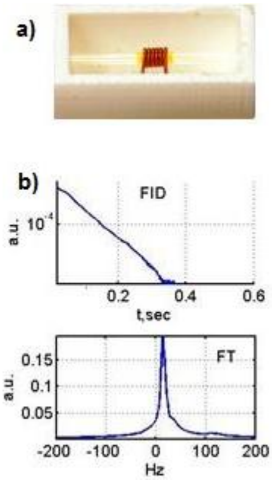

Fig.2: a) Probe Solenoid; b) Probe FID and FT

Results and Discussion: Fig.2b shows a typical FID and FT of a probe without applying gradient, signal lifetime of about 200ms and a FWHM of about 11Hz. For each time delay $d\varphi_{eddy}/dt$ were determined and Fig. 3b shows the dynamics of eddy currents for a 'tray' of 16 probes over a time interval of 1500 ms after applying a gradient G_x=20mT/m. The probes positions were validated using the modified FID sequence by applying 90 deg hard pulse, ramping the gradient slowly to an amplitude of 100µT/m and readout during the gradient. From the phase difference of gradient FID and gradient-free FID, and the gradient amplitude applied along *x*-,*y*-,*z*-axes, assuming linear gradients at this strength, we obtain the Cartesian coordinates for each probe in the scanner as shown in Fig.3a. Knowing the exact positions we can construct eddy currents offset maps for each probe position at a given delay time and gradient axis, that can be used to correct image distortions.

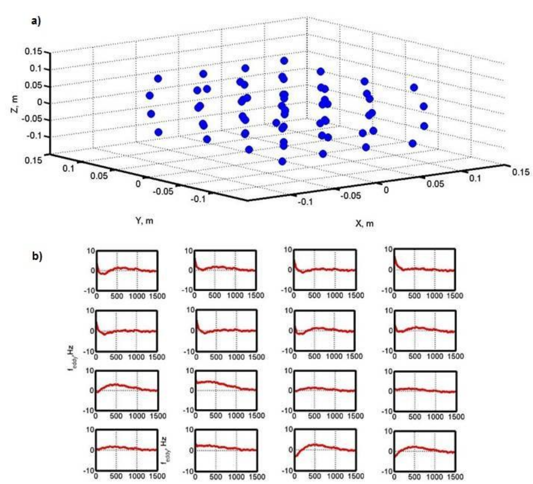

Fig.3: a) Probe Positions; b) f_{eddy} vs t_{delay} for a set of 16 probes.

References: *(1)De Zanche et al ISMRM 2005p 791; (2)DL Olson et al Science 270, no 5244, p. 1967(1995); (3) De Zanche et al., MRM 60:, 176-186, (2008), Sipila, P. et al, Sensors and Actuators A, 145-146 (2008), 139-146; (4)Bernstein, M. A. et al, 2004, handbook of MRI Pulse Sequences, Elsevier Academic Press.*