A new approach to shimming: The dynamically controlled adaptive current network

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Introduction: Magnetic field homogeneity is important for all applications of magnetic resonance imaging. Active magnetic shim coils, typically composed of sets of cylindrical layers (with each layer producing a magnetic field profile of a particular spherical harmonic) are used to correct for inhomogeneities produced by susceptibility differences between tissue interfaces. A radically different approach to shimming would be to dynamically and adaptively control the flow of current over a single surface using a network of metal-oxide-semiconductor field-effect transistors (MOSFETs). By altering the current path appropriately, multiple different magnetic field profiles can be created with a single shim coil, driven by a single amplifier. To achieve this, one must first acquire a field map of the region of interest. Next, a current density distribution can be solved for to shim out the field inhomogeneities. And finally, the current distribution can be projected onto the network of optically controlled MOSFETs. The recent optimization of the boundary element (BE) method of coil design [1] allowing high-performance gradient and shim coils to be designed in a matter of seconds has made this realization possible. In this abstract, we present computer simulations demonstrating the benefit this technique offers as a supplementary, region specific shim coil, and present experimental results of a proof-of-principle prototype.

Methods: _Computer Simulations_: A field map was acquired on a single human subject using a Siemens Tim Trio 3 T scanner with a 32-channel head only RF coil over a single slice. A challenging slice was chosen which suffered inhomogeneity problems caused by susceptibility effects from both the sinus and ear canal. Before taking the field map, the scanner's auto shim was implemented along with a manual interactive shim to ensure that any inhomogeneity that could be removed by the system shims alone were eliminated. From this field map, two regions were selected as regions of interest (ROIs): one spanning the frontal lobe and the other approximately positioned over the right temporal lobe. Field targets were obtained from the ROIs for the design of two distinct shim coil wire patterns using the BE method following the approach of [2]. Both designs were calculated over a cylinder 30 cm in diameter and 40 cm in length. The minimum wire separation distance was controlled to be 1 cm and the maximum field homogeneity was specified to be 0.2 ppm of the main 3 T field. The maximum current flow through each wire pattern was restricted to be less than 2 A. A separate 1 cm x 1 cm square mesh grid was created over the same cylindrical surface as the shim wire patterns. This grid represents the finite discretization that would result from using a network of MOSFETs to represent a current density distribution. Using a custom-built computer algorithm, the two wire patterns produced by the BE method were super-imposed onto the grid. Field calculations were made over the two ROIs with their respective ideal (smooth) wire patterns and realistic (discretized) wire patterns. The resulting "shimmed" field was compared with the original field maps over each individual ROI. For ease in visualization the mean value of magnetic field over each region was subtracted from the data before comparison. Histograms were found over ROI #1 and #2 using 20 bins, spanning ± 2 μT and ± 1.5 μT respectively and were fit with either a Gaussian or Gumbel distribution depending on skewness. Full width half maximum (FWHM) values were calculated from the fits.

Experiment: A rectangular mesh pattern, consisting of 48 nodes, was distributed over an acrylic cylindrical former with ¼" copper tape. Fourteen power HEXFET® MOSFET photovoltaic relays (International Rectifier Series PVN012APbF) were soldered between selective node connections, providing an open or closed variability for the current path between two conjoining nodes. The node connections selected to have MOSFET control were chosen to allow two distinct field profiles: an offset field shift and a z-gradient field. Custom software was written in LabView™ for control over the state of each MOSFET. Single current input and output wires were connected to opposite ends of the shim coil. The coil was placed within a 3 T Siemens Tim Trio system and field maps were acquired with a 12-channel head coil and neck matrix RF coil surrounding the shim coil in 'offset-field-mode' and 'gradient-mode' while being driven with 155 mA. The field maps were compared to the predicted values based on computer simulation of the two distinct current paths.

Results: Figure 1 (a) displays the smooth wire pattern created using the BE method along with its corresponding super-imposed, discretized pattern for ROI #1. Magnetic field homogeneity over ROI #1 when there is no additional shim coil and when the discretized shim coil is present is shown in Figure 1 (b) and (c) respectively. The coil was able to reduce the maximum magnetic field inhomogeneity over ROI #1 from 1.91 μT to 1.40 μT (a decrease of ~ 27%) and the total range of field inhomogeneity from 2.97 μT to 2.09 μT (a decrease of ~ 30%). The coil was able to reduce the maximum field inhomogeneity over ROI #2 from 1.22 μT to 0.99 μT (a decrease of ~19 %) and the total range of field inhomogeneity from 2.31 μT to 1.91 μT (a decrease of ~ 17%). Histograms over ROI #1 with and without the shim coil present are shown in Fig. 1 (d) and (e) respectively. It can be seen that the histogram has a much sharper peak when the shim coil is present. The FWHM values decreased from 1.27 μT to 0.61 μT and from 1.44 μT to 0.71 μT for ROI #1 and #2 respectively with the shim coil present. Figure 2 (a) displays the constructed proof-of-principle coil along with its predicted (b, d) and measured (c, e) field profiles over a single sagittal slice for the (b, c) gradient field and (d, e) constant field cases respectively. In both instances the measured field matches the predicted field very well producing no noticeable imaging artifacts.

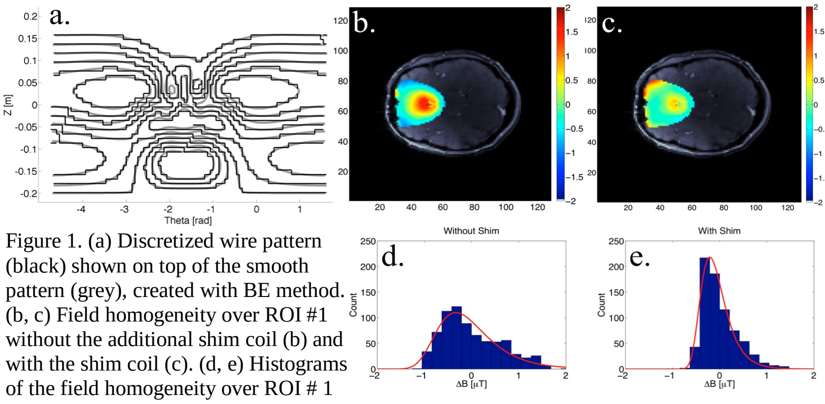

Figure 1. (a) Discretized wire pattern (black) shown on top of the smooth pattern (grey), created with BE method. (b, c) Field homogeneity over ROI #1 without the additional shim coil (b) and with the shim coil (c). (d, e) Histograms of the field homogeneity over ROI # 1 without (d) and with (e) the shim coil.

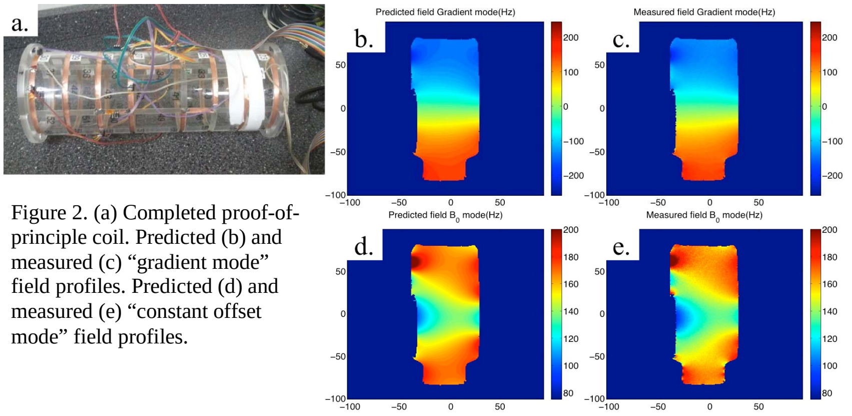

Figure 2. (a) Completed proof-of-principle coil. Predicted (b) and measured (c) "gradient mode" field profiles. Predicted (d) and measured (e) "constant offset mode" field profiles.

Discussion and Conclusions: In this work, an approach to dynamically control the shape of a current density distribution over a single surface has been described. This method has the potential to significantly improve magnetic field homogeneity over any desired region of interest and is particularly well suited for dynamic shimming applications. The method is feasible with current technology and construction techniques. The complexity of wire pattern and resultant field shape is dependent on the "fineness" of the MOSFET network, and as such, this approach will become more powerful as optically controlled, power transistors are reduced in size.

References: **[1]** C.T. Harris, et al., *Proc. ISMRM.* 3786 (2011). **[2]** C. T. Harris, et al., *Concepts Magn Reson B.* **41B**, *in press* (2012).