Permanent Magnet Shimming for the X-ray Detector in a Hybrid X-ray/MR System

Z. Wen[1], R. Fahrig[1], N. J. Pelc[1]

[1]Radiology, Stanford University, Stanford, CA, United States

Introduction In our x-ray/MR hybrid system[1], a flat panel detector is placed under the patient cradle close to the MR volume of interest (VOI), where the magnetic field strength is ~0.5T. Ferromagnetic components inside the detector that cannot be replaced with non-magnetic substitutes create an additional magnetic field that is superimposed on the original field of the scanner. Even after linear shimming of the field with the detector in place (using scanner-implemented algorithms) the field homogeneity is significantly degraded by the ferromagnetic components in the detector. Here we propose using permanent magnets with optimized strengths and positions to compensate for the second and higher order components of the additional field.

Methods All experiments were performed on a 0.5T interventional system (Signa SP, GE Medical Systems, Milwaukee, WI). To obtain field maps, signals of a large doped-water phantom in both real and imaginary (I and Q) channels were collected at two echo times with different ΔTE using a 2D GRE sequence (34x34cm FOV, 66 3mm contiguous slices). ΔTE of 2ms was mostly used, but a longer ΔTE= 3ms was used to improve the precision when the inhomogeneity was less severe. From the unwrapped phase difference map of two echo time images, the raw field map was calculated. The zeroth order offset and the first order linear component of the additional field were removed to account for those components readily handled by the shim correction algorithm of the scanner (assuming perfect performance). We assume that the ferromagnetic components inside the detector can be grouped at a few discrete locations with each location only a few centimeters in diameter, much less than the distance from the detector to the MR VOI. The magnetic field from the ferromagnetic components may therefore be closely approximated by the same number of magnetic dipoles pointing in the direction of the external field, located near these components. In principle, then, this field could have been produced by small permanent magnets acting as these magnetic dipoles. If the intrinsic coercivity of these magnets is sufficiently larger than the external magnetic field, reversing the polarity of the magnets in space will change neither their magnetization nor their magnetic field. Therefore the undesired magnetic field from the detector can be canceled by the permanent magnets oriented in a direction opposite to the main magnetic field.

This passive shimming approach was investigated using NdFeB magnets (Dexter Magnetic Technologies, Elk Grove Village, IL) of various sizes and strengths. Placement of the shimming magnets was selected based on non-linear fitting of the field produced by the detector to the sum of a small number of dipole fields. The permanent magnets were placed one at a time, and a least-squares fit to a dipole field was used to calibrate the strength of each magnet. An iterative procedure to refine the placement of the shimming magnets was developed.

The impact of the field degradation from the detector and the effectiveness of passive shimming with permanent magnets were quantified by measuring the peak-to-peak field inhomogeneity and the standard deviation of the field in a cylindrical volume (ϕ28x20cm). It was also evaluated qualitatively with an SSFP sequence (TR/TE= 11.64/5.56ms) since this imaging method is important for interventional guidance and is very sensitive to inhomogeneity.

Results In the absence of the detector, the peak-to-peak (p-p) deviation of the field map measured with ΔTE=2ms was 46mG and the standard deviation (σ) was 4.8mG. With ΔTE=3ms, the p-p and σ were 41mG and 4.3mG, respectively, reflecting the reduced noise in the field map. The inhomogeneity parameters were much larger with the detector in place, 121mG and 14.7mG (ΔTE=2ms), respectively. Nonlinear least-squares fitting, optimizing both strengths and locations of the dipoles, predicted that two ideal dipoles would reduce the field inhomogeneity of the detector to 44mG (p-p) and 4.5mG (σ). Two identical permanent magnets (0.2x0.2x0.5inch) were chosen because their strength was close to the results of the fit. A second fit to the field map of the detector was then performed with two ideal dipoles of the calibrated magnet strength and the dipoles were constrained to a plane at a chosen vertical distance to the VOI to compute the ideal in-plane locations. The result predicted that the field inhomogeneity of the detector (ΔTE=2ms) would be reduced to 48mG (p-p) and 5.1mG (σ) by these two ideal dipoles at the prescribed locations (F1), and the ideal dipole locations (F1) were then used to direct the placement of the two shimming magnets. The magnets were moved iteratively until their dipole locations (F1') were close to the intended dipole locations (F1) (errors< 5mm). Simulation showed that two dipoles placed at the dipole locations (F1') could also reduce the field map of the detector to the predicted level (48mG (p-p) and 5.1mG (σ)), indicating distance errors were small enough not to cause a significant error in the field. The detector was placed back at its original position with the magnets in place and the field map (F2) was measured. The homogeneity was improved to 77mG (p-p) and 7.3mG (σ), but not to the degree predicted by the fit. To further improve the shim, the field of only the two dipoles at locations (F1') was subtracted from the field map of the magnets with the detector (F2) to measure the effect of the detector when the dipoles are in position. The difference field map was once again fit to the field of two dipoles to find new prescribed locations, which called for the shimming magnets to be moved by 1-2cm. The field map of the detector together with the shimming magnets at the new locations was measured at ΔTE=3ms and showed a deviation of 54mG (p-p) and 5.3mG (σ), compared to 41mG and 4.3mG for the baseline field with no detector in the magnet. **Figure 1** shows SSFP images without the detector (a), with the detector (b), and with both the detector and the shimming magnets (c). The severe impact of the inhomogeneity due the detector is clear, and the improvement from the passive shimming is almost complete.

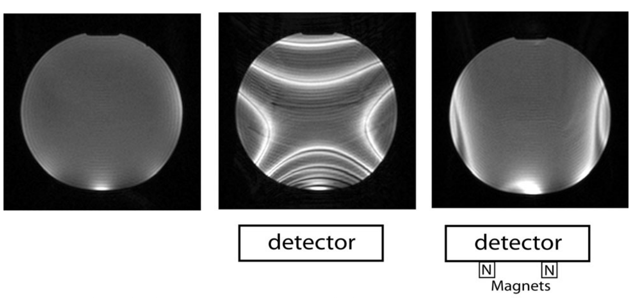

Fig. 1(a) Fig. 1(b) Fig. 1(c)

Discussion Properly selected permanent magnets, appropriately placed near the x-ray detector, can greatly diminish the degradation in magnetic field homogeneity caused by the detector. Interestingly, the location of the permanent magnets prescribed by the fitting process is close to the location of magnetic components in the detector. The iterative approach to magnet placement had important benefit. It is unclear why the shimming did not reach an ideal solution in one step. Possibly, the field of the shimming magnets may affect the field produced by the detector by changing the magnetization of the magnetic components. The iterative method with feedback seems to work well in this situation. This passive shimming approach of placing permanent magnets in proximity to objects that degrade field homogeneity may find other application in cases where such objects need to be placed inside the MR system.

References 1. Fahrig R, et al, Acad Radiol 2001; 8, p.1200-7.

Acknowledgments: This work was supported by NIH grants R01 EB00198 and P41 RR09784, the Lucas Foundation, and GE Medical Systems.