# Rapid In Vivo Shimming with Current Constraints

D-H. Kim[1], G. Glover[1], D. Spielman[1]

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

**Introduction**

The inherent increase in signal to noise ratio (SNR) for high field magnets has led to broader applications of Magnetic Resonance Imaging (MRI). Nevertheless, the increase in resonant frequency accompanies several technical challenges. One of these involve susceptibility effects. Compared to 1.5 Tesls (T) imaging, there is a factor of two increase in the $B_0$ inhomogeneity. Therefore, the ability to achieve a good shim can be a pivotal factor to a successful exam at 3 T.

Increasing number of MR systems now include shim coils. These include the higher-order shim coils (for example, ZY, $X^2$-$Y^2$, ZX, XY, $Z^2$, and $Z^3$) as well as the linear gradients. In all these cases, a procedure involving current distribution to the individual coils is executed to produce a homogeneous field. This procedure can be iterative or done in a single process. However, depending on the region of interest (ROI), the required shim currents can overrange the power supply's capacity. In particular, this situation arises frequently when shimming over a localized region where the inhomogeneity is severe. For example, we have seen that this was often the case in the C-spine region. In this case, truncating the required shim currents does not necessarily achieve a good shim. A more elegant way to approach the problem is to solve the shim current values with boundary conditions [1]. Also, when iterations of the shim process are performed, care must be taken to take into account downloaded shim values existing from previous iterations.

In this abstract, we implemented a rapid higher-order shimming method for 3 T which is targeted for arbitrary localized regions with constraints on the available shim currents. We show that by solving a contrained least squares, the homogeneity is improved compared to a simple truncation of the available currents.

**Methods**

A shimming procedure based on field mapping was used [2]. Spiral based readouts were used to rapidly acquire the field maps. From predetermined reference field maps of each shim coils, a least squares calculation with boundary conditions was used to determine the required shim currents from the region of interest selected by the user. For our 3 T system, the higher-order shim power supply had a upper/lower limit of ± 4 amps per channel. These values were used as the boundary conditions for solving the least squares problem. A built-in Matlab (mathworks, inc) function (lsqlin) was used which is based on a Newton algorithm [3] in searching for the minimum values.

Data were collected in vivo from the C-spine where the field inhomogeneity is severe and typically requested more current than available. First, we solved the least squares equation with no account of the maximum (minimum) current values of the shim supply. In this case, a truncated value of current was downloaded when overranges occur. Secondly, we solved a least squares algorithm with boundary conditions. Comparison of the RMS (root means square) field deviation was used to evaluate these two methods.

**Results and Discussion**

Figure 1 shows the region of interest that was typically used for shimming the C-spine. In Fig. 2, a situation where the required current is overranged in the first iteration of the shimming process is given. The RMS value of the field homogeneity is given before (left, 153 Hz) and after (right) shimming for the truncated method (72 Hz) and the constrained least squares method (67 Hz). Also shown between the RMS values are the downloaded higher-order shim current values for each method. The order of the higher-order shims are : ZY, $X^2$-$Y^2$, ZX, XY, $Z^2$, and $Z^3$. In this case, the required current for the XY channel was 4.67 amps but the hardware could only supply 4 amps for the truncated method. As for the constrained least squares method, the algorithm took into account the boundary condition and resulted in different download currents for the other channels while achieving better RMS value.

In Fig. 3, another example is given where the shimming process was iterated to further reduce the RMS field deviation. The top row shows the RMS value from the truncated method (167 → 46 → 53 Hz). In this case, the current requested from the least squares calculation for the $X^2$-$Y^2$ channel was -4.43 amps but only -4 amps were downloaded. This accounts for the increase in RMS value from 46 to 53 Hz. In the second row, the RMS value obtained from the constrained least squares method is given (167 → 48 → 41 Hz). Here the least squares algorithm took into account the boundary conditions of each channel and therefore resulted in no truncation of current as evidenced in the decrease by the RMS value. Typically, approximately 50 iterations were needed to find a solution for the constrained least squares which amounted to less than one second of process time.

**Conclusion**

A fast higher-order shimming method for arbitrary regions is introduced. In this method, the available current values are taken into account by solving a least squares algorithm with boundary conditions. This produces a shim procedure robust to hardware limitations. The whole shim process can be executed in less than one minute due to the fast field mapping technique.

**Acknowledgements**

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**References**

[1] H. Wen, et al., MRM, 34, 898-904, 1995. [2] D.H. Kim, et al., MRM, 48:715-722, 2002. [3] T.F. Coleman, et al., SIAM J Optim. 6(4): 1040-1058, 1996.

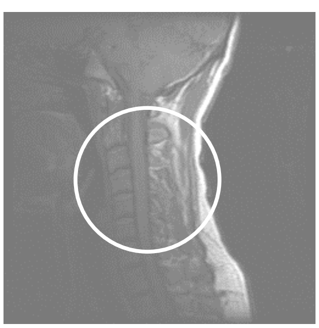

Figure 1. The region of interest used for in vivo shimming is shown. The main target was in the C4 and C5 region.

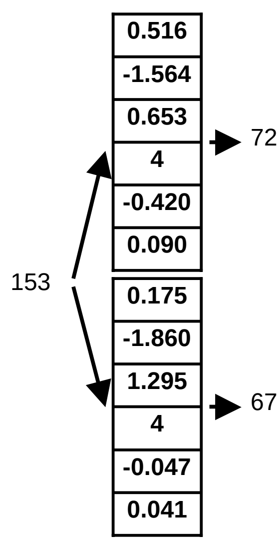


Figure 2. RMS value from the truncated method (153 → 72) and constrained least squares method (153 → 67). Also, the current values after downloading for the six higher order shims are given.

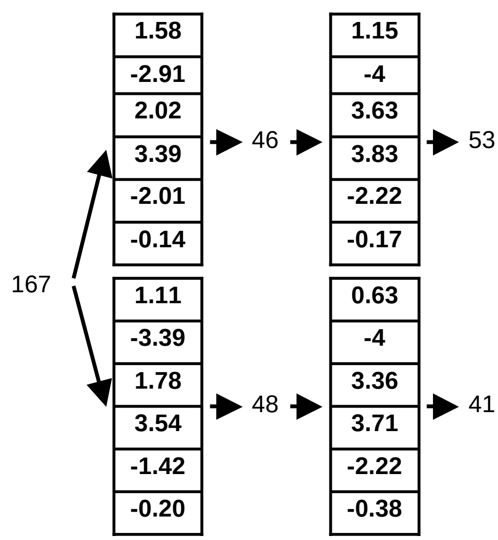


Figure 3. RMS value from the truncated method (167 → 46 → 53) and constrained least squares method (153 → 48 → 41). Also, the current values after downloading for the six higher order shims are given.