Automatic High-Order Shimming by Sampling Columns in the Cartesian Coordinates

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Introduction: Automatic shimming methods fall into two classes, field map-based shimming and projection-based shimming. In field map-based shimming [1-3], a two- or three-dimensional field map is acquired usually using EPI or spiral imaging, in order to shorten the scan time and avoid motion artifacts. These fast imaging techniques, however, are intrinsically prone to the artifacts of field inhomogeneity. The projection-based FASTMAP method (Fast, Automatic Shimming Technique by Mapping Along Projections) [4-6] acquires fields along a number of one-dimensional projections in radial manner. Because few projections are needed to calculate the field as precisely as practically needed (typically, a human scanner has shimming coils that are complete only to the second- or third-order in sphere harmonics), the shimming procedure can be accomplished in a short time. In FASTMAP, only the fields along the projections are sampled and used in calculating the correction field. Therefore, the technique is suitable for shimming cubic or spherical regions that have an isotropic center for the projections; however, it is not optimal for regions such as an imaging slice or a stack of slices, because field variations in a flat region are not best characterized by the FASTMAP projection field. In this work, we developed a novel technique, abbreviated as SCOLICC (Sampling COLumns In Cartesian Coordinates), which extended FASTMAP to shimming slices, by mapping the field using a group of columns in Cartesian coordinates.

Methods: The magnetic field was sampled in Cartesian coordinates on a pair of four columns in two separate planes, as shown in Figure 1. Following an approach similar to that of FASTMAP, we fitted each of the field curves to a third-order polynomial, and then we could prove that the correction field can be determined to the third-order of spherical harmonics. The shim currents were first determined in the logic frame by assuming the slices were in axial planes, and then uniquely and completely converted into the physical frame where the slices could be at any oblique angle, by using a newly introduced spherical harmonics rotation transformation. Therefore, in-slice and through-slice field variables remain independent in the determination of shim currents regardless of slice orientation. The technique of multiple stimulated echoes was incorporated into the method, allowing the use of at least eight shots to accomplish field mapping. The method was implemented on GE's Excite 3 T scanner, which was equipped with a complete set of second-order shim coils, and demonstrated on both phantom and human subjects with a standard head coil. Raw data were automatically saved at the end of each shimming scan and then processed by an on-site program installed in the scanner's host Linux computer. The program was written in-house with c language, with the graphic interface developed using the Motif toolkit. After the shim currents were determined, they were automatically downloaded into the shim coils.

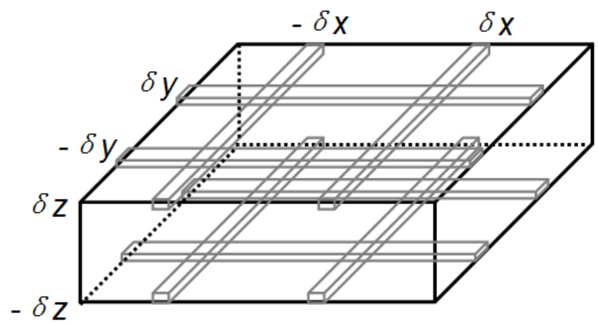

Figure 1. A pair of four columns in two separate slices represented by x=δx, x=-δx, y=δy, y=- δy. Upper and lower slices are denoted by z=δz, and z=-δz, respectively.

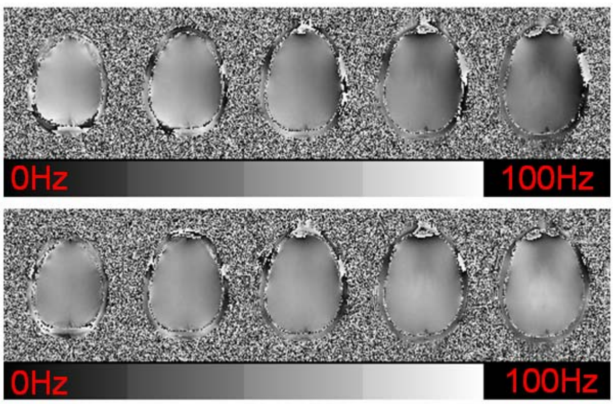

Figure 2. Field maps acquired using gradient echo imaging in a human brain before (top row) and after (second row) applying SCOLICC.

Results: Both phantom and in vivo experiments were conducted to assess the effectiveness of SCOLLIC. Figure 2 shows five axial slices in a human brain selected for field mapping, in order to compare the differences before and after use of SCOLICC. The manufacture's first-order shimming was applied for all images that were collected without applying SCOLICC. The phase maps were acquired using fast gradient echo imaging with slice thickness = 4.5 mm, slice spacing = 2.5 mm, and matrix size = 128 ×128. The field inhomogeneities were visibly improved after applying SCOLICC (second row); in addition, the difference in the mean field between the first image and the last image in the upper row was also remarkably reduced in the second row. Figure 3 shows that the artifacts of gradient echo EPI imaging (B) compared to the anatomic image in (A) and were substantially reduced after SCOLICC (C). The EPI images were acquired with: single shot, matrix size = 80×80, echo time = 21.3ms. The whole procedure was repeated twice to ensure that the distortions did not originate from the subject's motion and repositioning. In conclusion, both phantom and in vivo experiments showed that this newly introduced high-order shimming method is an effective and efficient way to reduce field inhomogeneity for the region of imaging slices. It samples a few one-dimensional columns for field mapping in a time window of ~ 10 s and is immune to the artifacts associated with the fast imaging. It has the flexibility that the columns can be positioned to cerate an optimized correction field for the region of interest.

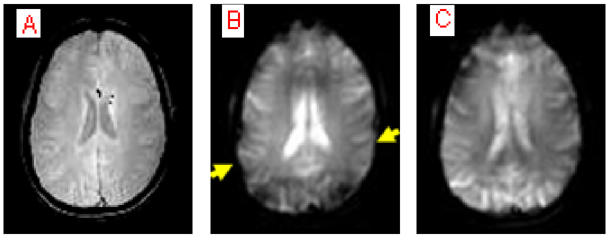

Figure 3. Comparison of human gradient echo EPI images (80×80, TE=21.3ms); scout image (A), gradient echo EPI before (B) and after (C) SCOLICC.

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