Phantom-Based Evaluation of Gradient Nonlinearity for Quantitative Neurological MRI Studies

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Synopsis: Structural MRI of the central nervous system is a promising method to diagnose and track the progression of neuro-degenerative diseases such as Alzheimer's disease. Multi-site clinical trials using quantitative MRI studies face a problem of characterizing gradient nonlinearity and monitoring small changes in geometric distortion over several years, with accuracies of a fraction of a percent. We have developed a phantom and analysis method capable of characterizing linear and nonlinear distortion in a scanner. This method can be used to qualify sites in a multi site study and to monitor stability of the hardware over time.

Background and Significance: Neuronal and synaptic loss in Alzheimer's disease correlates with global atrophy of the brain [1,2] and regional atrophy in several medial temporal lobe structures [3-5]. These indices in turn correlate with the severity of the cognitive deficit in affected individuals. Structural MRI of the brain is a promising surrogate marker for use in early diagnosis and disease tracking. To achieve clinical utility, these measurements should be performed with accuracy better than about ½ %. Ideally, inter subject variation in brain size/atrophy would be due entirely to the effects of disease. In practice other sources of variation in such measurements can arise from the hardware, analysis algorithms, patient handling/motion, and normal inter subject variability in brain morphology. The engineering challenge lies in minimizing all non patient related sources of measurement variation. In this work we seek to address the component of variability that comes from hardware, particularly gradient distortion. We have developed a technique to characterize gradient nonlinearity for use in multi-site trials that require objective criteria for scanner qualification and ongoing monitoring of gradient distortion.

Methods: We have developed a phantom-based calibration protocol for correcting geometric distortion [6]. The phantom, shown in figure 1, is a 20-cm sphere filled with distilled water, in which is embedded an array of 165 spheres filled with copper-sulfate solution. 160 of these spheres are used for geometric distortion measurement, and the remaining five are for signal-to-noise measurements and contrast measurements that have been discussed previously [6]. The small spheres appear bright in MR images relative to the distilled water background and can be localized with accuracy better than 10-20% of a voxel dimension. Geometric distortions in the images cause the apparent positions of these spheres to shift. By comparing these positions to the known positions of the spheres, a distortion map of the imaging volume is generated. The map can then be used for characterization of distortion and for correcting distortion in anatomical images. The phantom was manufactured by The Phantom Laboratory, Inc.

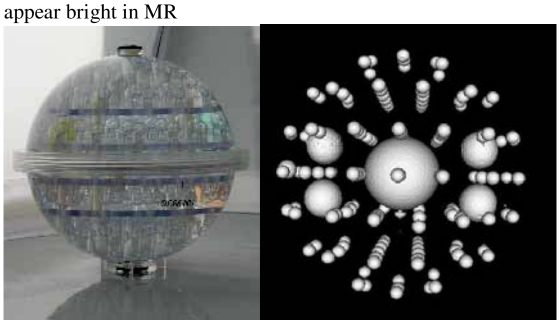

Figure 1: photograph of geometric distortion phantom (left) and surface rendering of 3D MR image (right).

To characterize nonlinearity of the gradient coils, the apparent positions of the spheres are fit to two types of distortions: an affine transformation that involves only translation and scaling in three dimensions, and a distortion that in addition to translations and scaling includes nonlinear terms up to a third-degree polynomial. From each type of distortion fit, the residual root-mean-square displacement errors are computed. The ratio of the mean square error under a linear distortion to the mean square error under polynomial distortion provides a relative measure of nonlinearity. We refer to this quantity as the 'nonlinearity ratio.' An ideal gradient coil with perfect linearity would have a nonlinearity ratio of one. Nonlinearity manifests itself in nonlinearity ratios greater than one. Higher nonlinearity ratios correspond to less linear gradient coils.

To validate the method, we have studied three gradient coils from multiple vendors. The analysis was run on 3D T1-wieghted volume MRI data before and after the vendors' software nonlinearity corrections were applied, to show the ability of the method to measure linearity. All handling of the MR data was done at the Mayo Clinic by one of the co-authors (JG) who is a member of the Alzheimer's Disease Neuroimaging Initiative (ADNI). No data or results specific to any particular MR system were released outside the MRI laboratory at Mayo (including non Mayo co-authors of this abstract).

Results & Discussion: Figure 2 shows a histogram of the nonlinearity ratios, both before and after the vendors' three-dimensional nonlinearity correction algorithms have been applied. For gradient coils that have had three-dimensional warping correction applied, the nonlinearity ratio generally comes in around 1.5 or less. For those with no correction, the nonlinearity ratio is typically larger than 3, and usually larger than 4. These results show that this analysis technique is a simple, sensitive measure of nonlinearity and can be used to qualify sites and provide quality control to evaluate the quality of nonlinear gradient correction.

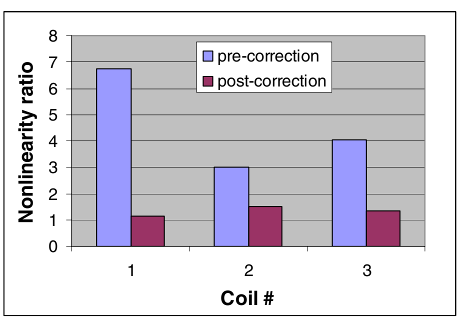

Figure 2: Nonlinearity ratio for three different gradient coils. The blue traces are before 3D distortion correction software has been applied, and the red traces are after correction software has been applied.

An important observation is that even with three-dimensional distortion correction, measurable nonlinearity remains on some systems. This is evident from nonlinearity ratios that are appreciably greater than one, even after software distortion correction

Conclusions: We have developed a simple, quantitative, phantom-based measurement for gradient nonlinearity for use in quantitative imaging applications of the head. This technique is suitable for scanner qualification and data quality control for multi site longitudinal studies, to ensure that gradient nonlinearity corrections are performing properly.

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