Phantom-Based Data Quality Control for Quantitative Imaging of Neurological Disorders

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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. Such techniques often require longitudinal measurements on multiple scanners over periods of months to years, with stability of fractions of a percent. We have developed a phantom-based calibration technique to enable MR scanners to meet these stringent requirements. The technique has been successful in correcting very small errors due to geometric distortion. We also present work addressing signal-to-noise measurements relevant for multi-element arrays.

Background and Significance: Neuronal 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]. 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 %. Variation in such measurements can arise from the hardware, analysis algorithms, patient handling/motion, and true biological variability. In this work we seek to reduce the variation due to the hardware to negligible levels.

Hardware-induced variations have been suggested as an important source of error in MR brain volumetric measurements [2]. Longitudinal volumetric studies can span several years; any change in scanner equipment, such as upgrades or new coils, could jeopardize the entire existing set of longitudinal data for a clinical site. It is important, therefore, to have a means of maintaining continuity between different hardware configurations as well as to maintain high stability within a single scanner. Geometric distortion correction can be applied in a very general way, but SNR measurements have more stringent requirements to be suitable for use in multi-element coil arrays. Because of non-uniformity in the receiver profile, noise measurements must be performed in the same region of space used for signal is measurement, leading to difficulty with non-random variation in the signal that corrupts the measurement of noise.

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 171 one-cm diameter spheres filled with copper-sulfate solution. The small spheres appear bright in the MR images and can be localized with sub-voxel accuracy. Geometric distortions in the images cause the apparent positions of these spheres to shift, and from this information a distortion map of the imaging volume is generated. The map is then applied in reverse to the anatomical images to undo the effects of the distortion.

Figure 1: photograph of geometric distortion phantom

Measurements of contrast and signal-to-noise must deal with non-random variation of signal. Since multi-element arrays are less uniform than birdcage coils, measurements made with these coils cannot use empty-space regions for noise measurement. Hence, both signal and noise must be measured in regions of signal. Important questions to answer are how large a region is necessary to perform this measurement accurately. To correct for variation of the signal and for partial volume effects, we fit the signal variation to a low-order polynomial to remove non-random variation, and then perform multiple erosions on the region of interest. We study the capability of the SNR measurements as a function of region size and number of erosions.

Results & Discussion: Figure 2 shows the results of a scaling experiment on phantoms. Gradient scaling errors were introduced in a controlled manner by altering the amplifier settings. Volume measurements were then made using a spoiled gradient recall acquisition on ½-liter spherical phantoms. Variations from 0.1% to 3.0% were applied and corrected. The vertical axis shows the measured volume deviations of the spheres, before (blue) and after (red) correction. The uncorrected volume errors match the applied errors very closely. After correction, volume variation has been reduced to within 0.2% for all applied scaling distortions.

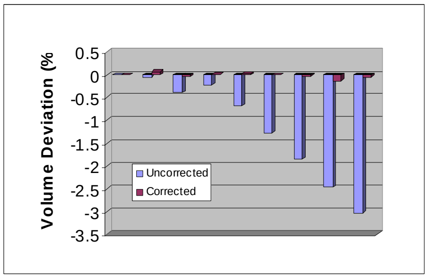

Figure 2: Correction of linear scaling errors. Y-axis is measured volume deviation for uncorrected (blue) and corrected (red) scaling errors. After correction, errors have been kept under 0.2%

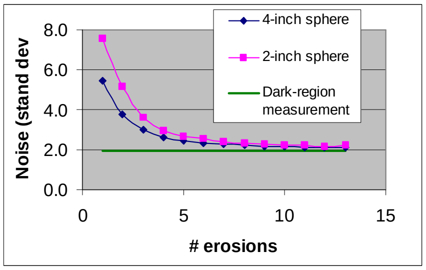

Figure 3: Noise measurements in a 4-inch (blue) and 2-inch (magenta) spherical region, as a function of number of single-pixel erosions performed. The green line is the 'correct' measurement, as determined from measurements in the dark region of the image.

Figure 3 shows measurements of noise, as measured by the standard deviation of the signal in a spherical region of interest, filled with copper-sulfate solution. The contribution from signal non-uniformity has been largely removed by first fitting a 2^{nd} -order polynomial to the signal and subtracting the fit from the actual signal. This step is essential for removing non-random variation of signal, though it is not a complete abatement. An additional difficulty in such measurements is Gibbs ringing, which introduces additional non-random variation to the signal. These problems are overcome by performing multiple image erosions on the region of interest before the noise computation. The graph is a plot of the noise measurement as a function of erosion number, where each erosion has a 3D kernel with width one. The horizontal line represents the 'correct' noise measurement, as determined by measuring the noise in the dark region and scaling appropriately to account for the non-Gaussian distribution of noise in the dark regions of the image. One can see from the figure that either a two or four inch sphere can perform the measurement accurately, with appropriate number of erosions. This information is important for phantom designs for quantitative imaging, as enough room must be left outside of the SNR measurement region to perform other functions, such as geometric distortion correction.

Conclusions: The phantom-based calibration technique has demonstrated geometric distortion correction to 0.2%. Experiments to determine the necessary size of a region for local SNR measurements conclude that a 2-inch diameter sphere is sufficient, when combined with subtraction of the low-spatial-frequency signal variation and 5-10 image erosions to eliminate Gibbs ringing artifacts.

References:

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