INTRODUCTION

Frame-wise image registration is an important step to reduce motion artifacts in functional MRI data sets. A critical step in every registration algorithm is the resampling of the misregistered images, which may itself introduce new artifacts into the corrected data sets which are not related to the accuracy of the registration method, but rather are intrinsic to the alignment process. The nature of these artifacts is directly related to the manner in which data are acquired in MRI experiments. In this discussion, a rectangular k-space sampling scheme and a square sampling region will be assumed. If the underlying object is rotated through an angle $\psi$ between two image acquisitions, the Fourier representation of the image is also rotated through the same angle. In the object frame of reference, rotation through $+\psi$ corresponds to a rotation of the sampling region boundary through $-\psi$ (Fig. 1). Thus, the raw data at the two frames are sampled from mostly, but not entirely, overlapping regions from the object’s frequency space. Consequently, during realignment, there are portions of the reference sampling region, represented by the shaded triangles, which were never sampled in the misaligned frame, leading to an unavoidable high-frequency loss. In full data sets, this frame-to-frame variability of high spatial frequency content is a source of temporal variability in subsequent pixel-wise temporal analysis.

This registration-related noise may be reduced by a tailored post-registration spatial filter which selectively attenuates the regions of k-space near the corners of the sampling region, i.e., those regions which become undefined following the correction of small rotations. Such a filter was realized using the two-dimensional frequency transformation method with the McClellan transformation kernel, based on a one-dimensional Kaiser-Bessel low-pass filter ($\alpha_p = 0.85\pi$, $\alpha_s = 0.97\pi$, pass-band variation < 0.02 dB, stop-band attenuation $>60$ dB), yielding the frequency response shown in Figure 2.

VALIDATION

A set of 32 simulated MR images was synthesized consisting of identical simulated images through a perfect homogeneous cylinder. The simulated set was subsequently rotationally “corrected” over a linear range or rotation spanning 4° using the frequency regridding method. As this object would theoretically generate the same k-space matrix data regardless of rotation, any differences in the corrected image set must be due entirely to rotational correction. Experimental human data was collected with a 1.5 T Signa scanner with ANMR echoplanar quadrature head coil in an axial slice through the thalamus as the subject slowly rotated his head at a constant velocity over a 4° range. The images were registered using the 2D DART registration algorithm. Registration-related noise in each motion-corrected image was computed as the RMS difference between each registered image and the reference image.

RMS noise with and without filtering is shown in Figure 3 with values plotted against absolute rotation. Data are presented for both frequency regridding (3A) and spatial bilinear interpolation (3B). Prior to filtering, bilinear interpolation resulted in the addition of over three times the error as compared to frequency regridding, consistent with the lower fidelity of the bilinear interpolation technique previously described. Reductions in error with filtering were nearly identical at all angles studied, averaging 49.6% ± 0.02% for frequency regridding, and 24.5% ± 0.001% for bilinear interpolation. Linear regression was performed on the human data (not shown). Estimated RMS errors as a percentage of mean brain signal were 0.69|$\psi$| + 2.93 and 0.46|$\psi$| + 2.45 before and after post-registration filtering, respectively. The reductions in intercept and slope with filtering were 16.4% and 32.5%, respectively. The reduction in slope demonstrates the effectiveness of the filter in reducing noise related to registration, as it represents a systematic reduction in noise as a function of rotation, comparable directly to the simulation reductions. The unfiltered intercept can be interpreted as an estimate of background frame-to-frame variation due to scanner noise and background physiologic fluctuations.

DISCUSSION

The spatial filtering method described successfully reduces noise in both simulations and experimental data sets. Not surprisingly, a smaller improvement is seen in the human experimental data, likely due to differing frequency content of the idealized simulated data and additional errors related to angular displacement, e.g., out-of-plane effects and field inhomogeneities. We have approached only the correction of rotational misalignment. Fortunately, translations in the spatial domain map to phase shifts in k-space, such that the sampling of a translated object, with or without concurrent rotation, is not associated with any further undersampled regions.

The application of post-registration spatial filtering may reduce the temporal variability of time sequences which have been corrected for rotational errors, potentially increasing the power to detect activation. Additionally, filtering may be important in data contaminated by stimulus-correlated motion, where the registration-related errors at any given pixel are also likely to be stimulus-correlated, and in experiments where spatial correlations of time signals are sought, e.g., studies of functional connectivity, where the high spatial frequency nature of the registration-related noise may result in spurious spatial correlations. These improvements come at the cost of a small reduction in spatial resolution which must be considered in subsequent statistical analysis. For the detection of very small regions of activation, the reduction in variability may be counteracted by the reduction in effective resolution.