Translational and Rotational Motion Correction via the Analysis of Point Spread Functions

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Introduction: Various techniques have been proposed for motion correction in MRI [1-3]. Some require the acquisition of additional data [1-2], while others need computationally intensive iterative approaches [3]. In this work, a simple and rapid technique for correction of both in-plane translational and rotational motion is described, based on point spread functions (PSF) measured from two point sources (PSF markers), rigidly attached to and co-imaged with the main imaging object. No additional data or iterative processing is required. The effectiveness of the method is verified by both phantom and in vivo experiments.

Theory: The effect of a bulk in-plane translation of (Δx, Δy) on signal *S* can be formulated as $S_{motion}(k_x,k_y) = S_{still}(k_x,k_y)e^{-j2\pi(k_x\Delta x+k_y\Delta y)}$, where the phase term is the modulation transfer function (MTF) caused by the motion. Taking the inverse Fourier transform, one obtains

$$f_{motion}(x,y) = f_{still}(x,y) \otimes P(x,y), \qquad P(x,y) = FT^{-1}[e^{-j2\pi(k_x\Delta x+k_y\Delta y)}] \tag{1}$$

where *P(x,y)* is the PSF. The corrupted image (f_{motion}) is the convolution of the motionless image (f_{still}) and the PSF. The Fourier relationship between the PSF and the MTF provides a means to remove the MTF phase factor induced by the translations directly without the need to compute the actual motion. To achieve this, a region containing the blurred PSF is first isolated, zero-filled to the full resolution, and Fourier transformed to compute the MTF (**Fig. 1a,b**).

To detect rotational motion, the actual shifts of two markers are needed [2]. The translations of the markers could be computed separately by fitting each k_y line of the MTF phase to a linear equation. Alternatively, if the distance (D) between the two markers is fixed, only the relative x-axis shifts $X(k_y)=\Delta x_1 - \Delta x_2$ need to be detected, and the relative shifts along the y-axis $Y(k_y)$ can be derived by simple geometry. The latter method is preferred since it avoids the difficulty associated with phase wrapping when computing the y-axis shifts. The rotation can then be determined as:

$$\Delta\alpha(k_y) = \sin^{-1}[(X(k_y)Y_0 - Y(k_y)X_0)/D], \tag{2}$$

where (X_0, Y_0) is an arbitrary reference. $X(k_y)$ can be estimated either from the number of phase wraps in each k_y line of the MTF (**Fig. 1b**), or by tracking the PSF in x-k_y space (**Fig. 1c**). To minimize the error in computing Y, one of the markers should be offset with respect to the other along the y-axis. Following the correction for rotation by rotating the k-space data by -Δα, using, for example, a k-space shearing method [4], the remaining translation could be corrected directly using the phase of the MTF of one of the markers as described above. However, one must ensure that the PSF markers are sufficiently separated from the main object for accurate PSF measurement.

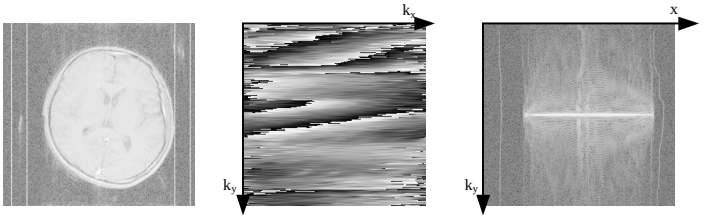
Methods: The proposed technique was investigated in a phantom experiment and an in vivo brain scan. A 2D spin-echo sequence with the following parameters was used: TE/TR 15/500 msec, 24cm FOV, 5mm thickness and 256×256 matrix. Two 1.0 mm inner diameter pipettes filled with Gd-doped water were used for the PSF markers. The pipettes were securely attached to the main imaging object, offset from the edge of the object by approximately 1.5cm in the readout direction.

In the phantom experiment, 4 discrete in-plane translation/rotations were applied manually during the course of the scan. For the in vivo experiment the volunteer was instructed to rotate his head randomly, making both continuous and sudden rotations during the scan. For the purpose of comparison, motion-free images were also acquired separately. Raw data were subsequently transferred to a PC for processing.

Results and Discussion: The processing time was approximately 30 sec in both experiments. For the phantom experiment (**Fig. 2**), the corrected image is indistinguishable from the motion-free image. For the in vivo experiment, the technique significantly alleviated the adverse effects of the combined rotational and translational motion (**Fig. 3)**. Motion estimation revealed that the rotation was in a range of 6.5 degrees, containing both continuous and abrupt movements (**Fig. 4**). Rotations often cause "pie-slice" sections of the k-space to be incomplete, which can lead to residual errors in the corrected image [5].

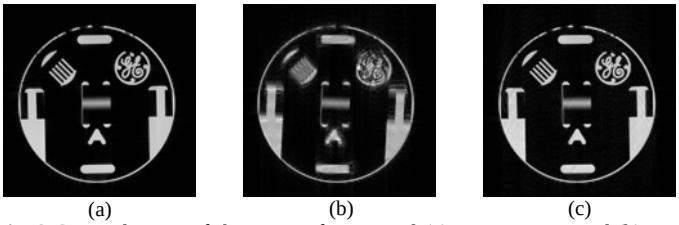
Although a PSF marker width of approximately 1 pixel is ideal (considering both SNR and the ability to use the MTF directly for motion correction), it can be shown that a marker width up to 2 pixels is sufficient to yield reliable MTF phase. Noise may interfere with the accurate measurement of the PSF, and in the current experiment, a SNR of approximately 100 for the PSF marker was needed for accurate motion detection. Optimal Wiener filtering was used for improved performance. A separate dedicated RF coil can also be used [6] to enhance the PSF signal from the marker in high-resolution applications.

Conclusion: In this work, a novel method for correcting in-plane translational and rotational motion via the measurement of the PSF is presented. The method is simple and rapid, and does not require the acquisition of additional data.



(a) (b) (c)

Fig. 1 Motion correction in an in vivo experiment. (a) Motion-corrupted image scaled to show the PSF markers. Two vertical bands indicate regions used to detect the PSF signals. (b) Phase map of the MTF for the left PSF marker. (c) Magnitude of the *x*-k_y space (log intensity scale). The two discontinued vertical lines are PSF markers and indicate the shifts Δx_1 and Δx_2 for different k_y.



(a) (b) (c)

Fig. 2 Cropped views of the motion-free control (a), motion-corrupted (b), and motion-corrected (c) images from the phantom experiment.

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References

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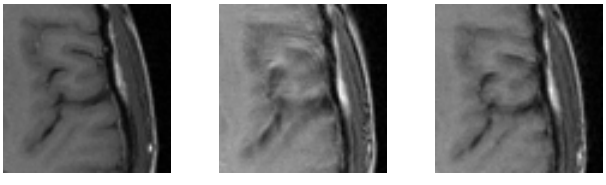

(a) (b) (c)

Fig. 3 (Top) Magnified views of the brain images from the in vivo experiment. (a) Motion-free control. (b) Corrupted with both translational and rotational motion. (c) Motion-corrected images.

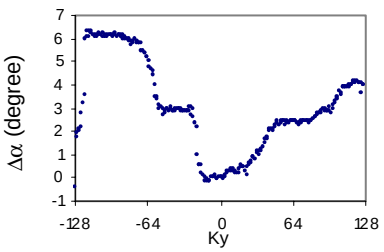

Fig. 4 (Left) Rotational angle profile recovered for the in vivo brain scan shown in Fig. 3.