Quantitative evaluation and optimization of 3D PROspective MOtion (PROMO) through offline simulation

J. Zhang[1,2], D. Rettmann[3], E. Han[4], C. Roddey[5], N. White[5], J. Kuperman[5], J. Santos[1], A. Dale[5,6], and A. Shankaranarayanan[4]

[1]Department of Electrical Engineering, Stanford University, Stanford, CA, United States, [2]Department of Radiology, Stanford University, Stanford, CA, United States, [3]Global Applied Science Lab, GE Healthcare, Rochester, MN, United States, [4]Global Applied Science Lab, GE Healthcare, Menlo Park, CA, United States, [5]Department of Neuroscience, University of California, San Diego, La Jolla, CA, United States, [6]Department of Radiology, University of California, San Diego, La Jolla, CA, United States

INTRODUCTION Patient motions during an MRI scan can cause significant image artifacts. Several retrospective and prospective methods have been proposed to address this problem. Among these techniques, 3D PROspective MOtion correction (PROMO) has shown its uniqueness and robustness in many aspects [2, 3, 4]. However, similar to other motion correction techniques, inaccessibility of exact motion magnitudes limits the development of a quantitative metric that could be used to evaluate and optimize the algorithm performance. In this work, a simulated off-line motion correction system for PROMO has been developed and used to study the behavior of PROMO. We have demonstrated how the configuration parameters would impact the functionality of the algorithm quantitatively. Finally, a set of optimal parameters is presented and applied to online PROMO protocols.

METHODS A PROMO module is composed of three components: 1) (spiral) navigators which take instantaneous 3D snapshot of the subject; 2) EKF which estimates motion parameters; and 3) real-time prescription which adjusts gradients accordingly and schedules rescans if necessary. In this work, we will be focusing on navigator acquisition and reconstruction parameters since the latter two parts have already been adequately studied in previous work [1~4].

Simulation environment: The scheme of the off-line system is shown in Fig 1. A high resolution proton density (PD) weighted 3D volume is first acquired as a reference scan subject. A certain pseudo motion pattern, with each movement represented by six rigid motion variables (tx, ty, tz, rx, ry, rz), is applied to the volume in "real-time". At the same time, the output of EKF is immediately compensated as well to adjust the FOV and orientation of navigators. The error of motion correction $|m_n - \hat{m}_n|$ can be tracked to evaluate the accuracy of the algorithm.

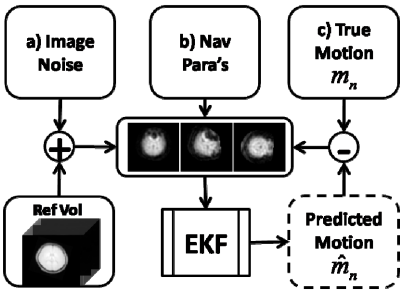


Figure 1: Scheme of off-line PROMO. It simulates on-line motion correction process. Three factors will be evaluated: a) image noise, b) navigator parameters and c) simulated pseudo motion pattern.

Factors Studied: Multiple impacting factors have been studied here, including (a) navigator trajectories, (b) image noise (or SNR), (c) navigator parameters (acquisition and reconstruction) and (d) pseudo motion pattern. The following paragraph gives small details of each of the studied factors.

(a)Trajectories: We compared two trajectories, namely spirals and EPI based on trajectory speed. These trajectories were compared for overall performances. Most of the imaging parameters were kept same for both trajectories.

(b)SNR: White Gaussian noises at different SNR levels were added to the reference volume.

(c)Navigator parameters: The parameters studied were: slice thickness, field of view, effective resolution, trajectory length, reconstruction filters, slice positions and etc. Each parameter was varied over a wide range and an optimal configuration was achieved which minimize the root-mean-square (RMS) correction error among all trials.

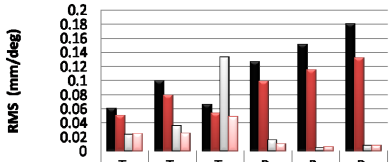
(d)Motion patterns: Two types of pseudo patterns were used. The first type was a random simulated motion sequence, in which each movement was treated as impulse functions simultaneously occurring to all axes, with their magnitudes Gaussian distributed and occurrence Poisson distributed. The second type was a measured motion sequence from on-line PROMO, with various levels of motions from volunteers. Filters were applied to the second type to reduce its adaptation to the algorithm.

In-vivo experiments: Two *in vivo* experiments were performed on cooperative healthy volunteers (IRB consented) by using a 3D XETA [5] FLAIR sequence combined with PROMO module [2]. The scans were done on a 1.5T GE Signa HDx Scanner (Waukesha, WI). The following parameters were used: TE/TR=80.2ms/6s, FOV=24cm, matrix-size=160x160x106 and rBW=31.25kHz. In the first experiment, two PROMO scans, one with old parameters and the other with new optimal parameters, were implemented on a still volunteer. Motion estimates from the two scans were compared as estimation errors. In the second experiment, the patient was allowed to perform intended motions during image acquisition with optimal navigator parameters.

	Optimal Vals
SNR	>5
Slice Thk	>20mm
FOV	32cm
Eff Res	10~15mm
Spiral Len	>2000
Fermi Filter	ON
Deapodize	ON/OFF
Slice Pos	See Discussion

Table 1: Optimal parameters.

RESULTS With similar FOV and effective resolution, it was found that spiral navigators perform much better than EPI ones, mainly due to their higher SNR efficiency. Therefore, for the rest of the experiments, spiral trajectories were used. Table 1 summarizes the optimization results for spirals. Fig 2 compares RMS correction errors between current parameters and optimal ones [3] for both simulations and *in vivo* experiments (data obtained from experiment 1). For both cases, the overall residual errors can be significantly reduced by switching to optimal parameters. Fig 3 shows the plot of estimated motions and one motion corrected image from the second experiment. It can be seen that two large motions were immediately corrected successfully and there are no visible artifacts on the right image.



	Tx	Ty	Tz	Rx	Ry	Rz
Current Sim	0.060	0.099	0.065	0.125	0.150	0.179
Optimal Sim	0.049	0.078	0.052	0.098	0.114	0.131
Current I.V.	0.022	0.035	0.132	0.015	0.004	0.007
Optimal I.V.	0.023	0.024	0.048	0.009	0.005	0.007

Figure 2: Comparison of RMS errors between current configuration and optimal one for simulation and *in vivo* experiments.

DISCUSSION AND CONCLUSION According to the quantitative results shown in Fig 2, the RMS errors could be reduced by 20 to 25 percent when using optimal parameters in simulation. The results from *in vivo* experiments also prove that the proposed optimal configuration can improve the accuracy of motion estimation and make the algorithm more stable, e.g., for Tz. The simulation experiments show that SNR is a key factor to the accuracy of motion estimation. To achieve high SNR, long spiral readouts are desired and the flip angle should be as large as possible (not impacting the signal saturation on the image acquisition at the same time). To uncorrelate in-plane and out-of-plane motions for each navigator slice, thicker slices are preferred. On the other hand, PROMO seems to be not too sensitive to in-plane navigator resolution as long as adequate low frequency image contrasts such as subject contours are preserved. During reconstruction, turning on proper Fermi filters would greatly reduce ringing artifacts and significantly improve the accuracy. Furthermore, slice positions also affect the accuracy of the algorithm, especially for axial rotations. An empirical criterion is to choose an axial slice that has least circularly symmetric image contour so that it would be sensitive to in-plane rotations. Finally, it should be noted that there are some aspects that have not been evaluated through our off-line simulation, such as susceptibility and aliasing artifacts arisen from coronal and sagittal navigators because of the difficulty in simulating these parameters. In conclusion, we have successfully studied and optimized configuration parameters of PROMO through quantitative offline simulations. With its independent coordinate translation and gradient adjustment simulation module, our off-line PROMO system could be easily adapted to evaluate other motion correction algorithms as well.

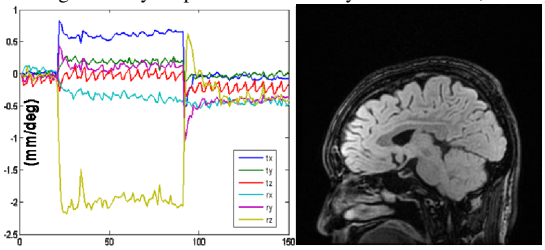


Figure 3: PROMO scan with intended patient motion. Left: estimated patient motions in mm or degree. Right: acquired motion corrected image.

REFERENCES 1. White N et al, ISMRM 2007, p1829; 2. Shankaranarayanan A et al, ISMRM 2007, p2117; 3. Shankaranarayanan A et al, ISMRM 2008, p1475; 4. Roddey C et al, ISMRM 2008, p1476; 5. Busse R et al, Magn Reson Med, 55, 1030-1037, 2006.