Evaluation of Rigid and Non-Rigid Motion Compensation of Cardiac Perfusion MRI

H. Xue[1,2], J. Guehring[3], J. V. Hajnal[1], D. Rueckert[2], S. Zuehlsdorff[4], K. Saddi[3], and C. Chefdhotel[3]

[1]Robert Steiner MRI Unit, Imaging Sciences Department, MRC Clinical Sciences Centre, Hammersmith Hospital, Imperial College London, London, London, United Kingdom, [2]Department of Computing, Imperial College London, London, London, United Kingdom, [3]Imaging and Visualization, Siemens Corporate Research, Princeton, NJ, United States, [4]MR Research and Development, Siemens Medical Solutions USA, Inc., Chicago, Illinois, United States

Introduction Myocardial Perfusion MRI can be undermined by subject motion, which makes sequences of images acquired during contrast uptake inconsistent. Although motion compensation methods have been studied throughout the past decade, no clinically accepted solution has emerged. This is partly due to lack of comprehensive validation. To address this deficit we collected a large multi-center MR perfusion dataset and used this to first characterize typical myocardial motion and then to develop a proposed solution which includes both rigid/affine and the non-rigid image registration. Quantitative validation has been conducted using 6 different statistics to provide a comprehensive evaluation, showing the proposed techniques to be highly robust to different myocardium motion and MR imaging acquisition parameters.

Understanding the datasets Data from 76 patients scanned in 4 different institutes was collected, with a total of 586 image series, including 28,241 2D frames. Three different MR perfusion imaging sequences (TurboFLASH, TrueFISP, and GRE-EPI) were used in these scans. All scans were performed with a minimum of three slice positions (basal, medial and apical). To verify the necessity for motion compensation in the clinical setting, we visually reviewed all datasets and classified them into two categories (no significant motion and with significant motion) according to the maximal motion magnitude presented. No discernible motion was found in 196 series (33%) while the other 390 series (67%) clearly require motion compensation. The motion affected series were further analyzed to determine patterns of myocardium motion. In 122 series the myocardium shows no visible local deformation and a rigid transformation (translation and rotation) is therefore adequate. The other 368 series displayed discernible non-rigid deformation of the myocardium, suggesting the use of non-rigid registration for these cases. Note that no data was excluded from the qualitative analysis, or from the evaluation of motion correction procedures, maximizing the fidelity to the real clinical setting.

Motion compensation As both rigid and non-rigid deformations are noticeable in perfusion datasets, the proposed solution consists of a robust rigid/affine registration and a non-rigid registration step. **a) Rigid/affine registration:** A general rigid/affine registration is implemented in optimized C++ code. The key step to achieve a highly robust rigid/affine registration is a multi-level optimizer which is defined as a container of a specific single-step optimizer. Within this scheme, the step-size of the optimization algorithm is reduced by a factor of two after every optimization step. A multi-resolution image pyramid is also employed in the registration to enlarge the capture range. **b) Non-rigid registration:** A Free-Form Deformation (FFD) based non-rigid registration algorithm [1] is applied after the rigid/affine motion correction. In this framework, a dense 2D deformation field is parameterized at a sparse control point lattice. The motion vector at every control point is estimated to optimize the cost function. A multi-level B-spline FFD transformation is used to allow non-uniform control point lattice spacing and facilitate the capture of large deformation fields, as suggested in [2]. For both rigid/affine and non-rigid motion correction, the normalized mutual information (NMI) is maximized during the registration, as the MR perfusion series commonly show large intensity changes within myocardium and left ventricle (LV) during the contrast agent passage. A slice selected for peak signal change during first pass of the contrast in the myocardium is used as a template and all other slices are transformed into the template coordinate system. We found the registration to be more robust if the slices to be aligned have similar contrast, even when NMI is used. Therefore, registration is performed consecutively between temporally adjacent slices, starting from the template and its direct neighbors (previous and next). For the rigid/affine registration, the computed transformation matrices are easily concatenated while for the non-rigid registration, a slice is registered to its warped neighbors that have been transformed into the template coordinate system. Registration performance is evaluated by means of visual inspection and by means of quantitative measures based on manually delineating the left ventricle and myocardium. For every selected series, two single 2D slices were selected. One is the template and the other one is chosen when the myocardium motion was more discernible. For the subjects without significant motion, 5 series are selected for every slice position, while for the group with significant motion a total of 30 images are used (10 for each slice position). As a result, a total of 45 images are randomly selected, covering all the different sequences. Six statistical measures are computed to give a comprehensive quantification for every case: the relative motion of the left ventricle center point between the template and the registered slice ($D_{A\text{-}I}$ and $D_{S\text{-}L}$, *Anterior-Inferior and Septal-Lateral directions*); the myocardium overlap ratio (Dice ratio [3]); the false positive and false negative ratios of the myocardium mask (FP and FN); the myocardium boundary errors (MBE) defined as the minimal distances between myocardium contours (endo and epi) extracted from the template and the registered slice.

Results Qualitative evaluation revealed that for all 196 series without significant motion, the motion correction does not introduce discernible errors. For 390 series with significant motion, 6 series (~1.5%) have large motion remaining after correction, while all others are noticeably improved. In all cases the non-rigid motion correction works well if the rigid/affine registration is successful. An example of MR perfusion motion correction is given in Fig. 1. Table 1 summarizes the results from the quantitative measures before and after motion correction. For the series without significant motion, these measures show very small changes after the motion correction, while for the series with significant motion, the improvement is noticeable.

Conclusion The analysis of a large collection of MR perfusion time series, obtained under clinically relevant conditions, confirmed that motion correction is a frequent requirement (67% of cases in this sample). The registration based methods we developed were found to be effective in 98.5% of the cases tested. The next step is to test these in clinical practice.

References [1] D. Rueckert, et al., IEEE TMI 18, 712-721, 1999. [2] J. A. Schnabel, MICCAI 2001, 573-581. [3] L.R. Dice, Ecology 26 (3), 297-302, 1945.

Acknowledgement The authors would like to thank the following institutions for providing datasets: CCB (Frankfurt, Germany), Elisabeth-Krankenhaus (Essen, Germany), NHLBI (Bethesda, MD, USA), and the Royal Brompton Hospital (London, UK).

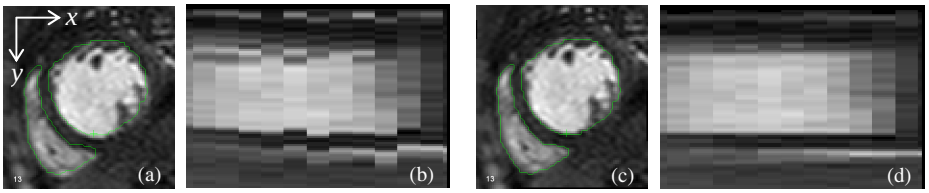

Fig. 1. An example of MR perfusion motion compensation. Before registration: (a) A 2D slice overlaid with myocardium contour extracted from the template slice; (b) The intensity-time relationship for this series. After registration: (c) the same slice as (a) and (d) the corrected intensity-time relationship.

Table 1. Quantitative measures for the performance of motion compensation for perfusion time series.

		D_{AI} [mm]			D_{SL} [mm]			Dice Ratio			False Positive			False Negative			MBE [mm]		
		no	r/a	ffd	no	r/a	ffd	no	r/a	ffd	no	r/a	ffd	no	r/a	ffd	no	r/a	ffd
No Motion	Basal	0.713	0.713	0.442	0.359	0.359	0.653	0.942	0.942	0.940	0.092	0.092	0.071	0.024	0.024	0.050	0.042	0.042	0.024
	Medial	0.761	0.758	0.507	0.361	0.353	0.438	0.922	0.921	0.909	0.079	0.079	0.086	0.078	0.079	0.097	0.008	0.009	0.005
	Apical	0.391	0.391	0.574	0.660	0.660	0.807	0.906	0.906	0.888	0.127	0.127	0.122	0.062	0.062	0.102	0.003	0.003	0.013
	Total	0.621	0.621	0.507	0.460	0.457	0.633	0.923	0.923	0.912	0.099	0.099	0.093	0.055	0.055	0.083	0.011	0.010	0.002
With Motion	Basal	4.006	0.893	0.745	6.925	1.210	0.837	0.783	0.926	0.935	0.241	0.073	0.069	0.193	0.075	0.061	1.814	0.004	0.013
	Medial	4.027	1.122	0.625	6.291	0.644	0.521	0.674	0.890	0.913	0.360	0.119	0.105	0.293	0.102	0.069	1.382	0.012	0.002
	Apical	2.314	1.487	0.943	7.172	1.257	1.197	0.674	0.882	0.894	0.378	0.136	0.126	0.274	0.101	0.086	1.463	0.151	0.049
	Total	3.449	1.168	0.771	6.796	1.037	0.852	0.710	0.899	0.914	0.326	0.109	0.100	0.253	0.093	0.072	1.553	0.056	0.021