Improved T2-Weighted Cardiac Imaging using Retrospective Motion Correction and Optimal Image Combination

H. Xue[1], X. Bi[2], C. Guetter[1], S. Zuehlsdorff[2], M-P. Jolly[1], J. Guehring[1], and P. Kellman[3]
[1]Imaging and Visualization, Siemens Corporate Research, Princeton, NJ, United States, [2]CMR Research and Development, Siemens Medical Solutions USA, Inc., Chicago, IL, United States, [3]National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland, United States

Introduction T2-weighted (T2w) cardiac MR imaging has established reputation as a sensitive technique to depict myocardial edema related to acute infarction. Together with delayed enhancement technique, T2w demonstrated valuable clinical potentials to differentiate acute damage from chronic infarction [1]. To minimize the myocardial signal loss caused by through-plane motion, T2w can be performed in a single-shot fashion using a recently developed T2-prepared SSFP (T2p-SSFP) sequences which outperformed established turbo spin echo based techniques for fewer artifacts and better diagnostic accuracy [2]. Instead of performing segmented imaging which requires multiple breath-holds to image the heart, the clinical acquisition tends to execute free-breathing studies, partly due to considerable difficulties/discomfort of breath-holding for patients who had recently experienced an acute myocardial infarction. As a shortcoming, the free-breathing, single-shot T2w imaging often has to compromise spatial/temporal resolution or sacrifice signal-to-noise ratio (SNR) to fit into a tight acquisition window within the cardiac cycle, despite the broad use of parallel imaging and rapid imaging sequences. On the other hand, recent development in cardiac MR shows that improved SNR can be achieved by selectively averaging motion-corrected free-breathing images using non-rigid image registration methods. Substantial SNR gains have been reported for high spatial and temporal resolution cardiac cine [3], free-breathing delayed enhancement imaging [4], and free-breathing single-shot fat-water separated cardiac imaging [5]. All these studies rely on retrospectively applying image registration to correct heart motion across multiple heart beats. The corrected images can be averaged to achieve good noise suppression. In this work we present dedicated retrospective techniques to improve the free-breathing, single-shot T2w imaging using motion correction and image combination. Unlike previous studies where heuristic criteria were applied to exclude some frames from final averaging to avoid visible artifacts introduced by imperfect non-rigid motion correction, an optimal image combination algorithm was utilized here, computing a weighting function to minimize the total deformation brought into the averaging.

Material and Methods ***Patient Study***: T2w free-breathing, single-shot SSFP imaging was performed on 11 patients using 1.5T imaging systems (MAGNETOM Avanto/Espree, Siemens AG Healthcare Sector, Erlangen, Germany). A total of 24 series were acquired. The MR sequence parameters are as follows: T2 prepared single-shot SSFP readout, TR 3.2ms, TE 1.6ms, matrix 256×144, rectangle FOV (75%), flip angle 60°, reconstructed voxel size of 1.4×1.4×6mm, bandwidth 977 Hz/pixel, T2 preparation TE 60ms. To correct the intensity variation caused by surface coil inhomogeneity, a proton-density (PD) image was acquired during the same cardiac phase in the subsequent RR interval after each T2w acquisition. This PD image is necessary for compensating the profile variation of the phased-array receiver coils, which is essential for correct differentiation of hyper-intense edema [1]. For every patient, the single-shot acquisition was repeated eight times with free-breathing, resulting in a series of 8 T2w and 8 PD images. ***Motion Correction (MOCO)***: For every series, a key/reference frame was first selected by searching for the minimal mean square error to all other frames on the T2w images. A fast variational non-rigid registration algorithm [6] was applied between this reference and all other T2w images, outputting the warped T2w and corresponding pixel-wise deformation fields. The same procedure was repeated for PD images. Finally one more registration was preformed to align the reference of PD to T2w, which compensated heart-beat variations. The localized cross correlation was used as the cost function to robustly handle the substantial image contrast variation between T2w and PD frames. ***Optimal Image Combination (OIC)*****:** As the quality of non-rigid registration is not uniform across different frames and different regions in one frame, the deformation fields, as the outputs of the non-rigid registration process, carry information that relates to the accuracy of motion correction. Often large deformation is more related to visible smearing artifacts introduced by motion correction. To utilize this information, an optimal image combination algorithm [6] was applied here to estimate a weighting function, minimizing the total deformation brought into the resulting image after averaging. Compared to the simple uniform averaging used in previous studies, this approach achieves good noise suppression and provides better tolerance to artifacts possibly introduced by imperfect motion correction. ***Surface coil correction (SCC)*****:** The surface coil map is estimated using an algorithm [7] based on Expectation-Maximization (EM) iteration and B-Spline Free Form Deformation (BFFD). This approach interleaves tissue classification and bias estimation, controlling the smoothness of surface coil map by adjusting the number of control points in B-Spline grid. With the aligned PD images, a homogeneous T2w image is generated by normalizing to the estimated coil map. ***Inline Processing:*** All processing steps were implemented as an inline processing module on the MRI scanner. The computational time is less than 5s on the scanner and combined T2w images were automatically calculated without any user interaction.

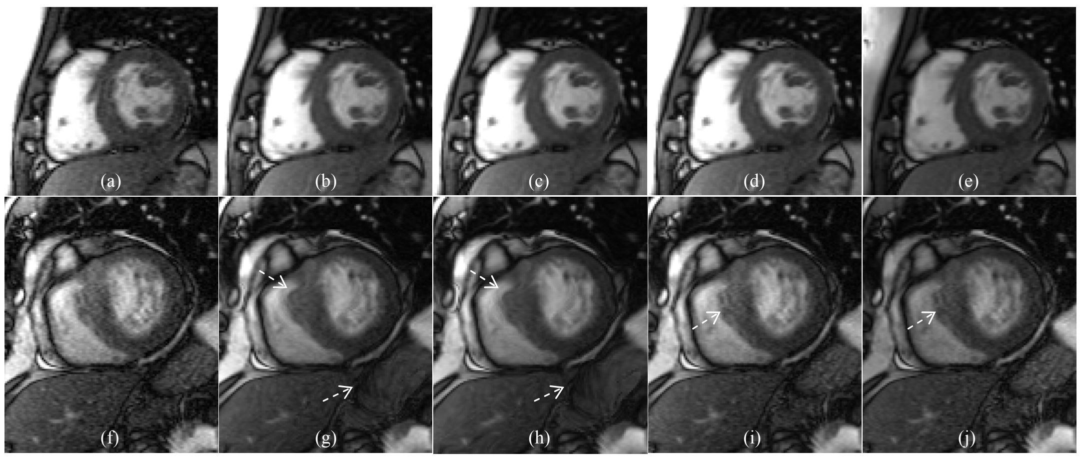

Fig. 1. An illustration of improved T2w imaging. From left to right, (a, f) the single shot T2w image; (b, g) 50% combination, (c, h) 100% combination, (d, i) OIC result before SCC, (e, j) OIC result after SCC. The first row (a-e) shows an example where MOCO is successful. In this case, the OIC result shows similar SNR to 100% combination. The second row (f-j) shows a case where MOCO fails due to large through-plane motion. The smearing artifacts are even visible in the 50% combination (g), but not in the OIC image (i). The effect of SCC is noticeable in (i) and (j).

Results Effectiveness was first evaluated by visual reading of all results. Fig. 1 illustrates the superior performance of optimal image combination on T2w imaging. Although the 100% combination image shows the similar SNR to the OIC result, the latter can lead to less smearing artifacts possibly introduced by motion correction. Image quality for all subjects was assessed by one reader using a 4-point scale (with increment 0.5) as described below. The rating was based on: 1) SNR and image artifacts; 2) intensity inhomogeneity; 3) readability of edema. A score of 4 (excellent) was assigned when all three aspects were rated as excellent. A score of 3 (good) was assigned when all aspects were rated as good, with some fine structures visible, but not necessarily all. A score of 2 (fair) meant the image quality was sufficient to depict edema but not optimal. A score of 1 meant images were seriously impaired and non-diagnostic. The mean scores were 2.5±0.2 for original T2w, 3.1±0.5 and 3.6±0.7 for 50% and 100% combination and 3.8±0.3 for proposed approach.

Conclusion A retrospective image processing workflow is presented to improve the free-breathing, single-shot T2w imaging using motion correction and image combination. The whole process is automated and implemented on the MRI scanner. Initial experiments show that a noticeable SNR gain can be achieved without introducing smearing artifacts, which is mainly attributed to the optimal image combination. Further validation includes applying proposed techniques to the large cohort of patients with suspicious myocardial infarction and measuring potential gain of better differentiating acute infarction from chronic injury.

References [1] Abedl-Aty H et al., Circulation 109:2411-2416 (2004) [2] Kellman P et al., MRM 57:891-897 (2007) [3] Kellman P et al., MRM 59:771-778 (2008) [4] Kellman P et al., MRM 53:194-200 (2005) [5] Kellman P et al., ISMRM 3662 (2010) [6] Chefd'hotel C et al., ISBI 753-756 (2002) [7] Xue H et al., MICCAI 741-749 (2009)