Motion-Corrected Real-Time Cine Magnetic Resonance Imaging of the Heart
Initial Clinical Experience

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Objective: Free-breathing real-time (RT) imaging can be used in patients with difficulty in breath-holding; however, RT cine imaging typically experiences poor image quality compared with segmented cine imaging because of low resolution. Here, we validate a novel unsupervised motion-corrected (MOCO-RT) reconstruction technique for free-breathing RT cardiac images, called MO CO-RT. Motion-corrected RT uses elastic image registration to generate a single heartbeat of high-quality data from a free-breathing RT acquisition.

Materials and Methods: Segmented balanced steady-state free precession (bSSFP) cine images and free-breathing RT images (Cartesian, TGRAPPA factor 4) were acquired with the same spatial/temporal resolution in 40 patients using clinical 1.5 T magnetic resonance scanners. The respiratory cycle was estimated using the reconstructed RT images, and nonrigid unsupervised motion correction was applied to eliminate breathing motion. Conventional segmented RT and MO CO-RT single-heartbeat cine images were analyzed to evaluate left ventricular (LV) function and volume measurements. Two radiologists scored images for overall image quality, artifact, noise, and wall motion abnormalities. Intraclass correlation coefficient was used to assess the reliability of MO CO-RT measurement.

Results: Intra class correlation coefficient showed excellent reliability (intra class correlation coefficient ≥ 0.95) of MO CO-RT with segmented cine in measuring LV function, mass, and volume. Comparison of the qualitative ratings indicated comparable image quality for MO CO-RT (4.80 ± 0.35) with segmented cine (4.45 ± 0.88, P = 0.215) and significantly higher than conventional RT techniques (3.51 ± 0.41, P < 0.001). Artifact and noise ratings for MO CO-RT (1.11 ± 0.26 and 1.08 ± 0.19) and segmented cine (1.51 ± 0.90, P = 0.088 and 1.23 ± 0.45, P = 0.182) were not different. Wall motion abnormality ratings were comparable among different techniques (P = 0.96).

Conclusion: The MO CO-RT technique can be used to process conventional free-breathing RT cine images and provides comparable quantitative assessment of LV function and volume measurements to conventional segmented cine imaging while providing improved image quality and less artifact and noise. The free-breathing MO CO-RT reconstruction method may have considerable clinical utility in cardiac magnetic resonance imaging for patients with difficulty breath-holding.

Key Words: cardiac magnetic resonance imaging, motion correction, real-time imaging, cardiac function

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Cardiac magnetic resonance (CMR) imaging is widely considered the criterion standard modality for evaluation of cardiac structure and function.1 The basic CMR protocol is based on a segmented electrocardiogram (ECG)-gated cine acquisition, which requires multiple breath-holds for complete heart coverage. This can be challenging in vivo, particularly in sick patients who cannot hold their breath or sick children who cannot follow instructions. An alternative strategy for patients who have difficulty in breath-holding is to use free-breathing real-time (RT) cine imaging using parallel imaging to accelerate the acquisition, such as TGRAPPA (temporal generalized autocalibrating partially parallel acquisitions).2 However, a major limitation with parallel imaging is that the higher the acceleration factor employed to shorten the acquisition time, the worse the temporal and spatial resolution, and this limits image quality,3,4 resulting in lower diagnostic performance compared with segmented breath-hold imaging approaches.

Another approach to speed up the acquisition speed with RT cine magnetic resonance imaging (MRI) relies on compressed sensing techniques, which reconstruct sparse images from undersampled k-space data.5 This has been implemented for both segmented and RT cine MRI;6–8 however, drawbacks with this approach include long reconstruction times, which limit their clinical use and reconstruction artifacts that get propagated through the images resulting in poor image quality. Instead of attempting to accelerate the acquisition at the outset, motion correction techniques can be used retrospectively to nullify the motion artifacts resulting from cardiac and respiratory movement. One approach4 relies on applying motion correction, via image registration and tissue tracking, to RT imaging techniques to generate breath-hold cine images. In this approach, images are acquired with high spatial resolution but reduced temporal resolution, and then retrospectively, high temporal resolution images are reconstructed by respiratory motion correction and rebinning of data over multiple heartbeats.4 This technique, however, is computationally demanding and reported implementations are limited by lengthy processing times.

A computationally less demanding unsupervised motion correction technique for RT cardiac images9 uses a simplified, generalized approach without tissue tracking that could generate single-heartbeat, high-signal-to-noise ratio (SNR) images without respiratory motion from a free-breathing RT acquisition covering multiple heartbeats. The purpose of this study was to compare the free-breathing motion-corrected RT (MOCO-RT) method with standard breath-hold segmented cine imaging and accelerated RT cine imaging in patients.

Methods

Study Population

This research study was approved by the institutional review board. Images were collected prospectively for 40 subjects using clinical 1.5 T MR scanners (MAGNETOM Avanto; Siemens Healthcare, Erlangen, Germany). Inclusion criteria were patients aged 18 to
89 years undergoing a clinical CMR examination at our institution. Informed consent was obtained for all the subjects.

**Imaging Protocol**

Conventional segmented bSSFP cine images at end-expiration and free-breathing RT cine images (Cartesian, TGRAPPA factor 4) were acquired with the same spatial/temporal resolution (192 base matrix, 45-millisecond temporal resolution) in all patients as part of clinical routine. Real-time cine images were single ungated free-breathing acquisitions covering 16 to 20 beats per slice. Slice positions were copied between all methods to acquire the same slice position. During all imaging techniques, a full short-axis stack (10–12 slices, 8-mm slice thickness, 2-mm interslice gap, 45-millisecond temporal resolution, 45-millisecond repetition time, 1.25-millisecond echo time, 2 mm pixel size) was obtained. Slice thickness and interslice gap were always the same between MOCO-RT and segmented images.

**MOCO-RT Processing**

This reconstruction algorithm was applied retrospectively to the RT cine images and generated single-heartbeat, high-SNR cine images without respiratory motion over multiple heartbeats (Fig. 1) that can be directly analyzed on commercially available cardiac function assessment software. Briefly, RT free-breathing images were processedinline in an unsupervised fashion using an investigational prototype motion correction algorithm, which comprised the following steps:

**Ensure Equivalent Number of Cardiac Phases per Heartbeat**

The number of RT images reconstructed per beat and per slice varied due to heart rate fluctuations during the RT acquisition. As a first postprocessing step, each RT image group corresponding to a single heartbeat was temporally interpolated to generate a fixed number of cardiac phases per beat and per slice (25 phases).

**Extract Respiratory Cycle Using Deformation Fields**

Interpolated images for all the heartbeats were averaged for each slice to obtain a reference image at the most representative respiratory and cardiac phase, which is usually end-expiration during diastole; however, it is possible for the average to occur at other representative cardiac/respiratory phases. For each slice, each RT image is aligned with its corresponding reference image using 2-dimensional elastic image registration, and corresponding deformation fields are extracted. The pixelwise sum of the deformation fields at each time point resulted in a 1-dimensional vector representing the net deformation or motion between each image and the corresponding reference image. Because this motion also includes cardiac motion and noise, a low pass filter with a cutoff frequency of 0.67 Hz (or 1.5 seconds, slower than an expected heart rate) was applied to this 1-dimensional time series, and respiratory motion for each slice was estimated. The low pass filter was not applied to the images but rather to the physiological signal data to eliminate noise for reliable extraction of respiratory motion. This entire process took a few seconds per RT cine slice on the scanner's reconstruction workstation. Previously, we showed good agreement between respiratory cycle obtained from deformations fields and conventional image-based navigator at the lung-diaphragm interface (Fig. 2).

**Sorting and Motion-Corrected Averaging**

Once the respiratory motion is extracted, for each slice, images were sorted by how closely they matched with the reference image for each cardiac phase. A good match corresponds to minimal deformation; lowest value on the respiratory motion signal represents best match to the reference image. For each cardiac phase, corresponding respiratory motion signal time points were extracted and sorted, and a new reference image per phase was calculated using the 60% best matching heartbeats (ie, first 60% of the sorted heartbeats). The 60% was defined empirically given the tradeoffs of scan time and image quality, and also corresponded to the typical portion of the respiratory cycle spent in end-expiration. Finally, images from the selected beats were registered to their respective reference image for each cardiac phase, and motion-corrected images were averaged to obtain a high SNR image.

As a result, motion-corrected RT cardiac cine images with a predefined number of phases were reconstructed retrospectively from the free-breathing RT images without user interaction from any slice orientation.

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**FIGURE 1.** Schematic view of the algorithm generating MOCO-RT images from RT free-breathing data.
Data Analysis

Conventional segmented cine, RT cine, and MOCO-RT single-heartbeat cine images were analyzed in a blinded manner on an external workstation by manually drawing endocardial and epicardial contours at end-systole and end-diastole to evaluate left and right ventricular (LV and RV) function, mass, and volume on the short-axis stack of slices for each technique in each patient using CVI42 software (V.5.3, Calgary, Canada). Quantitative assessment was performed by 2 CMR physicians with CMR segmentation expertise with more than 5 years (A.A.R.) and 1 year (R.S.D.) of experience in CMR image postprocessing. Papillary muscles were considered part of the ventricular cavity and excluded from segmentation. The software then calculated ejection fraction, end-systolic volume, end-diastolic volume, cardiac output, and myocardial mass.

Two experienced radiologists with 8 (ARG) and 15 (MLS) years of experience in diagnostic imaging assessment evaluated the images for the qualitative analysis in blinded manner. For patients with arrhythmia, usually due to irregular heartbeat, SSFP images were not analyzable.

FIGURE 2. Top, Respiratory cycle obtained from deformation field (unsupervised). Bottom, Conventional image-based navigator obtained by plotting a strip of pixels at the lung-diaphragm interface as a function of time. Figure 2 can be viewed online in color at www.investigativeradiology.com.

FIGURE 3. Short-axis images of the heart acquired in patients with good breath-holding (A–C) and poor breath-holding ability (D–F). Four chamber images of the heart in a patient with poor breath-holding ability (G–I). In the first patient, the image quality of MOCO-RT and segmented images are comparable; however, for the second and third patients, poor breath-holding ability resulted in poor image quality in segmented images, whereas MOCO-RT images had high quality. RT indicates real-time; MOCO, motion corrected.
for cardiac function measurements. In this group of patients, the accepted method of function evaluation is visual estimation by an experienced radiologist. For the subgroup of patients with arrhythmia, LV and RV functions were visually estimated, and then results were compared with derived results from RT and MOCO-RT. For all the subjects, image quality was assessed in a blinded manner using a 5-point Likert scale from 1 to 5 independently by conventional breath-hold, ECG-gated segmented bSSFP cine images, RT cine images, and MOCO-RT cine images for the basal, mid, and apical LV, which were scored separately. As suggested previously, the presence of high contrast between myocardium and blood, sharp borders, and distinct appearance of fine structural details were the determinant factors for assigning the image quality score. Regional wall motion abnormalities (WMAs) were scored as a dichotomous variable (present, absent) in the 16-segment AHA model. To scale the noise and artifact, a score of 5 (excellent) was assigned when there was no appreciable artifact and no appreciable noise. A score of 4 (very good) was assigned when there was mild artifact and mild noise. A score of 3 (good) meant that the images have moderate amount of artifact and moderate amount of noise. A score of 2 (fair) meant that images were seriously impaired with considerable amount of artifact and noise. Finally, a score of 1 (poor) meant that images were nondiagnostic secondary to severe artifact or severe noise. These ratings were summed across all 16 segments to derive a global WMA score and scores for basal, mid LV, and apical regions.

Statistical Analysis

Normally distributed continuous variables, including LV function, mass, and volume, were expressed as means ± SD. One-way analysis of variance (ANOVA) was used to compare these parameters between 3 methods. To evaluate the absolute agreement, we used 2-way mixed intraclass correlation coefficients (ICCs) test to assess LV function, mass, and volume derived from MOCO-RT and RT techniques with respect to the reference standard segmented cine measurements. An ICC greater than 0.8 was considered excellent agreement. To further assess the agreement between MOCO-RT and RT with segmented cine, Bland-Altman analysis was performed to compare the quantitative measures and results were shown as mean difference (lower limit of agreement, upper limit of agreement). Interobserver variability of volumetric and mass measurement was evaluated using the ICC. Wall motion abnormality measures, image quality, noise, and artifact ratings were averaged. The averaged values for MOCO-RT were then compared with segmented cine and RT using Mann-Whitney U test. The qualitative analysis was also performed in a subgroup of patients with arrhythmia. P value less than 0.05 was considered statistically significant. Statistical analysis was performed using SPSS statistical software (IBM, Armonk, NY).

RESULTS

Patient’s Characteristics

Analyzable images were reconstructed in all 40 patients using the MOCO-RT approach. The mean age of the subjects was 56 ± 14, and 50% were male, 10% were smoker, 22.5% were diabetic, 65% were hypertensive, and 42.5% were dyslipidemic. Image acquisition times for segmented cine and RT free-breathing cine were 10 seconds per slice.

FIGURE 4. Short-axis images of the heart acquired in patients with atrial fibrillation (A–C) and dilated cardiomyopathy (D–F). RT indicates real-time; MOCO, motion corrected.
and 16 seconds per slice, respectively, which is typical of clinical routine. Image reconstruction for the MOCO-RT cine images took 16 seconds per slice. Figures 3 and 4 present short- and long-axis images for different subjects with good and poor breath-holding capabilities, with arrhythmia and LV dysfunction. Included subjects were those with suspected cardiomyopathy (n = 20), those who were referred for further evaluation of arrhythmia (including patients with history of persistent atrial fibrillation and PVCs) (n = 4), suspicion of aortic valve disease or aortic dilation referred for MR angiography/CMR (n = 11), patients with history of myopericarditis (n = 2), and congenital cardiac disease (n = 3).

Quantitative Assessment of 3 Techniques

Table 1 summarizes LV function, mass, and volume measurements for MOCO-RT, RT, and segmented techniques. The MOCO-RT measures showed excellent reliability with segmented cine; the coefficient for LVEF% approached unity (ICC, 0.99; 95% confidence interval [CI], 0.92–0.99), left ventricular end-diastolic volume (LVEDV) (ICC, 0.98; 95% CI, 0.94–0.99), and left ventricular end-systolic volume (LVESV) (ICC, 0.99; 95% CI, 0.95–0.99). The MOCO-RT showed excellent reliability in measuring LV mass (ICC, 0.98; 95% CI, 0.91–0.99). Intraclass correlation coefficient showed excellent reliability (ICC ≥ 0.80) of RT with segmented cine in measuring LV function, mass, and volume; the coefficient for LVEF was 0.98 (95% CI, 0.97–0.99). Coefficients for LVEDV, LVESV, and LV mass were 0.97 (95% CI, 0.95–0.99), 0.99 (95% CI, 0.97–0.99), and 0.98 (95% CI, 0.95–0.99), respectively. Right ventricular volumetric analysis for MOCO-RT technique showed excellent reliability with SSFP technique. The coefficient for right ventricular ejection fraction (RVEF), right ventricular end-diastolic volume (RVEDV), and right ventricular end-systolic volume (RVESV) were 0.97 (95% CI, 0.90–0.98), 0.95 (95% CI, 0.91–0.97), and 0.97 (95% CI, 0.94–0.98), respectively. The analysis showed that agreement between RT and SSFP technique was excellent for RVEF and volumetric analysis (Table 1). Bland-Altman analysis showed minimal systematic bias of quantitative measurements by MOCO-RT compared with segmented cine. In addition, Bland-Altman analysis for quantitative measurements by RT and segmented cine showed minimal systematic bias with mean difference (Figs. 5, 6). The 1-way ANOVA did not show any statistically significant difference between the 3 methods’ measurements.

### Quantitative Assessment of 3 Techniques

Table 1. Measurements of LV and RV Function, Mass, and Volume Obtained With Different Techniques

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Technique</th>
<th>Mean ± SD</th>
<th>P</th>
<th>ICC</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEF, %</td>
<td>Segmented</td>
<td>59.1 ± 14.6</td>
<td>0.798</td>
<td>0.98</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>59.3 ± 13.1</td>
<td>0.798</td>
<td>0.98</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>57.4 ± 12.7</td>
<td>0.99</td>
<td>0.92–0.99</td>
<td></td>
</tr>
<tr>
<td>LVEDV, mL</td>
<td>Segmented</td>
<td>144 ± 45.3</td>
<td>0.937</td>
<td>0.97</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>144 ± 47.5</td>
<td>0.937</td>
<td>0.97</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>147.3 ± 47.2</td>
<td>0.98</td>
<td>0.94–0.99</td>
<td></td>
</tr>
<tr>
<td>LVESV, mL</td>
<td>Segmented</td>
<td>63 ± 47</td>
<td>0.917</td>
<td>0.99</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>62.6 ± 41.9</td>
<td>0.917</td>
<td>0.99</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>66.3 ± 42</td>
<td>0.99</td>
<td>0.95–0.99</td>
<td></td>
</tr>
<tr>
<td>LV mass, g</td>
<td>Segmented</td>
<td>116.8 ± 45.1</td>
<td>0.927</td>
<td>0.98</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>117.9 ± 47</td>
<td>0.927</td>
<td>0.98</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>114 ± 42.7</td>
<td>0.98</td>
<td>0.91–0.99</td>
<td></td>
</tr>
<tr>
<td>RVEF, %</td>
<td>Segmented</td>
<td>55.6 ± 13.1</td>
<td>0.660</td>
<td>0.90</td>
<td>0.78–0.95</td>
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<tr>
<td></td>
<td>RT</td>
<td>53.1 ± 12.8</td>
<td>0.660</td>
<td>0.90</td>
<td>0.78–0.95</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>53.2 ± 11</td>
<td>0.97</td>
<td>0.90–0.98</td>
<td></td>
</tr>
<tr>
<td>RVEDV, mL</td>
<td>Segmented</td>
<td>141 ± 52</td>
<td>0.656</td>
<td>0.97</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>136.6 ± 47.4</td>
<td>0.656</td>
<td>0.97</td>
<td>0.95–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>130.6 ± 44.7</td>
<td>0.95</td>
<td>0.91–0.97</td>
<td></td>
</tr>
<tr>
<td>RVESV, mL</td>
<td>Segmented</td>
<td>67.2 ± 48.9</td>
<td>0.929</td>
<td>0.98</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>67.1 ± 41.2</td>
<td>0.929</td>
<td>0.98</td>
<td>0.97–0.99</td>
</tr>
<tr>
<td></td>
<td>MOCO-RT</td>
<td>63.9 ± 37.1</td>
<td>0.97</td>
<td>0.94–0.98</td>
<td></td>
</tr>
</tbody>
</table>

The 1-way ANOVA showed no statistical difference among 3 techniques. LV indicates left ventricular; RV, right ventricular; ICC, intraclass correlation coefficient; CI, confidence interval; RT, real-time; MOCO-RT, motion-corrected real-time; EF, ejection fraction; EDV, end-diastolic volume; ESV, end-systolic volume.

Qualitative Assessment of 3 Techniques

Ratings for the different readers were averaged to compare MOCO-RT CMR images with segmented cine and RT for image quality, noise, and artifact (Fig. 7). Comparison of the qualitative ratings indicated comparable image quality for MOCO-RT (4.80 ± 0.35) with segmented cine (4.45 ± 0.88, P = 0.215) and significantly higher than conventional RT techniques (3.51 ± 0.41, P < 0.001). Artifact ratings for MOCO-RT (1.11 ± 0.26) tended to be lower than segmented cine ratings (1.51 ± 0.90), however, the difference was not statistically significant (P = 0.088). Real-time ratings for artifact (2.07 ± 0.62) were significantly higher than for MOCO-RT (P < 0.001). Noise levels were nearly identical for MOCO-RT and segmented cine techniques (1.08 ± 0.19 vs 1.23 ± 0.45) (P = 0.182), whereas noise ratings for RT (2.45 ± 0.50) were significantly higher than MOCO-RT (P < 0.001). Overall, 64 (10%) segments were recognized with WMA. Comparison showed no differences in WMA ratings between different techniques (MOCO-RT: 1.12 ± 2.92 vs segmented cine: 1.26 ± 3.15, P = 0.960) and (MOCO-RT: 1.12 ± 2.92 vs RT: 1.21 ± 3.06, P = 0.980).

Subgroup Analysis of Subjects With Arrhythmia

Ten patients had irregular heartbeats during the MR examination. Left ventricular and RV function were visually estimated by an experienced radiologist, and then the agreement between the visual estimation and cardiac function measured with MOCO-RT and RT techniques were evaluated. Our results indicate that there was an excellent to very good agreement between visual estimation and measured cardiac function in patients without arrhythmia, indicating the reliability of visual estimation by our experienced radiologist. After this validation, we found that, in patients with arrhythmia, there was an excellent agreement between visual estimation and MOCO-RT and RT measurements of LV function assessment; however, we did not observe this agreement for RV function assessment (Table 2).

In this subgroup analysis, in comparison with MOCO-RT, image quality ratings (4.6 ± 0.5), segmented cine (3.3 ± 0.8, P = 0.002), and RT images (3.2 ± 0.25, P = 0.001) had significantly lower ratings. Artifact ratings for segmented and RT were 2.75 ± 0.92 and 2.35 ± 0.74, respectively, which were significantly higher than MOCO-RT (L.2 ± 0.34) (P < 0.001). Noise ratings were also significantly higher in segmented (1.65 ± 0.41, P = 0.023) and RT images (2.85 ± 0.5, P < 0.001) images, when compared with MOCO-RT images (1.25 ± 0.25) (Fig. 7, bottom). As only one of the patients had WMA, the ratings between different techniques were not evaluated.

Interobserver Variability

Volumetric and mass measurements were repeated for 7 patients using all 3 techniques. Intraclass correlation coefficients showed excellent interobserver agreement between 2 readers in quantitative measurements. As expected, the level of agreement was higher for LV-related measurements compared with RV measurements. Moreover, due to the lower image quality in RT technique, the level of agreement was lower in comparison with SSFP and MOCO-RT methods (Table 3).
Assessment of Wall Motion

Wall motion between end-diastolic and end-systolic phases was determined for each segment. Figure 8 shows the summarized segmental ICC values when the agreement was checked for different techniques. Our results indicate an excellent to very good agreement between SSFP and RT techniques and SSFP and MOCO-RT techniques.
except for 1 apical segment) (Fig. 8). The 1-way ANOVA did not show any significant difference in segmental wall motion values derived from the 3 methods.

**DISCUSSION**

This study demonstrates that the MOCO-RT reconstructed cine technique, which can be applied to standard ungated free-breathing RT cine images, produces comparable quantitative assessment of LV size and ejection fraction compared with conventional cine methods with breath-holding while providing better image quality and comparable artifact and noise. The agreement between MOCO-RT and segmented cine in measuring LV and RV function, volume, and mass was excellent (ICC ≥ 0.95) with similar performance observed for detection of regional wall motion abnormalities. Real-time cine imaging demonstrated excellent agreement (ICC > 0.90) for LVEF and RVEF and size compared with conventional segmented cine imaging. Intraclass correlation coefficient for measurement of RVEF% was excellent (ICC = 0.97) for MOCO-RT technique and was very good (ICC = 0.90) for RT technique. Because of the highly variable shape of the RV, volumetric analysis of RV can be very challenging, and better image quality plays an important role in confidence and speed of the reader to measure RV volume. Thus, the better agreement between MOCO-RT versus SSFP in comparison with RT versus SSFP images should be attributed to the better image quality and higher confidence of reader in determining RV boundaries. Image quality, noise, and artifacts were inferior for RT compared with MOCO-RT and conventional cine imaging, as expected. In addition, Bland-Altman plots showed very good agreement between MOCO-RT with segmented and RT with segmented technique. However, the upper and lower limits of agreement with conventional segmented cine imaging were wider with the RT technique compared with MOCO-RT, which are attributable to the lower image quality and thus less precise boundary detection.
Abnormal wall motion is suggestive of pathology and is associated with higher risk of cardiovascular disease independent of cardiovascular risk factors. Traditionally, visual evaluation of abnormal wall motion was the only method that physicians used for assessment of wall motion. With the recent development of these newer software products, we are able to measure wall motion throughout cardiac cycle with high definition.

In this article, we demonstrated an excellent to very good agreement in segmental wall motion changes between our MOCO-RT and SSFP techniques, which are also in line with the qualitative analysis of the images performed by physician readers with years of clinical experience.

The MOCO-RT technique that was evaluated in this study demonstrated comparable performance to the common clinical segmented cine technique for quantitative measurement of ejection fraction and ventricular volume. These results compare favorably to other published studies investigating accelerated cine MRI techniques. Allen et al evaluated the performance of an accelerated CMR protocol featuring iterative SENSE reconstruction and spatiotemporal L1-regularization (IS SENSE), and found no significant difference in ventricular quantification between this accelerated method and conventional segmented cine imaging. These 2 methods had breath-hold times of ~3 seconds; however, in pediatrics and sick patients, these cannot be applied successfully if the patient does not follow the instructions. In a study by Feng et al, authors used an 8-fold accelerated RT cardiac cine MRI pulse sequence using a combination of compressed sensing and parallel imaging (k-t SPARSE-SENSE) and compared the results with

![Qualitative Analysis of Three Different techniques in All Patients](image1.png)

![Qualitative Analysis of Three Different techniques in Patients with Arrhythmia](image2.png)

**FIGURE 7.** Ratings for image quality, noise, artifact, and global wall motion abnormality by 2 experienced radiologists in all the patients (top) and subgroup of patients with arrhythmia (bottom). WMA indicates wall motion abnormality. Mean $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ for comparison with MOCO-RT. Figure 7 can be viewed online in color at www.investigativeradiology.com.

<p>| Table 2: Intraclass Correlation and 95% Confidence Interval Between Visually Estimated LV and RV Function and Measured LV and RV Function |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>LVEF RT</th>
<th>MOCO-RT RT</th>
<th>RVEF RT</th>
<th>MOCO-RT RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrhythmia (−)</td>
<td>0.90 (0.75−0.95)</td>
<td>0.92 (0.83−0.96)</td>
<td>0.7 (0.28−0.86)</td>
<td>0.73 (0.1−0.9)</td>
</tr>
<tr>
<td>Arrhythmia (+)</td>
<td>0.88 (0.56−0.97)</td>
<td>0.97 (0.85−0.99)</td>
<td>0.09 (−0.38−0.61)</td>
<td>−0.03 (−0.56−0.56)</td>
</tr>
</tbody>
</table>

RT and MOCO-RT techniques were used to calculate LV and RV function in patients with and without arrhythmia. LV indicates left ventricular; RV, right ventricular; EF, ejection fraction; RT, real-time; MOCO-RT, motion-corrected real-time.
breath-hold cine MRI. Quantitative analysis showed that LV function measurements were comparable between both 8-fold accelerated RT cine and breath-hold cine MRI. Although qualitative grading yielded lower image quality for 8-fold accelerated RT cine MRI, both image quality and wall motion grading scores were reported adequate to achieve acceptable diagnostic images. Despite highly accelerated RT techniques as mentioned, our presented method not only demonstrated the same quantitative LV volume measurement, but also showed comparable image quality and less artifact and noise and same accuracy in detecting wall motion abnormalities.

The MOCO-RT technique demonstrated better image quality, lower noise, and artifact in the subgroup of 10 patients with an irregular heart rhythm compared with segmented cine. This may be attributed to the acquisition duration (~12 beats), which may have afforded a smaller ratio of irregular heartbeats compared with regular heartbeats. Even if an irregular phase is used as a good match for an end-expiration respiratory phase, it will be registered to the reference image, which will not represent irregularity, and the varied heartbeat duration will be compensated with the averaging approach. Although the results of this subanalysis are promising, application of MOCO-RT in a larger group of patients with arrhythmia will need to be investigated.

In our study, we found comparable image quality between MOCO-RT and the segmented cine technique, and this is in agreement with the results of Kellman et al.9,14 that showed motion-corrected images can have similar image quality as conventional methods, although they did not compare quantitative results between conventional and motion correction techniques. The presented method in this article has several benefits compared with previously proposed methods.1,4 This method is capable of processing long-axis cardiac images (including 3 and 4 chamber view images in several subjects who had difficulty in breath-holding), which may be challenging for parallel imaging methods due to coil configurations. In the previous approaches,1,4 an imaged-based navigator signal was used to determine an end-expiratory reference heartbeat for image registration and also to determine which data should be accepted in the final image reconstruction. However, in our method, we simply used the nonrigid deformation to estimate this signal.1 The method described in Kellman et al9 also uses image rebinning into the appropriate respiratory phase, so that motion-corrected images can be transferred back to k-space. However, in our method, image rebinning is not used and we are simply averaging motion-corrected images. In the method of Kellman et al,9 images (approximately 540) were acquired continuously for 60 seconds without ECG gating during free-breathing and then retrospectively reconstructed offline using MATLAB from raw data with embedded ECG timing data. The total time of reconstruction was reported as 480 seconds in a previous publication9; however, the method proposed here is computationally more straightforward with a processing time that is more than an order of magnitude faster (~16 seconds per slice depending on reconstruction hardware). Reconstructed images are directly compatible with commercially available cardiac function assessment software tools.

Recently, Cross et al15 used a distributed Gadgetron implementation to reconstruct motion-corrected images on a computer cluster. Our method uses the native reconstruction workstation on the scanner and provides clinically acceptable reconstructed cine images at no additional cost. Image acquisition times for RT free-breathing cine is 16 seconds per slice. Image reconstruction from routine RT cine images takes 5 to 16 seconds per slice, depending computational speed with different scanners. Routinely, 10 to 12 slices are required to cover entire LV with RT cine imaging, indicating that it would take 210 to 320 seconds total to generate a similar stack of images using the MOCO-RT reconstruction method. In addition, in our experience, each slice acquisition and reconstruction for segmented cine is ~12 seconds (considering that most of the patients are elderly) and the pause between each slice that patient needs to catch his/her breath is ~20 seconds. The duration of image acquisition and reconstruction for MOCO-RT is thus even shorter than for segmented cine images, and the patient can breathe normally during the scan.

Another advantage of the motion correction technique presented here is that it is independent of the image acquisition scheme; it works

### TABLE 3. Interobserver Reliability for Measurements of LV and RV Function, Mass, and Volume Obtained With Different Techniques

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Segmented RT</th>
<th>MOCO-RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV EF, %</td>
<td>0.97 (0.78–0.99)</td>
<td>0.97 (0.89–0.99)</td>
</tr>
<tr>
<td>LVEDV, mL</td>
<td>0.99 (0.97–0.99)</td>
<td>0.98 (0.93–0.99)</td>
</tr>
<tr>
<td>LVESV, mL</td>
<td>0.99 (0.95–0.99)</td>
<td>0.99 (0.97–0.99)</td>
</tr>
<tr>
<td>LV mass, g</td>
<td>0.95 (0.04–0.99)</td>
<td>0.97 (0.02–0.99)</td>
</tr>
<tr>
<td>RV EF, %</td>
<td>0.84 (0.31–0.96)</td>
<td>0.76 (0.36–0.95)</td>
</tr>
<tr>
<td>RVEDV, mL</td>
<td>0.94 (0.73–0.98)</td>
<td>0.90 (0.51–0.98)</td>
</tr>
<tr>
<td>RVESV, mL</td>
<td>0.91 (0.63–0.98)</td>
<td>0.82 (0.02–0.96)</td>
</tr>
</tbody>
</table>

Data have been reported as ICC (95% CI).

LV indicates left ventricular; RV, right ventricular; RT, real-time; MOCO-RT, motion-corrected real-time; EF, ejection fraction; EDV, end-diastolic volume; ESV, end-systolic volume; ICC, intraclass correlation coefficient; CI, confidence interval.

![Figure 8](https://www.investigativeradiology.com)
with any RT data acquisition method without any code changes because postprocessing is applied to reconstructed images. Usman et al.\textsuperscript{16} recently proposed a novel motion-corrected compressed sensing framework for free-breathing dynamic cardiac MRI in conjunction with motion-corrected algorithm. Because our simple and fast proposed method does not depend on the acquisition technique, it can be easily incorporated into compressed sensing algorithms to eliminate the motion artifacts in the reconstructed images. Although compressed sensing is a very promising investigational imaging method that could help to avoid breath-holding, our understanding is that it will not be commercially available for use in the clinical routine for a couple of years due to its computational requirements and clinically unacceptable reconstruction times. However, our MOCO-RT method in conjunction with standard parallel Cartesian imaging is ready to be used in clinical practice now.

LIMITATIONS

This study is subject to some limitations. Only 10 patients with arrhythmia were included. Because this technique is most useful in this type of patient, or patients who were uncooperative, it would have been interesting to assess more examples of this subgroup. However, we acknowledge that this technique could potentially mask arrhythmia during the sorting process and needs to be optimized for patients with arrhythmia.

CONCLUSIONS

In conclusion, we have presented a novel reconstruction technique that generates single-heartbeat, high-SNR motion-corrected cine images from an accelerated conventional RT cine imaging technique free of breath-holding. This method is able to recover the image quality (SNR, contrast-to-noise ratio) lost compared with a segmented acquisition, and at the same time eliminates respiratory motion. This validation study in clinical patients indicates that LV measurements obtained with MOCO-RT show excellent reliability with the reference standard segmented cine images while providing better image quality with comparable artifact and noise while overcoming limitations in image quality, noise, and artifact on RT imaging without motion compensation. The free-breathing MOCO-RT technique may have considerable clinical utility in cardiac MRI for patients with difficulty breath-holding (including children), sedated patients, and patients with arrhythmia.

REFERENCES


