

# Real-time CMR Fourier Analysis for Temporospacial Characterization of Ventricular Wall Motion in Health and Disease

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## Technical advance

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# Abstract

## Background

Cardiovascular magnetic resonance (CMR) has been largely dependent on retrospective cine for image acquisition. Real-time imaging, although inferior in image quality to retrospective cine, is advantageous in examining temporospatial behaviors of cardiac motion over a series of sequential cardiac cycles. The presented work is a proof-of-concept of assessing cardiac function quantitatively with novel temporospatial indices in real-time CMR.

## Methods

Fourier analysis was introduced for temporospatial characterization of real-time CMR signals arising from ventricular wall motion. Two quantitative indices, temporal periodicity and spatial coherence, were provided for function assessment in the left ventricle (LV) and right ventricle (RV). We prospectively investigated these temporospatial indices in a CMR study with healthy volunteers and heart failure (HF) patients.

## Results

Real-time images were collected and analyzed in 12 healthy volunteers during exercise and at rest, and also in 12 HF patients at rest. The statistics indicated that the healthy volunteers presented an increase of temporal periodicity due to ventricular response to exercise (resting-state  $0.24 \pm 0.037$  vs. exercising-state  $0.31 \pm 0.040$  in LV; resting-state  $0.18 \pm 0.030$  vs. exercising-state  $0.25 \pm 0.038$  in RV;  $P < 0.001$  for both). The HF patients gave lower temporal periodicity ( $0.14 \pm 0.021$  for LV;  $0.10 \pm 0.014$  for RV;  $P < 0.001$  for both) than that in the healthy volunteers. The spatial coherence of LV and RV wall motion was also lower in the HF patients than that in the healthy volunteers ( $0.38 \pm 0.040$  vs  $0.52 \pm 0.039$  for LV;  $0.35 \pm 0.035$  vs.  $0.50 \pm 0.036$  for RV;  $P < 0.001$  for both). Both temporal periodicity and spatial coherence were found to be correlated to end-systolic volume (ESV) and ejection-fraction (EF) ( $R > 0.6$ ,  $P < 0.001$ ). However, the HF patients and healthy volunteers were well differentiated in the scatter plots of spatial coherence and temporal periodicity while they were mixed in those of ESV and EF.

## Conclusions

Real-time CMR Fourier analysis enables a new approach to quantitative assessment of cardiac function with temporal periodicity and spatial coherence. The temporospatial characterization of real-time CMR images has the potential for intricate analysis of ventricular wall motion beyond conventional methods.

## Background

Cardiovascular magnetic resonance (CMR) can image systolic and diastolic motion for quantitative assessment of cardiac function [1, 2]. To date, CMR image acquisition has been largely dependent on a retrospective cine technique with breath holding and electrocardiogram (ECG) gating [3, 4]. This technique performs image reconstruction from retrospectively-sorted data, providing a set of multi-phase images for visualizing cardiac motion within a single cardiac cycle. Volumetric measurements with retrospective cine have been used as a clinical standard for function CMR studies [1]. Recently with the development of parallel imaging and compressed sensing [5-7], real-time imaging has been demonstrated to be feasible [8-13]. In comparison to retrospective cine, real-time CMR gives worse image quality, but offers several advantages including less logistical challenges from breath-holding or ECG gating [14], more reliable images in arrhythmia patients [15], and the potential to investigate cardio-respiratory coupling [16]. In addition, real-time CMR is more informative because it permits visualization of the temporal and spatial behaviors of cardiac motion over a series of sequential cardiac cycles. This multi-cycle temporospatial information, although potentially beneficial to functional CMR, has not been extensively investigated.

The presented work aims to explore a new approach to quantitative assessment of cardiac function by characterizing temporospatial behaviors of cardiac motion from real-time CMR images with Fourier analysis. Fourier analysis is a classic mathematical tool for decomposing a time series into periodic signals with different frequencies by Fourier transform and characterizing its temporal behaviors by spectral analysis in frequency domain [17, 18]. In this work, we sought to analyze the real-time CMR images as time-series signals at different spatial locations and calculate two quantitative indices, temporal periodicity and spatial coherence, for quantitative assessment of ventricular function. The new temporospatial indices were investigated prospectively in a CMR study with healthy volunteers and heart failure (HF) patients.

## Methods

### Experimental study

The prospective CMR study was approved by the Institution Review Board. Written consent was obtained from all the subjects. Questionnaire that screened comprehensive medical history was collected. The study exclusions included metallic hazards, pacemaker/defibrillator, claustrophobia and conditions not appropriate for exercise. In addition, resting heart rate greater than 90bpm and systolic blood pressure greater than 180mmHg were excluded. Human imaging data were acquired in compliance with the regulations of the institution's human ethics committee.

A healthy volunteer was recruited if there was no history of cardiovascular disease and no major risk factor. In addition, 12-lead ECG and echocardiography examination were normal. A HF patient was recruited if there was history of hospitalized heart failure. The healthy volunteers were scanned at rest and during exercise. The HF patients were scanned at rest only. All the scans were run with a balanced steady state free precession sequence and a 12-channel coil array on a 1.5T clinical scanner (Siemens Healthineers, Erlangen, Germany). In exercising-state scans, an MR-compatible exercise supine bicycle

(Lode B.V., Groningen, the Netherlands) was mounted on the scanner table. Heart rate and rhythm, and oxygen saturation were monitored continuously. Blood pressure was measured every 3 minutes. The intensity of exercise was adjusted by the bike resistance, which was increased by 25 Watts every 3 minutes until the heart rate was consistently in the range of 100-110bpm. The imaging data during exercise were acquired while the volunteers were exercising inside the scanner.

Retrospective cine and real-time imaging data were collected respectively in the resting-state volunteers, exercising-state volunteers, and resting-state HF patients. The retrospective cine scan was run with breath-holding and ECG gating. The real-time imaging scan was run using radial sampling during free-breathing and without ECG gating [12, 19]. Both scans covered the whole ventricular anatomy with the same 10 short-axis slices. The other acquisition parameters are below:

- ECG-gated retrospective cine: FOV 340×(220-250)mm, voxel 1.5-1.9mm, segments 5-8, iPAT factor 2, ECG-synchronized phases 30, TR/TE 2.6/1.3ms, FA 50°-75°, slice thickness 8mm, slice gap 2mm, bandwidth 1420Hz.
- Real-time imaging data with radial sampling: FOV 230-250mm, voxel 1.5-1.9mm, TR/TE 2.2-3.0/1.1-1.5ms, FA 50°-75°, slice thickness 8mm, slice gap 2mm, bandwidth 1510Hz, time frames 384, a total of 3072 radial views.

## Image reconstruction

Retrospective cine images were reconstructed on the MRI scanner. Each series of retrospective images included 30 phases in a single cardiac cycle, providing a temporal resolution of 30-40ms. Real-time images were reconstructed from the raw data offline in MATLAB (The MathWorks, Inc., Natick, MA 01760). The reconstruction algorithm was based on a correlation imaging framework developed by the authors in previous studies [12, 19]. Each series of real-time images included 7-16 cardiac cycles with a temporal resolution of 18-30ms in a time window of ~7 seconds. Approximately on average, there were 33-48 phases in every cardiac cycle at rest and 24-32 phases during exercise.

### ***Fourier analysis for temporospatial characterization of LV and RV wall motion***

Figure 1 provides an illustration of the Fourier analysis approach to temporospatial characterization of ventricular wall motion. As shown Figure 1(a), end-diastole and end-systole images were first selected from the real-time CMR images. Ventricular boundaries were delineated respectively in the averaged end-diastole and end-systole images for the segmentation of ventricular anatomy. Two regions of interest (ROI) were defined respectively in the LV (LV-ROI) and RV (RV-ROI) by subtracting the end-systole segmentation from the end-diastole segmentation. With the ROI definition, real-time CMR images were rendered into time-series at different spatial locations and a reference CMR signal was generated by spatially averaging these time-series signals within an ROI. The Fourier spectrum of this reference CMR signal was calculated with Fourier transform [18]. The Fourier cross spectrum was calculated between the reference CMR signal and every time-series signal at different spatial locations [18, 20]. From the

resultant Fourier spectrum and Fourier cross spectrum, two quantitative indices, temporal periodicity and spatial coherence, were calculated respectively as follows.

The temporal periodicity of ventricular wall motion was measured in the Fourier spectrum of a reference CMR signal with the below equation:

$$\begin{aligned} & \textit{Temporal Periodicity} \\ = & \frac{\textit{Root Sum Square \{Fourier spectral intensities at cardiac frequencies\}}}{\textit{Root Sum Square \{Fourier spectral intensities at all frequencies\}}} \end{aligned} \quad (1).$$

Equation 1 implies that temporal periodicity is higher if the cardiac frequency components are more dominant in the Fourier transform. As an example, Figure 1(b) shows the Fourier transforms of two reference CMR signals. The spectrum with stronger cardiac frequency components had temporal periodicity of ~60% higher than that in the other. We attributed more dominant cardiac frequency components to greater wall motion and thus better ventricular performance.

The spatial coherence of ventricular wall motion within the LV-ROI or RV-ROI was calculated from the Fourier cross spectrum as follows:

$$\begin{aligned} & \textit{Spatial Coherence} \\ = & \frac{\textit{Sum \{Fourier cross spectral intensities at cardiac frequencies\}}}{\textit{Power normalization term}} \end{aligned} \quad (2),$$

where the denominator term was calculated from the Fourier spectral power of real-time CMR signals and used to normalize the measurement between 0 and 1 for improved inter-subject comparability. As a Fourier cross spectrum calculates the temporal correlation of two time-series signals at every frequency, Equation 2 gives a higher value at a spatial location where the real-time CMR signal has stronger temporal correlation with the reference CMR signal at the cardiac frequencies. For example, Figure 1(c) provides two Fourier cross spectral in a human subject. The measurements of spatial coherence in these two spectra were 0.90 and 0.38 respectively due to different spectral peaks (temporal correlation) at the cardiac frequencies. By calculating the spatial coherence between every CMR time-series signal and the reference CMR signal from LV-ROI or RV-ROI, two spatial coherence maps were generated respectively for evaluating how cardiac motion was correlated with the LV and RV wall motion over the entire ventricular anatomy. We attributed lower correlation to less efficiency in ventricular wall motion and thus poorer ventricular performance. For global assessment, spatial coherence was evaluated by spatially averaging every spatial coherence map within the ventricular anatomy.

## Post-processing

In post-processing, a semi-automatic segmentation method was used to delineate the LV and RV borders in end-systole and end-diastole images [21, 22]. LV and RV volumes were measured in retrospective cine images by following the standard methods used in previous studies [23-25]. The measurement results were manually reviewed. In the processing of real-time images, end-systole and end-diastole images were respectively selected and averaged (Figure 1a). The ROIs (LV-ROI and RV-ROI) were defined from the segmentation in the averaged end-systole and end-diastole images. Fourier analysis was performed to calculate temporal periodicity and spatial coherence.

## Statistical analysis

Volumetric measurements with retrospective cine images provided four quantitative indices including end-diastole volume (EDV), end-systole volume (ESV), stroke volume (SV), and ejection fraction (EF). Fourier analysis with real-time CMR images provided two quantitative indices including temporal periodicity and spatial coherence. These quantitative indices were statistically analyzed: First, all the indices from exercising-state images were statistically compared to those from resting-state images in the healthy volunteers. Second, all the indices from CMR images in the HF patients were statistically compared to those in the healthy volunteers. The statistical comparison was based on a repeated measures ANOVA method [26] with  $P < 0.05$  considered to be statistically significant in MATLAB. The analysis of Pearson correlation coefficient [27] was used to evaluate the correlation between the quantitative indices in real-time CMR Fourier analysis and those in volumetric measurements.

## Results

### Subjects and images

A total of 12 healthy volunteers and 12 HF patients were recruited in the presented work. The healthy volunteers included 7 females and 5 males with ages ranged from 22 years to 72 years (average age 56 years). The HF patients included 4 females and 8 males with ages ranged from 29 years to 74 years (average age 51 years). All the HF patients had reduced left ventricular systolic function. One of them was in atrial fibrillation.

Figure 2(a) provides an example of retrospective cine and real-time images collected from a resting-state healthy volunteer, an exercising-state healthy volunteer, and a resting-state HF patient. In comparison to retrospective cine, real-time imaging gave more noise and artifacts. However, real-time images covered a series of sequential cardiac cycles, providing more temporospatial information about systolic contraction and diastolic relaxation. Figure 2(b) provides the bar plots for the measurements of blood-pool signal to noise ratio (SNR) and blood-myocardium contrast to noise ratio (CNR) in all the subjects. At rest, real-time imaging gave ~50% lower SNR and CNR than those given by retrospective cine. During exercise, the SNR and CNR of real-time images were slightly lower than those of retrospective cine images. By observation,

all the images gave sufficient quality for visualizing geometric changes of ventricular anatomy during systole and diastole.

## **Volumetric measurements with retrospective cine**

Figure 3 provides the repeated measures ANOVA statistics of volumetric measurements with the retrospective cine images. It was found that EF presented an increase in response to exercise in the healthy volunteers ( $P < 0.01$ ) while EDV and ESV were not different at rest and during exercise. As expected, the HF patients presented lower EF, higher EDV and higher ESV than those in the healthy volunteers ( $P < 0.05$  for all). No statistical significances were detected in the comparison of SV measurements.

## **Measurements of temporal periodicity with real-time CMR**

Figure 4(a) provides an example of the reference CMR signals arising from LV and RV wall motion in the same subjects as in Figure 2(a). All the reference CMR signals showed a periodic alternation of increment and decrement associated with ventricular contraction and relaxation over a series of sequential cardiac cycles. In addition, noise-like fluctuation was observed either within a single cardiac cycle or across different cardiac cycles, introducing aperiodicity. In comparison, the HF patient exhibited the highest aperiodicity, and the exercising-state healthy volunteer the lowest. Due to different temporal aperiodicity, the Fourier transforms of these CMR signals showed different spectral intensities at the cardiac frequencies (Figure 4b): The exercising-state healthy volunteer gave the strongest cardiac frequency components and the HF patient the weakest (marked by arrows). Figure 4(c) provides the repeated measures ANOVA statistics of temporal periodicity. The measurements of temporal periodicity for both LV and RV were found to be higher during exercise than those at rest in the healthy volunteers ( $P < 0.001$ ). They were lower in the HF patients than those in the healthy volunteers ( $P < 0.001$ ).

## **Measurements of spatial coherence with real-time CMR**

Figure 5(a) provides the examples of spatial coherence maps measured in the same subjects as in Figure 2(a). Figure 5(b) provides the ANOVA statistics of the spatial average of spatial coherence maps within the ventricular anatomy in all the subjects. It was found that the spatial coherence of LV and RV wall motion was comparable during exercise and at rest in the healthy volunteers. The HF patients presented significantly lower spatial coherence of LV and RV wall motion than that in the healthy volunteers ( $P \leq 0.001$ ).

## **Comparison of CMR Fourier analysis and volumetric measurements**

Figure 6(a) provides the Pearson correlation coefficients between the temporospatial indices (temporal periodicity and spatial coherence) and the volumetric indices (EDV, ESV, SV and EF). The temporospatial indices were most correlated to EF ( $R=0.64$  for spatial coherence of RV wall motion,  $R\geq 0.70$  for the others). They were also strongly correlated to ESV ( $R>0.60$ ). Their correlation with EDV, although not high, exists ( $0.40<R<0.50$ ). There was no considerable correlation with SV in all the cases ( $R<0.30$ ). Figure 6(b) provides the scatter plots of spatial coherence vs. temporal periodicity in reference to those of ESV vs. EF. The HF patients and healthy volunteers were clearly separated in the scatter plots of temporospatial indices while they were mixed in those of volumetric indices.

## Discussion

The presented work proposes a Fourier analysis approach to measuring temporal periodicity and spatial coherence of ventricular wall motion in real-time CMR images over a series of sequential cardiac cycles. We have demonstrated that the temporospatial evaluation of LV and RV wall motion can detect the difference of ventricular performance in healthy volunteers and in patients with HF, providing a proof-of-concept of real-time CMR Fourier analysis for quantitative assessment of cardiac function.

## Rationales for real-time CMR Fourier analysis

Real-time CMR permits the visualization of ventricular wall motion over a series of cardiac cycles for quantitative assessment of LV and RV myocardial function. Due to the lack of sufficient SNR and resolution, however, it is difficult to identify the anatomy of ventricular walls and track the wall motion directly in real-time images. The presented work seeks to assess myocardial function in the ventricles by analyzing real-time CMR signals arising from the ventricular wall motion. As illustrated in Figure 1, we can identify LV and RV ventricular anatomy in real-time images and define two ROIs (LV-ROI and RV-ROI) which gives an estimate of the range of ventricular wall motion during systolic contraction and diastolic relaxation. Although the real-time CMR signals within the ROIs are associated with both ventricular walls and pericardial tissues, their dynamic changes depend primarily on the systolic and diastolic motion of ventricular walls. By characterizing the temporospatial behaviors of real-time CMR signals within the ROIs, real-time CMR Fourier analysis provides an indirect approach to quantitative assessment of ventricular wall motion.

It is known that ventricular motion spread spatially through the ventricular walls during every heartbeat [28, 29], allowing the ventricular wall motion to be synchronized at different spatial locations. Due to the synchronization, there should exist a common motion pattern along the time across the anatomy of ventricular walls. This common motion pattern should dominate the dynamic changes of real-time CMR signals arising from the ventricular wall motion. In the presented work, a reference CMR signal was calculated from the spatial average of real-time CMR signals over an ROI (LV-ROI or RV-ROI in Figure 1), providing an estimate of the common motion pattern in the ventricular walls. The measurements of temporal periodicity and spatial coherence are both based on the calculation of the reference CMR signal.

Temporal periodicity is a traditional engineering concept for the study of periodic signals along the time. This concept has been introduced for characterizing the temporal patterns of a reference CMR signal. We believe that, to maintain a consistent cardiac output, a healthy heart should exhibit periodicity globally in the LV and RV contraction and relaxation over a series of sequential cardiac cycles. This periodic pattern, which can be measured quantitatively with temporal periodicity from the reference CMR signal, is expected to be stronger when there is a need for higher cardiac output. As demonstrated in our exercise stress CMR study (Figure 4), the reference CMR signal showed a periodic pattern that follows the heartbeats. The temporal periodicity became higher during exercise when ventricular wall motion increased. These findings validate the physiological relevance of temporal periodicity in real-time CMR Fourier analysis.

Spatial coherence (Equation 2) provides the spatial characterization of ventricular wall motion over a series of sequential cardiac cycles. Motion may spread along the ventricular walls [28, 29], and also from the ventricular walls to the around tissues inside or outside the ventricles during contraction and relaxation. We believe that ventricular performance should be dependent on how widely ventricular wall motion would spread over the entire ventricular anatomy. In the presented work, Fourier cross spectra (Equation 2) were used to calculate the temporal correlation between the reference CMR signal and every real-time CMR signal at different spatial locations in the ventricular anatomy. A spatial coherence map was generated from the Fourier cross spectra to investigate spatial spread of the primary temporal patterns of LV and RV wall motion. To globally assess the spatial spread of LV and RV wall motion, spatial coherence was evaluated by calculating the average of a spatial coherence map within the ventricular anatomy.

In the presented work, the measurements of temporal periodicity and spatial coherence were found to be lower in the HF patients than those in the healthy volunteers. This suggests that both temporal aperiodicity and spatial spread of the ventricular wall motion should contribute to the reduced myocardial contractility. The spatial coherence maps indicate that the LV and RV wall motion is spread less widely over the ventricular anatomy in the HF patients, suggesting that abnormal myocardium may suffer from the impediment of motion spread (Figure 5). These findings provide a validation of the ability of real-time CMR Fourier analysis to quantitatively assess ventricular performance in the healthy subjects and HF patients.

## **Real-time CMR Fourier analysis and volumetric measurements**

We have found that temporal periodicity and spatial coherence are correlated strongly ( $R > 0.5$ ) with EF and ESV, moderately ( $0.5 > R > 0.3$ ) with EDV, and weakly ( $R < 0.3$ ) with SV (Figure 6). These findings further evidence the physiological relevance of real-time CMR Fourier analysis. Especially, the temporospatial indices were found to be most correlated to EF ( $R > 0.6$ ), indicating that they should be related to both systolic contraction and diastolic preload in a cardiac cycle. This strong correlation may be partially

explained by the fact that both temporospatial indices and EF are normalized. Because of normalization, real-time CMR Fourier analysis provides inter-subject comparability.

Despite the correlation, real-time CMR Fourier analysis and volumetric measurements extract different information from the CMR images. Volumetric measurements give an estimate of the change of blood volume from the end of diastole to that of systole in a cardiac cycle and are thereby insensitive to dynamic events in the midst of ventricular filling and ejection. In contrast, real-time CMR Fourier analysis characterizes the ventricular wall motion temporarily and spatially throughout the systole and diastole over a series of sequential cardiac cycles. As Fourier transform is dependent on the data measurements at every time point, temporal periodicity and spatial coherence can evaluate how ventricular performance may be affected by the temporal variation of ventricular wall motion within each cardiac cycle and across different cardiac cycles. With more information, real-time CMR Fourier analysis can provide better assessment of the difference of ventricular performance between the healthy volunteers and the HF patients than that given by volumetric measurements. This explains why the HF patients and healthy volunteers are clearly separated in the scanner plots of spatial coherence against temporal periodicity and while they are mixed in those of ESV against EF (Figure 6b). Our findings suggest that spatial coherence and temporal periodicity may provide the metrics of ventricular performance that are superior to the conventional estimates in detecting change of myocardial performance that is independent of ventricular size. Therefore, real-time CMR Fourier-analysis has the potential to be complementary to the traditional volumetric measurements.

## Potential applications

Potential applications for real-time CMR Fourier analysis include quantitative assessment of left ventricular function during stress (exercise or pharmacological) MRI; measurement of left atrial functional performance parameters; assessment of left ventricular diastolic function; and assessment of the right ventricle in various disease states (including pulmonary hypertension and congenital heart disease). They may also have the potential to allow effective assessment of therapeutic response in patients with cardiomyopathy.

It should be mentioned that Fourier analysis offers a SNR gain over time-domain analysis because a spectral peak in Fourier transform arises from temporal summation that may suppress noise [18, 20, 30]. This SNR gain can compensate for the relatively low image quality in real-time CMR (Figure 2). This gain may be beneficial to clinical applications of real-time CMR Fourier analysis.

## Study limitations

The presented work is a proof-of-concept study on real-time CMR Fourier analysis for temporospatial characterization of ventricular wall motion. As ventricular wall motion is the cause of many mechanic events in a cardiac cycle, such as pressure, volume and flow velocity changes as well as the response to

the change of electrical conduction, this characterization may provide information about the intricacy of wall motion in normal subject and in patients with a number of different cardiac diseases. Accordingly, a small group of HF patients is not sufficient for a comprehensive evaluation of the clinical potential of real-time CMR Fourier analysis. The follow-up studies should expand into an experimental work on a wider range of cardiac diseases with a larger number of human subjects. Additional future work should also address inter-operator, intra-operator, and inter-exam reproducibility; comparison with other left ventricular functional parameters and techniques; and improving the reconstruction time of radial MRI data.

## Conclusions

Real-time CMR Fourier analysis provides an approach to characterizing temporospatial behaviors of ventricular wall motion with two quantitative indices, temporal periodicity and spatial coherence, which have the potential to provide quantitative assessment of the LV and RV myocardial function beyond conventional methods.

## Abbreviations

CMR: Cardiovascular magnetic resonance

MRI: Magnetic resonance imaging

ECG: Electrocardiogram

bSSFP: Balanced steady state free precession

LV: Left ventricle

RV: Right ventricle

SV: Stroke volume

EF: Ejection fraction

ROI: Region of interest

## Declarations

### ***Ethics approval and consent to participate***

This study was approved by the Institutional Review Board at St. Francis Hospital. All subjects provided informed consent for research participation.

### ***Consent for publication***

Not applicable

### ***Availability of data and materials***

The datasets generated and/or analyzed during this study are available upon request.

### ***Competing interests***

Not applicable

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### ***Author contributions***

Yu Li: Technical development, experimental design, protocol revision, data acquisition, image reconstruction, statistical analyses, manuscript preparation

Shams Rashid, Yang Cheng, William Schapiro, Kathleen Gliganic, Ann-Marie Yamashita, Marie Grgas: Subject recruitment and reception, Experimental implementation, Data acquisition, Image reconstruction

Elizabeth Haag: Protocol review, study documentation and administrative support

Jason Craft, J. Jane Cao: Study design, protocol development, clinical review and consultation, manuscript preparation

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## Figures

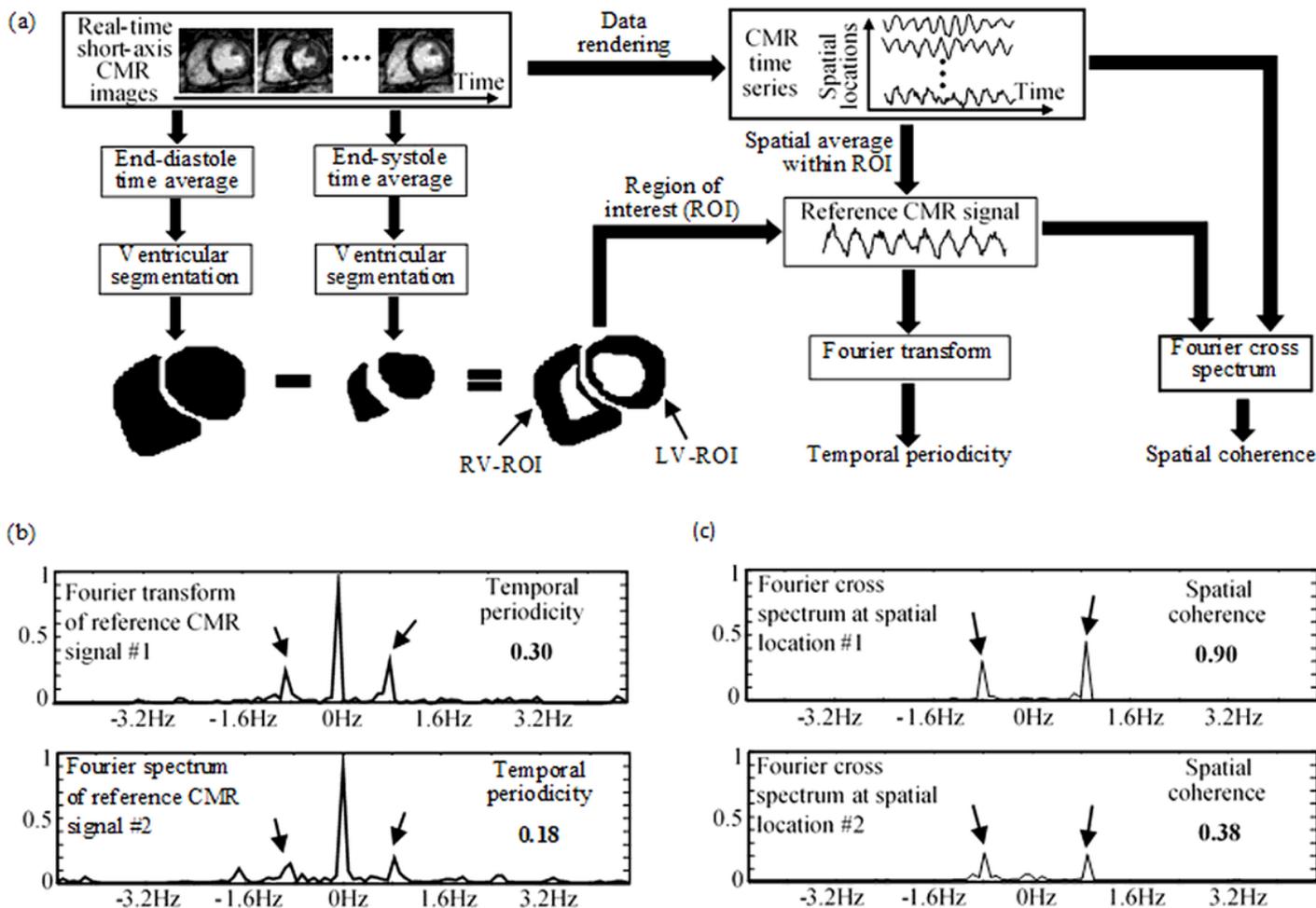
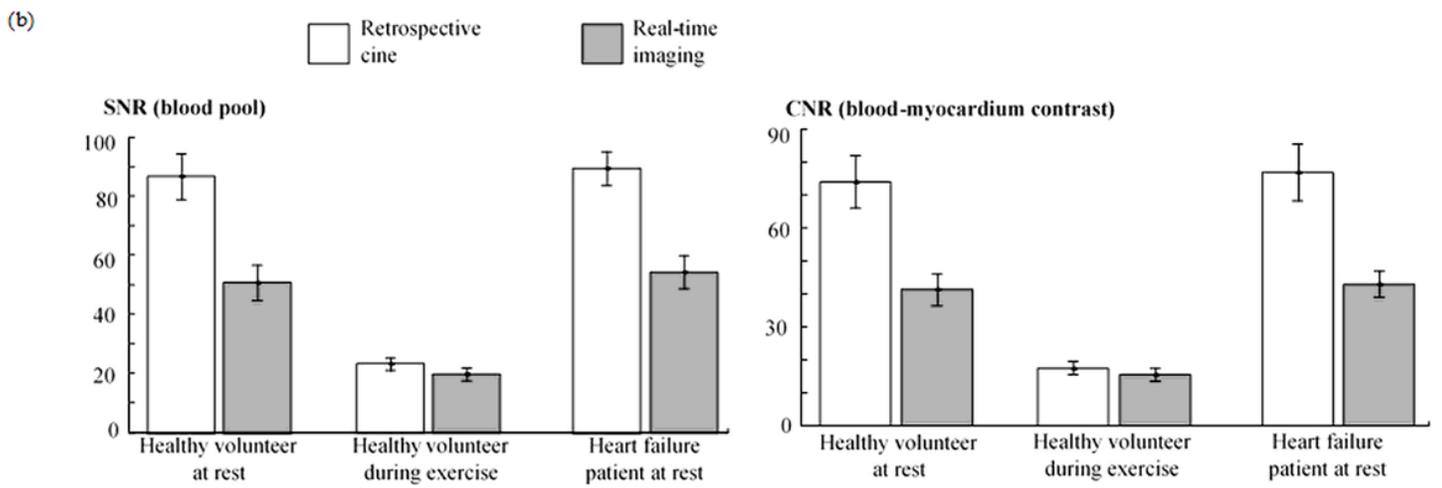
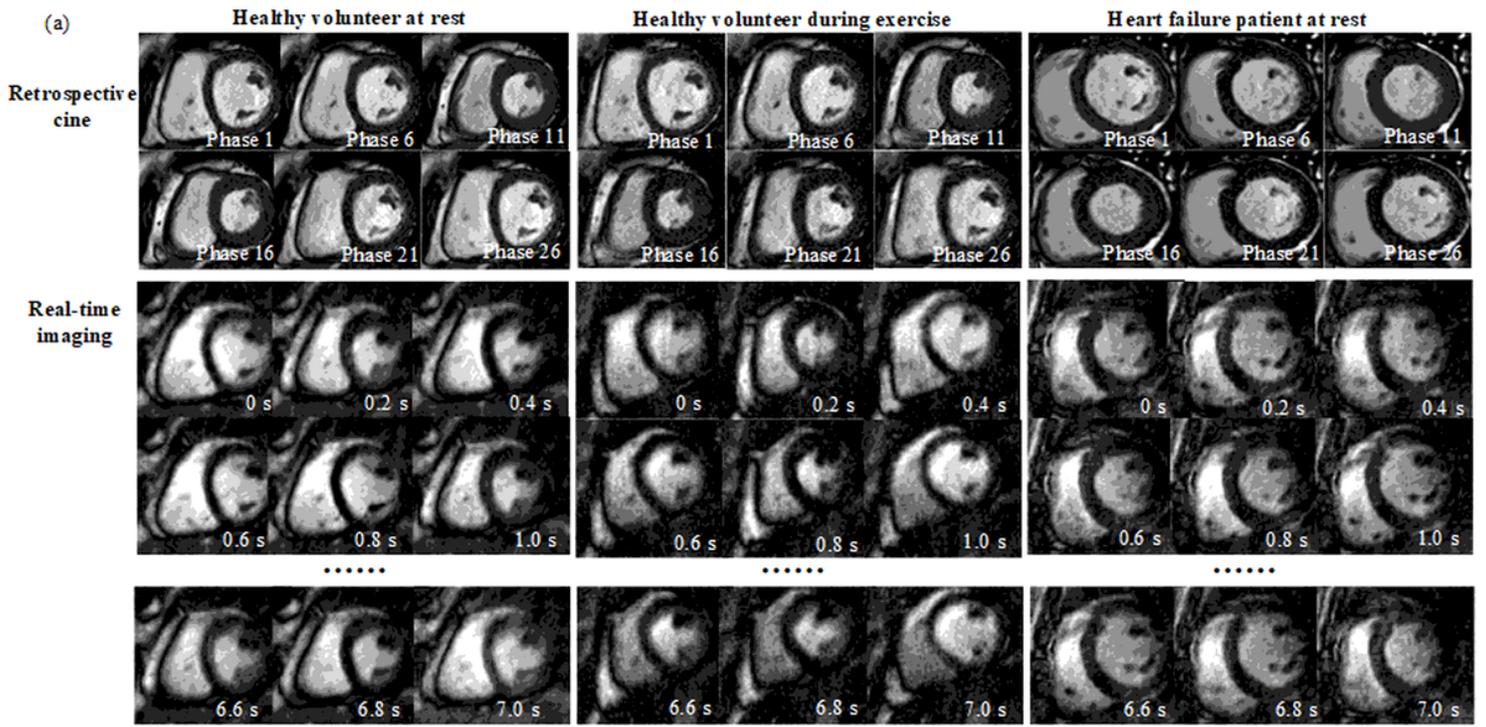


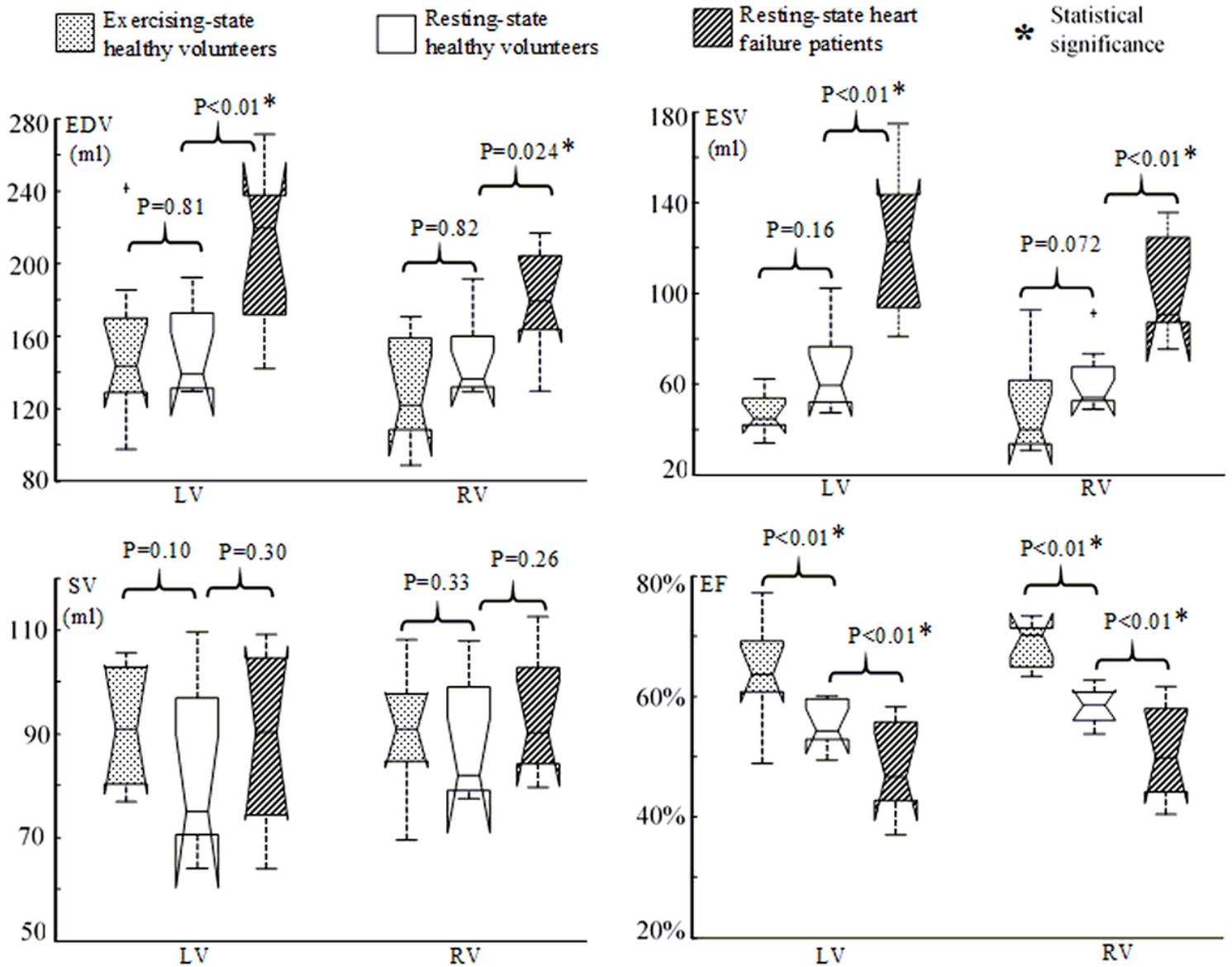
Figure 1

(a) Flow diagram for real-time CMR Fourier analysis. (b) Fourier transforms of two examples of reference CMR signals arising from ventricular wall motion. The spectra magnitudes are normalized with respect to the zero-frequency components. (c) Two examples of Fourier cross spectra at different spatial locations in ventricular anatomy. The arrows in the plots (b) and (c) mark the spectral peaks at cardiac frequencies.



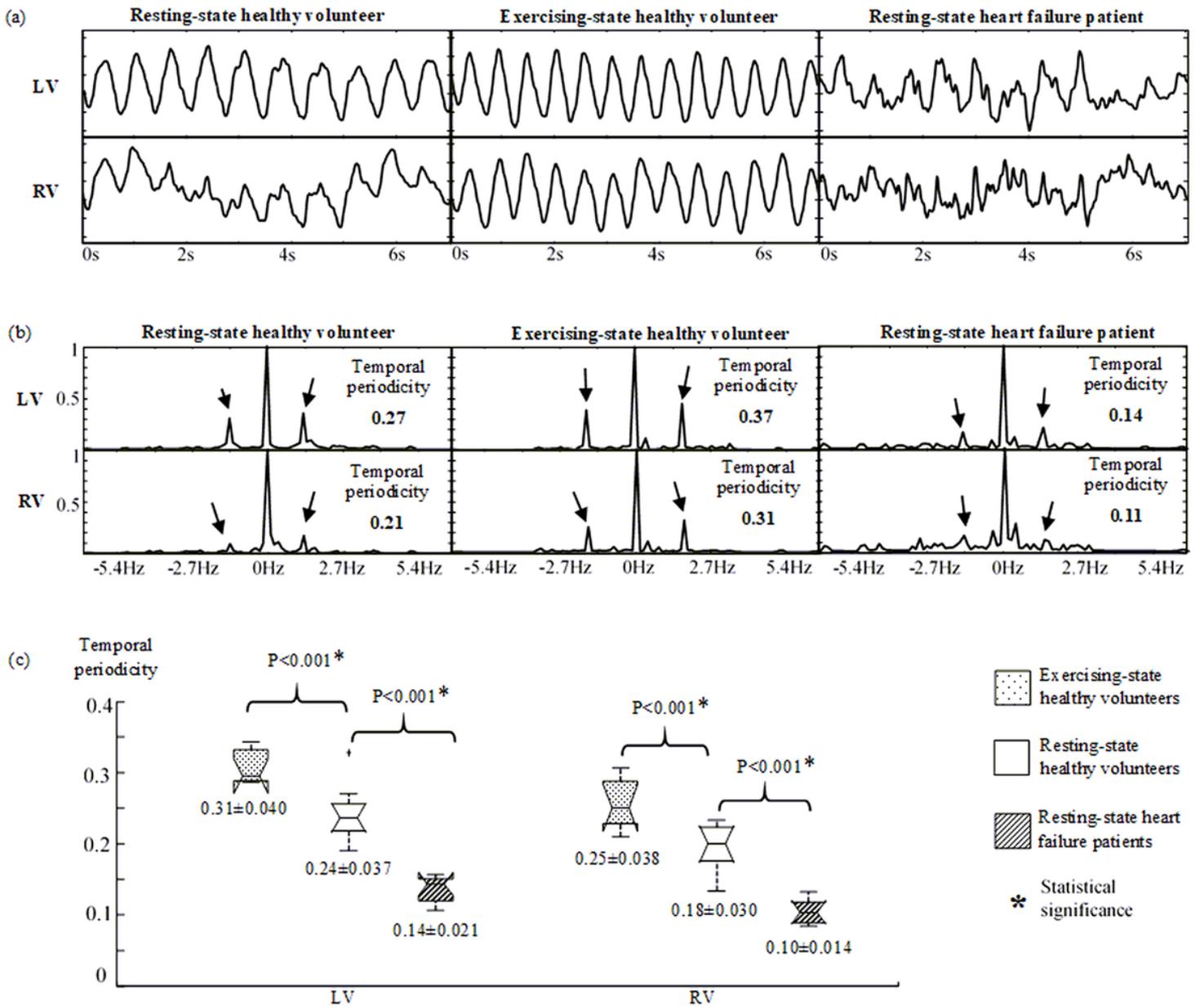
**Figure 2**

(a) Selected time frames of the image examples from retrospective cine and real-time imaging in a resting-state healthy volunteer, an exercising-state volunteer, and a heart failure patient. (b) Bar plots of the measured SNR and CNR in retrospective cine and real-time images from all the subjects.



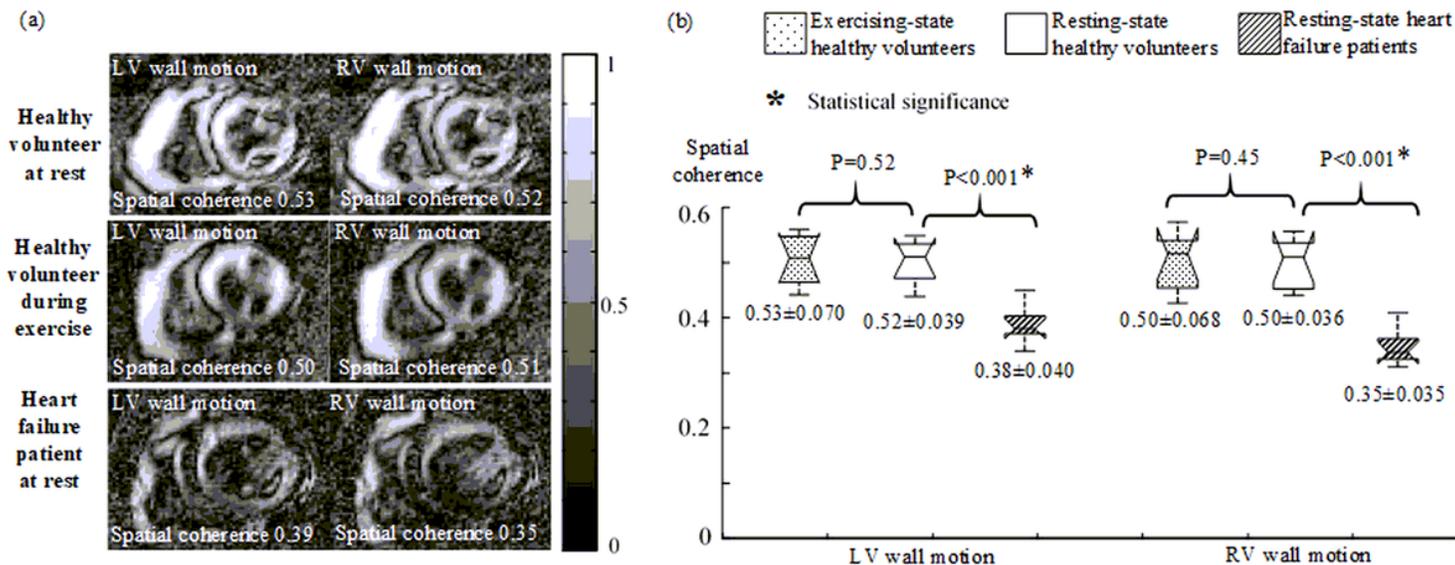
**Figure 3**

Box plots for the repeat measures ANOVA statistics of volumetric measurements, including end-diastole volume (EDV), end-systole volume (ESV), stroke volume (SV) and ejection fraction (EF), in retrospective cine images from the healthy volunteers and HF patients.



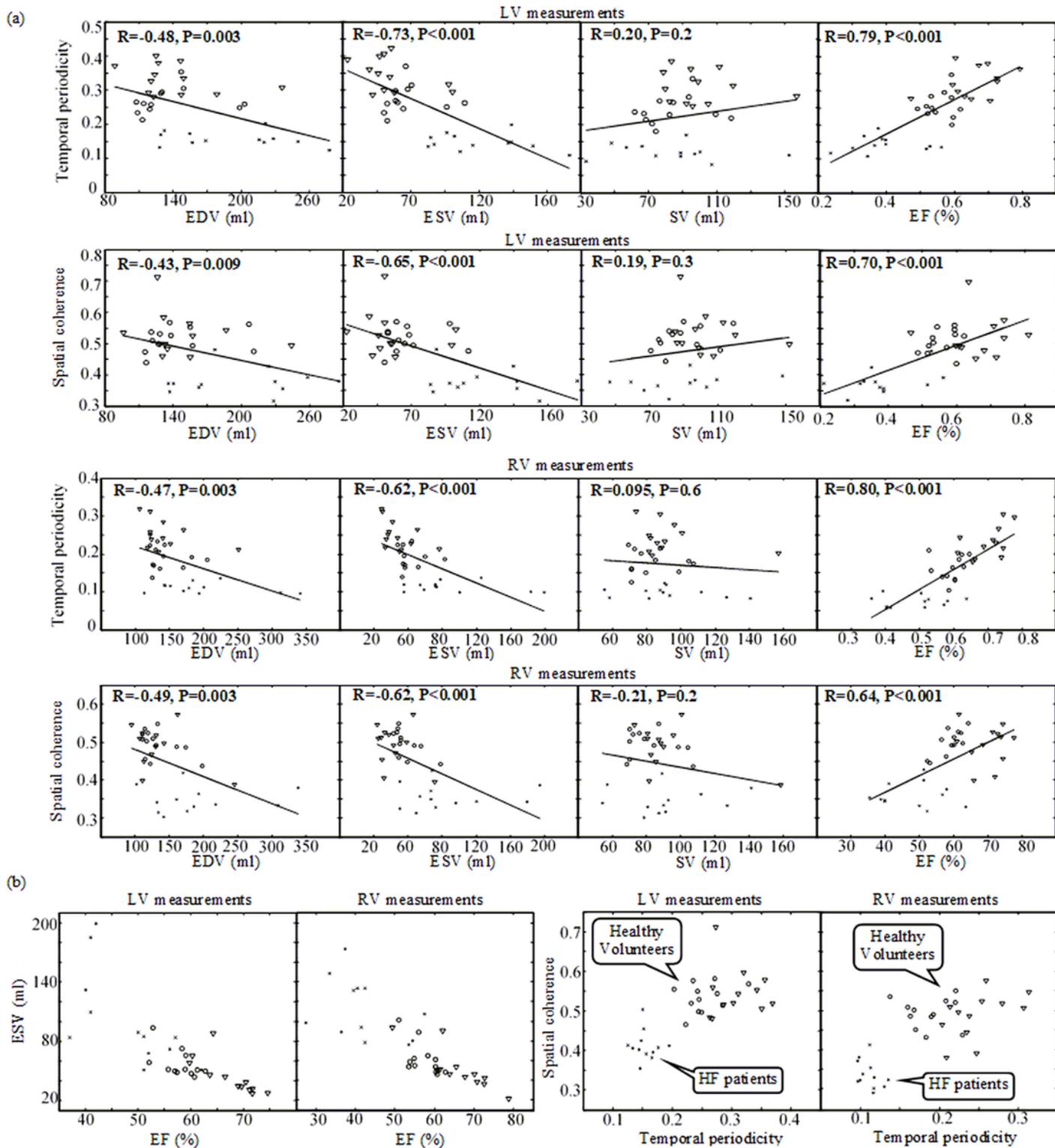
**Figure 4**

(a) Reference CMR signals generated from a spatial average of the real-time CMR signals within LV-ROI (top row), and RV-ROI (bottom row) in the real-time images given by Figure 2(a). The unit on vertical axes is arbitrary. (b) Fourier transforms of the reference CMR signals in (a). The spectral magnitudes are normalized with respect to the zero-frequency component. The measurements of temporal periodicity (Equation 1) are provided. (c) Box plots for the repeated measures ANOVA statistics of temporal periodicity measurements in the healthy volunteers and HF patients. The numbers below each box are the mean and standard deviation of the measurements.



**Figure 5**

(a) Spatial coherence maps calculated from the real-time images given by Figure 2(a). The measurements of spatial coherence are given by averaging spatial coherence maps within the ventricular anatomy. (b) Box plots for the repeated measures ANOVA statistics of spatial coherence measurements in the healthy volunteers and HF patients. The numbers below each box are the mean and standard deviation of the measurements.



**Figure 6**

(a) Pearson correlation coefficients between the temporospatial indices (temporal periodicity and spatial coherence) and the volumetric indices (EDV, ESV, SV and EF) in LV and RV. (c) Scatter plots of volumetric indices (ESV vs. EF) and those of temporospatial indices (spatial coherence vs. temporal periodicity). The measurements in the healthy volunteers at rest and during exercise are represented respectively with "o" and "□", and those in the HF patients with "\*".