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Myocardial strain assessment by cine cardiac magnetic resonance imaging using non-rigid registration

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ABSTRACT

Aims: To evaluate a novel post-processing method for assessment of longitudinal mid-myocardial strain in standard cine cardiac magnetic resonance (CMR) imaging sequences.
Methods and results: Cine CMR imaging and tagged cardiac magnetic resonance imaging (TMRI) were performed in 15 patients with acute myocardial infarction (AMI) and 15 healthy volunteers served as control group. A second group of 37 post-AMI patients underwent both cine CMR and late gadolinium enhancement (LGE) CMR exams. Speckle tracking echocardiography (STE) was performed in 36 of these patients. Cine CMR, TMRI and STE were analyzed to obtain longitudinal strain. LGE-CMR datasets were analyzed to evaluate scar extent. Comparison of peak systolic strain (PSS) measured from CMR and TMRI yielded a strong correlation ($r = 0.86$, $p < 0.001$). PSS measured from CMR and STE correlated well ($r = 0.75$, $p < 0.001$). A cutoff longitudinal PSS value of −13.14% differentiated non-infarction from any infarcted myocardium, with a sensitivity of 93% and a specificity of 89% (area under curve (AUC) 0.95). PSS value of −9.39% differentiated non-transmural from transmural infarcted myocardium, with a sensitivity of 75% and a specificity of 67% (AUC 0.78).
Conclusion: The present study showed a novel off-line post-processing method for segmental longitudinal strain analysis in mid-myocardium layer based on cine CMR data. The method was found to be highly correlated with strain measurements obtained by TMRI and STE. This tool allows accurate discrimination between different transmurality states of myocardial infarction.

1. Introduction

Assessment of regional cardiac function is an important objective of the diagnosis and prognosis in the case of coronary artery disease. Both ischemia and infarction can be detected and localized through analysis of the regional patterns of motion within the heart [1,2].

Cardiac magnetic resonance (CMR) imaging has emerged as an established technique providing accurate information on myocardial function and myocardial scar [3–6]. While late gadolinium enhancement (LGE) CMR is used for evaluating perfusion pathologies and for distinguishing between reversible and irreversible myocardial ischemic injury, myocardial deformation imaging allows for objective assessment of myocardial function.

The currently applied reference method for analysis of myocardial deformation in CMR is tagged MRI (TMRI) [7,8]. Myocardial tagging refers to a family of techniques that lay out a saturation grid or series of saturation lines across the heart. Deformations of these lines due to myocardial contraction are then monitored and provide an in-plane motion component (2D motion).

Tagging can be used to measure myocardial strain, but quantitative analysis of tagged images is not straightforward. Some disadvantages of tagging are that it requires a specific and unique acquisition protocol, it usually suffers from progressive deterioration of the tag signal during the cardiac cycle [9,10], and it requires long breath-hold acquisition and time-consuming post-processing [11].

Thus, for a routine comprehensive evaluation of myocardial function and viability, other methods are needed.

Abbreviations: CMR, cardiac magnetic resonance; MRI, magnetic resonance imaging; TMRI, tagged magnetic resonance imaging; STE, speckle tracking echocardiography; PSS, peak systolic strain; FWHM, full-width at half-maximum; MI, myocardial infarct; AVC, aortic valve closure; ROI, region of interest; LV, left ventricle; CP, corresponding points; ROC, receiver operating characteristic; ICC, inter-class correlation coefficient.

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Others MRI techniques for analysis of regional ventricular function include phase contrast MR imaging (PCMRI), displacement encoding with simulated echoes (DENSE), and strain encoding (SENC) MR. One drawback common to all of these approaches, among others, is that they require acquisition of a specialized image dataset at the time of the examination, typically in addition to the standard cine CMR of the ventricles. Thus, they require a priori planning, increase the duration of the examination, and cannot be applied retrospectively to existing CMR datasets.

Several techniques were proposed for myocardial strain analysis from standard cine CMR [12]. However, these methods were designed for short-axis views, which yield only the circumferential or radial strain analysis, and do not provide longitudinal strain data.

In this study, a novel method is proposed for longitudinal strain analysis in the mid-myocardial layer, based on cine CMR sequences. The method is based on non-rigid registration of subsequent frames, which yields a deformation field for each frame. Consequently, the mid-myocardial longitudinal strain can be calculated according to the strain measurements in the endocardial and epicardial boundaries.

The uniqueness of this method is that the CMR sequence does not need to be manipulated in any way in advance, as described above for the other methods, and the datasets may be processed retrospectively by the proposed method.

The objective of this study was to develop, validate and present a tool for assessment of longitudinal strain in standard CMR sequences. The method was validated with TMRI and compared to speckle tracking echocardiography (STE) and to the extent of scar tissue.

2. Methods

2.1. Study group

A total of 67 individuals were included in this study. The validation group consisted of 15 patients with previously diagnosed myocardial infarction (mean age 69 ± 12 years, 14 males) and 15 healthy volunteers without clinical history of cardiac disease (mean age 27 ± 5 years, 12 males). All these subjects underwent CMR and TMRI for reference strain analysis (two sources: Cardiac Atlas Project, STACOM 2011 challenge [13] and The University of Queensaland, Brinsbane, Australia).

The second group was used for the comparison stage of the study. This group included 37 patients (mean age 67 ± 14 years, 28 males), with previously diagnosed myocardial infarction, which underwent CMR for the definition of myocardial viability (source: Aachen University Hospital RWTH Aachen, Aachen, Germany). LGE-CMR was performed in all these patients and 2D echocardiography with myocardial deformation imaging was performed in 36 of these patients. The time interval from echocardiography to MRI was 4.8 ± 7.7 days. Difference in heart rate between CMR and echocardiographic datasets was 6.5 ± 5.5 bpm.

2.2. Cine cardiac magnetic resonance imaging

The cine CMR datasets were acquired during breath-hold on ECG gated MRI scanner (Philips, Intera/Achieva, Best, The Netherlands and Siemens, Sonata, Erlangen, Germany) at field strength of 1.5 T for the patients' group and 3 T scanner for the healthy volunteers' group. 2D + time cine slices, with steady state free precession (SSFP) protocol, were used for imaging the left ventricle (LV) at a temporal resolution of 21 to 66 frames/s. 5–8 mm thick slices were acquired in two apical planes: apical four-chamber (4CH) and two-chamber (2CH) views. Apical long axis (Aplax) view was not included in this study since it was not available for the TMRI datasets. As a result, validation for this view could not be performed. Scan parameters were as follows: repetition time, 2.7–47 ms; echo time, 1.33–1.76 ms; spatial resolution of (1.14–1.60) × (1.14–1.60) mm^2; flip angle, 39°–60°.

2.3. 2D tagged magnetic resonance imaging

The TMRI datasets were acquired at the same location as the SSFP images, during breath-hold, with a tag separation of 7–8 mm. Scan parameters were as follows: temporal resolution of 20–37 frames/s; repetition time, 6.8–48.0 ms; echo time, 3.14–3.70 ms; spatial resolution of (0.96–1.48) × (0.96–1.48) mm^2, flip angle, 8°–20°. A respiratory navigator was used to compensate for any respiratory miss-alignment during the acquisitions.

2.4. Contrast-enhanced magnetic resonance imaging

All patients underwent LGE-CMR with a 1.5 T whole-body MR scanner (Intera, Best, Philips, The Netherlands) using a five-element phased-array cardiac coil with the patient placed supine. After 15 min of intravenous injection of 0.2 mmol/kg body weight Gd-DTPA (Magnevist, Schering, Berlin, Germany), 8 mm long-axis slices were acquired with a prospective electrocardiogram (ECG)-gated gradient echo sequence, with an inversion pre-pulse, in the same projections as the CMR, to allow assessment of scar extent.

2.5. Echocardiography

For each patient, echocardiography was performed using a commercially available standard ultrasound scanner (Vivid 7, Vivid S6, Vivid E9 or Vivid i, General Electric Healthcare Inc., Horten, Norway) with a 2.5-MHz transducer. Conventional apical four-chamber, two-chamber and three-chamber views were obtained and digitally stored for subsequent analysis. All the images were obtained at a frame rate of 30–98 frames/s.

2.6. Data analysis

For measurement of longitudinal strain in TMRI, CMR and echocardiography, as well as for measurement of scar tissue, the ventricle in each view was divided into 6 segments [14] (4CH: basal inferoseptum, mid inferoseptum, apical septum, apical lateral, mid anterolateral and basal anterolateral; 2CH: basal inferior, mid inferior, apical inferior, apical anterior, mid anterior and basal anterior).

Analysis of MRI data was performed off-line using dedicated software (Matlab version 8.1, The MathWorks, Inc., Natick, MA, USA). Analysis of echocardiographic datasets was done using standard software package (EchoPAC PC SW Only, version BT12, GE Healthcare, Horten, Norway and Haifa, Israel).

2.7. Identification of scar on LGE-CMR

For comparison of strain values and delayed enhancement imaging, each myocardial segment was evaluated for the presence of hyper-enhancement. The definition of hyper-enhancement was based on a Full-Width at Half-Maximum (FWHM) criterion [15–17]. According to this criterion the maximum signal intensity (MX) within the myocardium is identified and segmented, and the myocardial infarct (MI) is identified as the area presenting a signal intensity 50% above the MX (MI ≥ MX * 0.5).

Areas of microvascular obstruction (MVO), defined as subendocardial hypo-enhanced (dark) regions surrounded by hyper-enhancement, were included as part of the infarct [18].

The segmental extent of hyper-enhancement was defined as the percentage of contrast-enhanced area as compared to the total