Regional Comparison of Left Ventricle Systolic Wall Stress Reveals Intraregional Uniformity in Healthy Subjects

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Abstract

This study aimed to assess the feasibility of using the regional uniformity of the left ventricle (LV) wall stress (WS) to diagnose patients with myocardial infarction. We present a novel method using a similarity map that measures the degree of uniformity in nominal systolic WS across pairs of segments within the same patient. The values of the nominal WS are computed at each vertex point from a 1-to-1 corresponding mesh pair of the LV at the end-diastole (ED) and end-systole (ES) phases. The 3D geometries of the LV at ED and ES are reconstructed from border-delineated MRI images and the 1-to-1 mesh generated using a strain-energy minimization approach. The LV is then partitioned into 16 segments based on published clinical standard and the nominal WS histogram distribution for each of the segment was computed. A similarity index is then computed for each pair of histogram distributions to generate a 16-by-16 similarity map. Based on our initial study involving 12 MI patients and 9 controls, we observed uniformity for intra-regional comparisons in the controls compared against the patients. Our results suggest that the regional uniformity of the nominal systolic WS in the form of a similarity map can potentially be used as a discriminant between MI patients and normal controls.

1. Introduction

Myocardial Infarction (MI) is often associated with localized and non-uniform degeneration of ventricular functions. The function of the left ventricle (LV) typically undergoes progressive degeneration accompanied by an enlargement in size after an acute MI. This process of degenerating LV function, also known as LV remodeling [1] is highly complex and results from the onset of myocardial necrosis that altered the mechanical properties of the infarcted region. Over time, such remodeling can affect the global function of the LV and eventually lead to the development of heart failure.

As heart failure becomes an increasingly prevalent healthcare problem globally, there is an urgent need to develop methodologies that can accurately characterize this LV remodeling process. Such methodologies can then be used to facilitate screening to aid in heart failure diagnosis and to monitor the therapeutic efficacy of treatment for existing heart failure patients. The latter use is further necessitated by the improvement in the survival rate for patients after initial acute MI owning to the advancement in medical care. Currently, clinical indices for monitoring LV remodeling include global properties such as LV volumes, ejection fraction, and stroke volume. However, such indices are not able to provide adequate information on the regional functions of the LV as the global values aggregate contribution from both the infarcted and non-infarcted regions. Therefore, there is a need to develop indices that can provide regional information about the performance of the LV. Previously, we had developed a methodology to compute such regional information and shown that the mean systolic wall stress (WS) was significantly increase at each LV segments in the patient group [2]. Using this regional index, we are able to successfully discriminate between normal controls and patients with ischemic dilated cardiomyopathy. However, this mean value comparison may obscure subtle local variations in the systolic WS across the different segments within the same patient. In this paper, we aimed to assess the feasibility of using the regional uniformity of the LV nominal systolic WS to diagnose patients with MI.

2. Methods

The cardiac magnetic resonance (CMR) scans of the subjects (9 control and 12 patients with MI) are taken using a 1.5T Siemens scanner (Avanto, Siemens Medical Solutions, Erlangen). The first (second) scans for the patients were acquired 1-3 (9-12) months after MI and the controls were sex- and age-matched to the patients. Spatial resolution of the scans is 1.5mm in-plane and 8mm out-of-plane, acquired in a single breath hold, with

22 temporal phases per heart cycle. Of these images, those corresponding to the cardiac cycle at end-diastole (ED) and end-systole (ES) are used for analysis.

The 3D LV geometries at ED and ES phases were reconstructed from semi-automated segmented MRI images. For each data sample, an in-house software was used to generate a 1-to-1 corresponding mesh pair of the LV for the ED and ES phases. The nominal systolic WS (hereafter denoted by WS) at each vertex point was computed and a WS histogram distribution for each of the 16 LV segment generated. A histogram similarity index was then computed for each pair of histogram distributions to generate a 16-by-16 similarity map (See Figure 1). Segments with similar (dissimilar) distribution of WS were reflected by a similarity index (denoted by *hdist*) with values close to 0 (1).

applications. Note that Segment 17 in the standardized nomenclature is omitted because it is difficult to acquire the true apex position from the imaging technique. As the standardized nomenclature is largely for image-based data, we extend the method for three-dimensional models as described in [4].

2.2. Computation of nominal systolic wall stress (WS)

The WS is obtained by the equilibrium of forces due to stresses in the wall and blood pressure acting on the wall. Following Grossman et al. [5], the regional peak WS was determined from the inner radius of curvature (R) and wall thickness (T) at end systole by the following
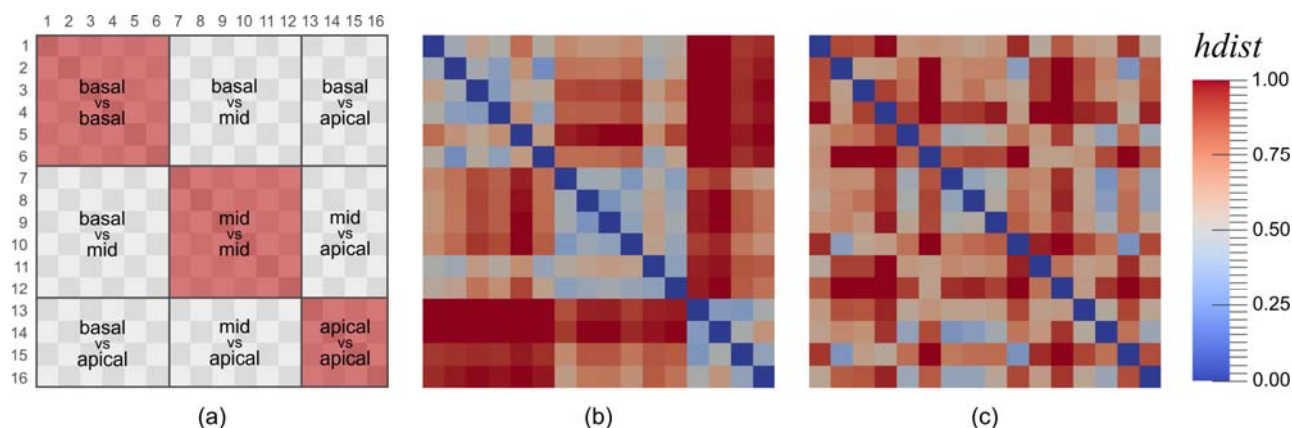

Figure 1. (a) The LV WS similarity map is split into 9 sections which are symmetrical about the diagonal. The diagonal sections (highlighted in red) are the intra-region similarity maps while the off diagonal sections are the inter-region similarity maps; (b) WS similarity map of a control subject, and (c) WS similarity map of a MI patient.

2.1. Reconstruction of LV endocardial geometry

The MRI images were processed using a semi-automatic technique that is included in the CMRtools suite (Cardiovascular Solution, UK). Both sets of short- and long-axis images are displayed together so that the reconstruction process can be proceeded interactively to reduce registration errors. Control points are fixed on the surface of the reconstructed endocardium and these points are defined by the intersection of the short- and long-axis views. To create a more realistic reconstruction, we use the angled axis views, which are oriented at regular angular intervals, to serve as the basis for fitting a series of B-spline curves that represent the contours of the endocardial surface. The endocardial surface is then discretized into a two-manifold structured triangle mesh.

This triangle mesh is then partition into 16 segments based on the published standard by the American Heart Association [3]. This recommended nomenclature allows us to achieve adequate sampling of the LV without exceeding the relevant limits for clinical and research

equation:

$$WS = \frac{R}{2T + \left(1 + T/2R\right)}. \qquad (1)$$

This WS can be converted into the actual systolic wall stress by multiplying by a conversion factor involving the peak systolic ventricular blood pressure. Further details on the WS computation can be found in [2].

2.3. Computation of the histogram similarity index

The WS histogram similarity index (hereafter denoted by *hdist*) is a quantitative index to characterize the differences in the WS distribution for any pair of segments within the same subject. For any two set of histograms that has identical distribution, the value of *hdist* will be zero. A larger value of *hdist* will imply greater dissimilarity of the distribution for the two sets of histograms.

For each subject, a 16-by-16 similarity map (See Figure 1) is generated with all diagonal terms equal to 0

(result of comparing the WS histogram distribution with itself). The methodology for computing *hdist* can be summarized as follow:

(I) Determine WS_{max} and WS_{min}, the maximum and minimum WS values, respectively, for this entire study.

(II) Specify the bin interval (*b*=0.025) and compute the number of bins (*n*) based on these maximum and minimum values:

$$n = \frac{WS_{max} - WS_{min}}{b}. \qquad (2)$$

(III) Compute the normalized frequency for the histograms distribution of each individual segment based on the defined bin intervals.

(IV) Compute the *hdist* between all pairs of segments using the methodolgy described in [7].

The main observation from our comparison is that there is greater uniformity in the WS across intra-regions for the control group as compared to the patient group scanned 1-3 months after MI. The group mean *hdist* across the basal-basal, mid-mid and apical-apical regions are significantly lower in the control group as compared to the patient group: 0.574 ± 0.098 vs. 0.704 ± 0.096, $p < 0.01$ (basal-basal), 0.550 ± 0.061 vs. 0.655 ± 0.107, $p < 0.01$ (mid-mid) and 0.497 ± 0.093 vs. 0.575 ± 0.083, $p < 0.05$ (apical-apical). All statistics tests for comparing control and patient group performed using a 1-tailed student t-test. Based on our observation, we proposed that the mean subject *hdist* across intra-regions can be used as additional indices to aid in the clinical diagnostic of MI.

We further postulate that our observations can be explained by the regional loss of functions in the LV for the patient group. Myocardial infarction affects the contractility of the cardiomyocytes and therefore the

Table 1. Mean subject *hdist* across intra-regions for the control group. The coefficient of variation (CV) is defined as the ratio of the standard deviation to the mean.

control group	basal-basal		mid-mid		apical-apical	
	Mean *hdist*	CV	Mean *hdist*	CV	Mean *hdist*	CV
C1	0.531 ± 0.186	0.350	0.520 ± 0.226	0.436	0.444 ± 0.124	0.278
C2	0.612 ± 0.157	0.256	0.538 ± 0.163	0.302	0.471 ± 0.114	0.241
C3	0.510 ± 0.142	0.279	0.441 ± 0.099	0.224	0.436 ± 0.121	0.278
C4	0.498 ± 0.214	0.429	0.573 ± 0.226	0.394	0.578 ± 0.143	0.247
C5	0.492 ± 0.158	0.322	0.604 ± 0.184	0.305	0.632 ± 0.266	0.421
C6	0.781 ± 0.196	0.251	0.613 ± 0.179	0.292	0.406 ± 0.119	0.293
C7	0.616 ± 0.201	0.326	0.544 ± 0.187	0.345	0.623 ± 0.173	0.277
C8	0.642 ± 0.201	0.312	0.492 ± 0.115	0.233	0.498 ± 0.101	0.203
C9	0.486 ± 0.177	0.365	0.626 ± 0.227	0.363	0.381 ± 0.081	0.212
Mean group *hdist* computed by averaging over the control group						
	0.574 ± 0.098	0.321 ± 0.056	0.550 ± 0.061	0.321 ± 0.070	0.497 ± 0.093	0.272 ± 0.064

3.   Results and discussion

Based on the data collected from 9 controls and 12 MI patients, we computed the individual WS similarity map as described in Section 2. All patients in this study has at least 1 infarct segments in the basal, mid-cavity and apical regions, as assess by late gadolinium enhancement CMR scans. For each subject, we compute the mean subject *hdist* across these intra-regions: basal-basal, mid-mid and apical-apical (See Table 1 for control group and Table 2 for patient group). These 3 intra-regions correspond to the 3 main diagonal blocks as shown in Figure 1(a). We also compute the mean group *hdist* (coefficient of variation, CV) for the two groups by averaging over the mean subject *hdist* (CV) of each individual subjects in that group. All mean *hdist* and CV values are presented in the form *mean ± standard deviation*.

regional LV function, resulting in heterogeneous and non-uniform WS across the intra-regions.

A comparison of the mean group *hdist* across intra-regions for the patient group at two different time points: 1-3 and 9-12 months after MI is also conducted. The mean group *hdist* across the basal-basal, mid-mid and apical-apical regions at 9-12 months after MI are 0.693 ± 0.070, 0.703 ± 0.102 and 0.612 ± 0.114, respectively. There are no significant differences in the mean group *hdist* for the 3 intra-region comparison (*p* values > 0.05 using a 2-tailed paired student t-test). This suggests that medical treatment was successful in preserving LV functionality and prevent further deterioration and remodeling.

We also conducted a sensitivity test by varying the number of bins used for computing the WS histograms distribution and found that our results are robust.

Table 2. Mean subject *hdist* across intra-regions for the patient group (1st Scan).

patient group	basal-basal		mid-mid		apical-apical	
	Mean *hdist*	CV	Mean *hdist*	CV	Mean *hdist*	CV
P1	0.659 ± 0.199	0.301	0.759 ± 0.205	0.271	0.650 ± 0.241	0.371
P2	0.787 ± 0.233	0.296	0.710 ± 0.171	0.241	0.537 ± 0.162	0.301
P3	0.515 ± 0.061	0.118	0.516 ± 0.097	0.187	0.626 ± 0.119	0.189
P4	0.660 ± 0.176	0.266	0.525 ± 0.077	0.146	0.624 ± 0.121	0.193
P5	0.637 ± 0.103	0.162	0.573 ± 0.116	0.202	0.520 ± 0.174	0.335
P6	0.686 ± 0.188	0.274	0.703 ± 0.227	0.323	0.490 ± 0.085	0.173
P7	0.625 ± 0.120	0.192	0.728 ± 0.205	0.282	0.676 ± 0.258	0.382
P8	0.809 ± 0.177	0.219	0.763 ± 0.175	0.229	0.491 ± 0.202	0.411
P9	0.656 ± 0.242	0.370	0.506 ± 0.121	0.240	0.659 ± 0.252	0.382
P10	0.825 ± 0.147	0.178	0.752 ± 0.186	0.247	0.669 ± 0.194	0.291
P11	0.798 ± 0.237	0.297	0.569 ± 0.086	0.151	0.441 ± 0.165	0.374
P12	0.788 ± 0.192	0.244	0.760 ± 0.189	0.248	0.522 ± 0.122	0.235
Mean group *hdist* computed by averaging over the patient group						
	0.704 ± 0.096	0.243 ± 0.072	0.655 ± 0.107	0.231 ± 0.052	0.575 ± 0.083	0.303 ± 0.086

4.   Conclusions

In this work, we provided the formulation for computing the uniformity of the nominal systolic WS in the LV. We had shown that the intra-regional comparison of this WS (using *hdist*) can be potentially used to discriminate between controls and patients with MI. Furthermore, our approach can also be useful for monitoring the therapeutic efficacy of treatment used to treat MI patients.

Future work involves (1) increasing the size of the control and patient group to establish better statistical significance and (2) correlating the location/severity of the infarction to the mean patient *hdist* to improve the accuracy of our diagnostic indices.

Acknowledgements

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