3D cardiac wall thickening assessment for acute myocardial infarction

A Khalid, B T Chan, E Lim, and Y M Liew

1Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

E-mail: amirahkhalid1@um.edu.my

Abstract. Acute myocardial infarction (AMI) is the most severe form of coronary artery disease leading to localized myocardial injury and therefore irregularities in the cardiac wall contractility. Studies have found very limited differences in global indices (such as ejection fraction, myocardial mass and volume) between healthy subjects and AMI patients, and therefore suggested regional assessment. Regional index, specifically cardiac wall thickness (WT) and thickening is closely related to cardiac function and could reveal regional abnormality due to AMI. In this study, we developed a 3D wall thickening assessment method to identify regional wall contractility dysfunction due to localized myocardial injury from infarction. Wall thickness and thickening were assessed from 3D personalized cardiac models reconstructed from cine MRI images by fitting inscribed sphere between endocardial and epicardial wall. The thickening analysis was performed in 5 patients and 3 healthy subjects and the results were compared against the gold standard 2D late-gadolinium-enhanced (LGE) images for infarct localization. The notable finding of this study is the highly accurate estimation and visual representation of the infarct size and location in 3D. This study provides clinicians with an intuitive way to visually and qualitatively assess regional cardiac wall dysfunction due to infarction in AMI patients.

1. Introduction

Acute myocardial infarction (AMI) is among the most commonly diagnosed cardiovascular diseases today, affecting over 800,000 people annually [1]. Excessive build-up of plaque and blockage in the coronary arteries causes inadequate blood supply to various parts of the cardiac tissue [2], leading to localized myocardial injuries and necrosis. Patients who had AMI have higher risk of developing ventricular remodeling, a pathological process whereby the left ventricle (LV) changes in size, shape and functions. Expansion of the infarct region can adversely lead to elevated systolic and diastolic wall stress. In severe cases, acute myocardial infarction causes functional irregularities, ventricular deformation, and total heart failure that kills lives [3].

The deviation of global indices such as myocardial mass, blood volume, and ejection fraction from baseline value of healthy subjects has long been used in current clinics to identify functional abnormality in AMI patients. Researches, however, has found that these indices have very limited sensitivity to provide accurate and reliable diagnosis for such group of patients at the early stage of disease development as the changes in cardiac function is rather localized instead of globalized [4]. In addition, infarct zone of the myocardium tends to become rigid and thinner as a result of injury and necrosis [5]. Regional assessment of wall thickness and thickness changes (i.e. wall thickening) may, therefore, provide a means to improve clinical diagnosis for better patient outcome. A comprehensive analysis of these regional indices in 3D could help clinicians to assess the extent of myocardial infarction in terms of size and location, providing them a useful and convenient way to visualize and understand cardiac wall condition of individual patients [5].
To date, regional deformation of cardiac wall has been investigated using various imaging modalities, including computed tomography (CT), echocardiography, and magnetic resonance imaging (MRI). Studies utilizing CT have shown limitations with respect to image quality that leads to an overestimation of the infarct size [6-7]. Echocardiography has been used widely but primarily for 2D deformation analyses of the cardiac wall and only few studies have attempted it in 3D [8]. Due to the inherent speckle noise, wall deformation analysis from echocardiography suffers from limited accuracy, i.e. with 87% of accuracy in tracking of the infarcted region reported [9]. MRI, as a gold standard cardiac assessment modality [6], has been useful in identifying infarct location and transmural utilizing the 2D late gadolinium enhancement (LGE) technique in AMI patients [10]. The impact of infarct on wall motion dysfunction has mostly been assessed from cine and tagged MRI using eyeballing in clinical practice. Increasing number of quantitative techniques [6,11] has been proposed to date to analyze motion dysfunction from cine and tagged MRI but majority of techniques focused on 2D MR images or in-plane measurement e.g. center-surface techniques, guide-point modeling, and active appearance models. These techniques are prone to error when the imaging plane does not intersect the cardiac wall orthogonally, which is a rather common problem as the LV is known to be concave and may become deformed in shape under disease conditions. The only notable 3D mesh-based wall thickness measurement was proposed by Tobon-Gomez et al. [11] but the technique was applied to differentiate the different phenotypes of LV hypertrophy (i.e. hypertrophy cardiomyopathy and hypertensive heart disease). None of the techniques proposed to date, which is based on more detailed 3D personalized computational model, has correlated anomaly in wall thickening to infarction in AMI patients.

In the present study, we develop a novel technique to extract regional wall thickness measurements in 3D from personalized cardiac models generated in-house with prior motion correction. We investigated the regional thickening of the cardiac wall across the full cardiac cycle and compared the thickening measurements between 5 AMI patients and 3 healthy subjects. In AMI patients, the localized abnormality in wall thickening was correlated and validated with the infarct region in LGE images. We have shown that our regional wall thickening assessment technique is useful for the localization of infarct region and extent, providing a means to directly correlate cardiac wall contractility dysfunction to infarct severity.

2. Methods

2.1 MRI data acquisition

Five patients diagnosed with AMI and 3 healthy volunteers were recruited at the University of Malaya Medical Centre with written consent. For each subject, multi-breath-hold steady-state free precession short-axis cine image stack (FOV: 350 × 350 mm, image matrix: 256 × 256, pixel size: 1.37 × 1.37 mm, slice thickness: 8 mm, gap: 0 mm, TE/TR: 1.6/3.7 ms, flip angle: 55°, number of slices: 10–15, number of cardiac phases: 20, breath hold time: 15 s) covering base to apex of the LV were acquired. A set of 6 multi-breath-hold long-axis cine images radially oriented around the center of the LV chamber at uniform angular interval were also prescribed with the same acquisition parameters by using the first short-axis slice at the base for planning.

For AMI patients, collocated short-axis inverse recovery fast gradient echo LGE MRI images were obtained. For this acquisition, patients were administered 140 lg/kg/min of adenosine infusion for 4 minutes, followed by 20 ml of normal saline flushing. An intravenous injection of gadolinium-based contrast agent at 0.2 ml/kg was subsequently performed for first-pass perfusion. A further 0.2ml/ kg of the gadolinium agent was administered for rest and delayed gadolinium enhancement at 10-minute intervals. Typical delay enhancement imaging parameters were used, as follows: TE/TR: 3.0/6.0 msec, inversion time (TI): 200–300 msec (depending on null point of normal myocardium), flip angle: 20˚, no gap between planes and breath-hold time: 18 seconds. The delay time was chosen to yield images in the
mid- to late-systolic phase. All cine and LGE MRI images were acquired during end expiration breath-hold using a 1.5T MRI system (Sigma HDxt 1.5T, GE Healthcare, WI, U.S.A). Our study protocol has received approval by University of Malaya Medical Ethics Committee (Ref: 989.75).

2.2 Image segmentation, motion correction and reconstruction of LV model in 3D

All short-axis and long-axis images were semi-automatically contoured to extract the LV endocardial and epicardial wall [12]. The contouring was performed by using automated border recognition tool and minor manual fixes. The papillary muscles were included in the blood pool and excluded from the myocardium. The displacement between images due to motion artifacts was corrected using in-house image registration algorithms and 3D LV model specific to each subject were reconstructed based on the B-spline fitting technique [13]. For each subject, twenty 3D LV surface mesh models were generated for a full cardiac cycle. Each LV model was formed by combining 2 quadrilateral meshes, one from the endocardial wall and the other one from the epicardial wall. Each mesh contains 100 x 100 surface points and was orientated in patient coordinate system.

2.3 Development of 3D cardiac wall thickness model

We used the sphere fitting approach to accurately estimate regional wall thickness of the cardiac wall. Specifically, for each subject, all 3D LV models were aligned by using principal component analysis so that the long axis of the LV was parallel to z-axis. A small moving window was subsequently applied across the entire epicardial mesh surface. At each window, k-nearest neighbor technique was used to search for 6 nearest neighbors in the endocardial wall for each epicardial point. This forms a small localized group of points whereby a maximally inscribed sphere was fitted within the convex hull. The window size was allowed to vary by location based on a prior rough estimation of Euclidean distance between endo- and epicardial wall through direct subtraction of wall coordinates. Regional wall thickness was extracted as the diameter of the fitted sphere. Figure 1 illustrates examples of spheres fitted on the cardiac wall for wall thickness extraction. To facilitate visualization of abnormality in cardiac wall thickening, the thickness measurements were color-coded onto the epicardial surface, generating a 3D cardiac wall thickness map for each cardiac phase. The accuracy of each wall thickness model was validated against LGE image which depicts the location of infarct. This involved superimposing the 2D LGE images onto the model for visual correlation of cardiac wall contractility dysfunction and location of infarct. The sphere fitting framework was implemented in MATLAB (vR2012a, Mathworks, Natick, MA) on an Intel(R) Core(TM) i5-3570 CPU @ 3.40 GHz computer using parallel computing.

![Figure 1](image-url)
3. Results

The present study utilizes the method of sphere fitting to extract the LV wall thickness in 3D. Figure 2 illustrates the 3D LV model of a healthy subject and an AMI patient, which has been color-coded with wall thickness measurement and overlaid with a short-axis cine MRI image. Blue color indicates thick myocardium whereas red color indicates thin myocardium.

Figure 2. The 3D wall thickness models of a subject (a, b) and patient (c, d), each in isometric view (a, c) and front view (b, d). The models were superimposed on the cine MRI image in 3D space. Both the model and image were taken from the same cardiac phase i.e. systolic phase (Phase 5) in a cardiac cycle. The colour bar depicts the wall thickness in mm.

In figure 2, the LV wall thickness for a healthy subject is compared with the LV wall thickness of an AMI patient during the systolic phase. During this phase, the myocardium thickness increases as the LV contracts to pump blood. In figure 2 (a) and 2 (b), the myocardium of the healthy subject is thicker (consider the light green and dark blue shading) in comparison to the wall thickness of the AMI patient in figure 2 (c) and (d) (consider the yellow and red shading). In addition, in the figure above, the exact superimposition of the LV wall thickness models on the cine images represents the accuracy of the technique used.

Figure 3 shows the average wall thickness of a healthy subject over a full cardiac cycle. The LV was divided into three segments, i.e. base, mid, and apex. As expected, the mid-ventricular region demonstrates the highest average wall thickness followed by the base. The lowest average wall thickness was found at the apex.

Figure 3. Average wall thickness of a healthy subject over a full cardiac cycle where ES indicates end systolic phase and ED indicates end diastolic phase. LV was divided into basal, midventricular, and apical segments.
The 3D wall thickness model was qualitatively assessed by superimposing it with the cine/LGE images and the 17-segment AHA LV division lines (figure 4). Direct correlation of anomaly in wall contractility (as conveyed by our wall thickness model) with the infarct location (as revealed by LGE image) is evidenced. The average wall thickness within the infarct region for the 5 AMI patients has been measured to be approximately 2.86±1.11 mm as compared to the healthy region 8.73±1.01 mm at end-diastole.

Figure 4. Correlation of infarct location on the cine (a) and LGE (b) images to thickness anomaly on 3D wall thickness model (c). The red arrows are pointing at the same infarcted region of the LV in all images. Yellow shading in A and B highlights the width of the infarct, which is located at the mid anteroseptal and mid inferoseptal region. Colour bar indicates wall thickness in mm.

4. Discussion

Wall thickness is an important clinical index to help clinician in identifying myocardial dysfunctional secondary to cardiac diseases. Regional assessment of wall thickness has recently received more attention for research especially in the case of focal myocardial disease, including acute myocardial infarction, as commonly used global indices (e.g. ejection fraction, blood volume and myocardial mass) have been shown to fail in aiding early diagnosis of this disease until later stage of disease progression [14]. While majority of the published techniques focused on in-plane wall thickness measurement in 2D, we adapted the use of sphere fitting technique to extract regional wall thickness in 3D from our in-house personalized quadrilateral LV mesh model, providing more accurate estimation of wall thickness. This technique does not suffer from error due to oblique intersection of MRI scanning plane with the cardiac wall as in 2D analysis. Our proposed method conducts over 10,000 fittings of maximally inscribed spheres over the entire LV myocardium from the base to the apex. The thickness measurements were mapped onto the 3D LV model for visualization and direct correlation of thickening abnormality to infarct region in LGE image.
For healthy subjects, the wall thickness measurement was found to fall within the normal range as reported in previous studies [15]. Furthermore, based on our assessment of the global indices, no significant differences exist among the measurements between the subjects and the patients. For instance, at the end-diastolic phase, the LV mass for a subject is 47.479 g, and the LV of the patient 50.202 g, the LV volume of another subject is 51.742 ml, and the LV volume of another patient is 68.035 ml respectively. This trend is found throughout the patient and subject database. In contrast, the average regional wall thickness between remote regions and infarcted regions varied extensively and is clearly evident in the color mapped 3D wall thickness; making the proposed technique useful for differentiating between normal and injured myocardium.

Moreover, the technique implemented in this study has shown promising results in terms of identifying localized myocardial injury via a 3D wall thickness assessment. In addition, it has potential applications in various cardiovascular diseases associated with changes in cardiac wall thickening. For example, the regional assessment of wall thickness may also be performed for patients with LV hypertrophy and dilated cardiomyopathy for identifying the extent of myocardial injury. However, this preliminary study requires a larger patient database for further validation and currently lacks a quantitative assessment of the wall thickness models. In the near future, we work to further improve our sphere fitting technique to achieve higher accuracy assessment of the localized myocardial injury.

5. Conclusions

We have described a sphere fitting approach to extract regional wall thickness from 3D motion corrected personalized LV mesh model. The proposed method was tested in 5 patients and 3 healthy volunteers. The wall thickness map was found to provide clinician with an intuitive and comprehensive means to visualize and identify wall thickening abnormality due to infarction in AMI patients in 3D.

References

[1] Boateng, S., & Sanborn, T. 2013 Disease-a-Month Acute myocardial infarction 59 83-96
[2] Thygesen, K., Alpert, J. S., & White, H. D. 2007 Journal of the American College of Cardiology 50 2173-2195
[3] Rischpler, C. 2016 Journal of nuclear medicine and molecular imaging 60 236-251
[4] Karamitsos, T. D., Francis, J. M., Myerson, S., Selvanayagam, J. B., & Neubauer, S. 2009 Journal of the American College of Cardiology 54 1407-1424
[5] Jung, J.-W., Kang, H.-R., Kim, M.-H., Lee, W., Min, K.-U., Han, M.-H., & Cho, S.-H. 2012 Radiology 264 414-422
[6] Ko, S. M., Kim, Y. J., Park, J. H., & Choi, N. M. 2014 The British journal of radiology
[7] Doltra, A., Amundsen, B. H., Gebker, R., Fleck, E., & Kelle, S. 2013 Current Cardiology Reviews 9 185-190
[8] Arai, K., Hozumi, T., Matsumura, Y., Sugioka, K., Takemoto, Y., Yamagishi, H., ... & Yoshikawa, J. 2004 The American Journal of Cardiology 94 552-558
[9] Bhan, A., Sirker, A., Zhang, J., Protti, A., Catibog, N., Driver, W., & Shah, A. M. 2014 American Journal of Physiology-Heart and Circulatory Physiology 306 H1371-H1383
[10] Doltra, A., Amundsen, B. H., Gebker, R., Fleck, E., & Kelle, S. 2013 Current Cardiology Reviews, 9 185-190
[11] Tobon-Gomez, C., Butakoff, C., Yushkevich, P., Huguet, M., & Frangi, A. F. 2010 2010 Annual International Conference of the IEEE In Engineering in Medicine and Biology Society 2642-2645
[12] Heiberg, E., Sjögren, J., Ugander, M., Carlsson, M., Engblom, H., & Arheden, H.
2010 **BMC medical imaging** 101

[13] Liew, Y. M., McLaughlin, R. A., Chan, B. T., Aziz, Y. A., Chee, K. H., Ung, N. M., ... & Lim, E. 2015 *Physics in medicine and biology* **60** 2715

[14] Christian, T. F., Gibbons, R. J., & Gersh, B. J. 1991 *Journal of the American College of Cardiology* **17** 1303-1308

[15] Kawel, N., Turkbey, E. B., Carr, J. J., Eng, J., Gomes, A. S., Hundley, W. G., ... & Lima, J. A. 2012 *Circulation: Cardiovascular Imaging* **5** 500-508