Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2009 February 10; 7260: . doi:10.1117/12.811411.

Myocardial wall thickening from gated Magnetic Resonance images using Laplace's equation

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Abstract

The aim of our work is to present a robust 3D automated method for measuring regional myocardial thickening using cardiac magnetic resonance imaging (MRI) based on Laplace's equation. Multiple slices of the myocardium in short-axis orientation at end-diastolic and end-systolic phases were considered for this analysis. Automatically assigned 3D epicardial and endocardial boundaries were fitted to short-axis and long axis slices corrected for breathold related misregistration, and final boundaries were edited by a cardiologist if required. Myocardial thickness was quantified at the two cardiac phases by computing the distances between the myocardial boundaries over the entire volume using Laplace's equation. The distance between the surfaces was found by computing normalized gradients that form a vector field. The vector fields represent tangent vectors along field lines connecting both boundaries. 3D thickening measurements were transformed into polar map representation and 17-segment model (American Heart Association) regional thickening values were derived. The thickening results were then compared with standard 17-segment 6-point visual scoring of wall motion/wall thickening (0=normal; 5=greatest abnormality) performed by a consensus of two experienced imaging cardiologists. Preliminary results on eight subjects indicated a strong negative correlation ($r=-0.8$, $p<0.0001$) between the average thickening obtained using Laplace and the summed segmental visual scores. Additionally, quantitative ejection fraction measurements also correlated well with average thickening scores ($r=0.72$, $p<0.0001$). For segmental analysis, we obtained an overall correlation of -0.55 ($p<0.0001$) with higher agreement along the mid and apical regions ($r=-0.6$). In conclusion 3D Laplace transform can be used to quantify myocardial thickening in 3D.

Keywords

Laplace's equation; MRI; myocardial thickness

1 Introduction

Myocardial thickness measurements throughout the cardiac cycle are of great interest from both a clinical and physiological point of view. Cardiac Magnetic Resonance Imaging (MRI) techniques have been utilized to produce high spatial and temporal resolution images of the

myocardium throughout the cardiac cycle. MRI acquisitions have been proven useful for the determination of LV wall parameters [1–5]. By providing good depiction of the LV epicardial borders, MRI allows for the assessment of LV wall thickening. Additionally, visual assessment of wall thickening from MRI is tedious, time consuming and associated with inter-observer variability [6, 7], disadvantages that can be overcome with automated or semi-automated image analysis software.

Local myocardial wall thickness can be derived from MRI acquisitions by manual or automatic tracing of endocardial and epicardial boundaries in each short-axis image. Currently, the methods for automatically determining the myocardial wall motion measurements in vivo using MRI are based on straight line distance techniques [6–16] and assume a 2D model for each short-axis slice. Estimation of wall thickness in 3D requires extrapolation from a series of 2D images. It is impossible to determine the thickness of the wall without including information from neighboring slices, unless the position of the imaging plane is known. Such an analysis is inherently data intensive, given the 3D nature of the problem. More advanced 2D algorithms, such as the improved centerline method, have been developed to minimize the error introduced whenever within-image perpendicularity is not fulfilled [6, 7]. However, the 2D techniques remain limited to measurements within individual 2D images, and carry the implicit assumption that the myocardial wall is always perpendicular to the acquisition plane.

3D wall thickness quantification techniques have been explored by several groups [7–19]. These methods are based on volume element approaches and, in some cases, require additional tagged MR imaging acquisitions [14–16]. Volume element techniques [17, 18] partition the myocardium into large volumetric segments. Average wall thickness is then derived for each element from its volume and geometric assumptions about its shape. The limitations of this approach include a relatively small number of segments along the circumference of the myocardium, creation of volume elements in between image slices, and assumptions regarding left ventricular shape. The use of MR tagging to assess wall thickening [14–16] is limited by poor spatial resolution if an insufficient number of tags are used. Also, when tag lines are oriented in parallel in long axis images, apical motion may be excluded. Van der Geest et al [7], and Holman et al. [8] have proposed a 3D technique based on a straightforward extension of the 2D centerline method. More recently, Beohar et al. have also analyzed regional LV function with cardiac MRI after myocardial function using a very similar approach [9]. However, these techniques are inherently straight-line based, and thus are sensitive to imperfect contours. In addition, the above mentioned methods work poorly with highly irregular surfaces, a frequent occurrence in high resolution MRI images of endocardial borders [19].

The purpose of this work is to develop an automated technique to compute the thickening of the myocardium in three dimensions (3D) over the end-diastolic and end-systolic phases using MRI, and to initially validate this approach by comparison to visual clinical scores derived from gated MRI scans. Current thickening techniques used for quantitative assessment of cardiac MRI are based on straight line distance techniques and do not take the convoluted appearance of the myocardium into account [7].

2 Methods

2.1 Tissue segmentation and preparation of boundaries

Eight consecutive subjects with short-axis slices acquired at multiple breathholds with thickness of 8mm, covering the whole myocardium and additional mid-ventricular 2-chamber and 4-chamber views were used in our experiment. Initially, for each study, the spatial misregistration of multiple breath-hold cine cardiac MR images resulting from respiratory and patient motion is corrected by minimizing the cost function derived from plane intersections for all phases [20]. The epicardial and endocardial boundaries were semi-automatically contoured in 3D with our “in-house” software toolkit (CSMR) by a cardiologist. This software allows manual refinement of automatically placed 3D contours with small number of guide-points [21].

2.2 Thickness calculation

The myocardium is a convoluted three-dimensional structure with variable thickness so the definition of thickness as a metric must be carefully considered. For instance, if thickness is defined as a straight-line distance between the two surfaces, this distance could be the perpendicular projection from one surface to the other or the minimum distance between one surface to the other. The problem with the straight-line definitions is that if the two surfaces are not parallel, the thickness will be different depending on which surface the measurement is made from [22–24]. To address this problem, tools from mathematical physics can be borrowed to present a definition of thickness that is non-straight line. Our approach for thickness computation models the myocardial wall as a series of nested sub-layers that are bounded by the epicardial and endocardial surfaces such as those shown in Figure 1.

By integrating along the direction perpendicular to each sub-layer between the two surfaces, the thickness at any point in the wall is calculated. Every streamline can be associated with its length and this can be used to define the thickness (between C and D or A and B in Figure 1b). The thickening measure is computed as the change in thickness at the two phases [end-systole (ES) and end-diastole (ED)] as determined from the 3D contours) and expressed as a percentage. The sublayers are modeled by assigning different boundary conditions to the two surfaces and solving Laplace’s equation at each point between them. Laplace’s equation is a second-order partial differential equation for a scalar field that is enclosed between boundaries S and S’. Mathematically, it takes the form:

$$\nabla^2 \Psi = \frac{\partial^2 \Psi}{\partial^2 x^2} + \frac{\partial^2 \Psi}{\partial^2 y^2} + \frac{\partial^2 \Psi}{\partial^2 z^2} \quad (1)$$

Equation 1 is solved iteratively throughout the entire data volume keeping the boundaries fixed. Laplace’s equation was solved using the simplest Jacobi technique that takes the form given by (2):

$$\begin{aligned} \Psi_{i+1}(x, y, z) \\ = [\Psi_i(x+\Delta x, y, z) + \Psi_i(x-\Delta x, y, z) + \Psi_i(x, y+\Delta y, z) + \Psi_i(x, y-\Delta y, z) + \Psi_i(x, y, z+\Delta z) + \Psi_i(x, y, z-\Delta z)]/6 \end{aligned} \quad (2)$$

where Ψ_i is the value at x, y, z when Laplace is solved during the i th iteration until convergence is achieved. The resulting scalar field makes a smooth transition from one surface to the other describing the nested sub-layers. Once the solution of Ψ is obtained, “field lines” are computed using

$$\mathbf{E} = -\nabla\Psi \quad (3)$$

that is normalized to

$$\mathbf{N} = \mathbf{E}/\|\mathbf{E}\| \quad (4)$$

represents a unit vector field defined everywhere between S and S' which always points perpendicular to the sublayer on which it sits. After computing $\mathbf{N}$, “field lines” or “streamlines” are computed by starting at any point on S and integrating $\mathbf{N}$ using finite differences, derived from Taylor series expansions.

For regional assessment, the automatically obtained thickening measurements were then mapped into traditional polar map coordinates (Figure 2), by a projection of the volumetric data. Polar maps were subdivided according to the standard 17-segment model containing 6 basal, 6 mid and 5 apical regions [24]. Visual clinical scores were recorded by a cardiologist using the same 17-segment model and using the 0–5 motion/thickening grading system since in a standard clinical reading, motion and thickening estimates are correlated. By considering both endocardial motion and myocardial thickening, the grading system defines score 0 = normokinesis, 1 = mild hypokinesis, 2 = moderate hypokinesis, 3 = severe hypokinesis, 4 = akinesis, 5 = dyskinesis. For global analysis, the mean thickening of the entire myocardium and the summed visual segmental motion scores at all segments were computed. Left ventricular (LV) ejection fractions were derived from LV cavity volumes at ED and ES with the use of the same ED and ES contours.

3 Experimental Test

Spearman’s correlation was used to evaluate the association between the thickening and visual wall motion scores along with quantitative LV ejection fractions. A correlation value of -0.8 ($p < 0.0001$) was obtained between the average (global) thickening of the myocardium and the visual summed motion scores. Correlation was also good between the ejection fractions and average thickening scores ($r = 0.72$, $p < 0.0001$). The ejection fractions ranged from 14% to 64% in the evaluated cases and the average thickening ranged from 0 to 86%.

5 Conclusion

This paper introduces an automated technique based on Laplace’s equation to compute 3D thickening measurements of the myocardium over the entire myocardial surface using MRI. Initial validation was carried out by comparison with visual segmental wall motion/wall thickening scores along with ejection fractions, and the results showed strong correlation. Regional analysis indicated higher correlation along the mid and apical regions compared to the basal regions. Previous thickening techniques, based on straight-line approaches are

inherently extensions of 2D approaches and are not capable of accurate mapping of the 3D thickening, especially in the apical area. Our technique based on the 3D Laplace transform is able to map 3D thickening directly from 3D epicardial and endocardial surfaces. Additionally, the smooth transition between layered surfaces makes the Laplacian technique robust in presence of less uniform shapes, such as encountered in the regions of the left ventricular papillary muscles. This new approach is an important step for accurate quantitative assessment of the myocardial function from cardiac MRI.

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Figure 1.

a) short-axis MRI slice showing contours at ED phase (yellow-epicardium, red-endocardium). (b) shows thickness defined using Laplace's equation (thickness lines) from A to B and C to D. The two surfaces S and S' are initialized with the boundary conditions.

Figure 2.

(a) 3D view at ED and (b) ES. (c) Short-axis MRI slice at approximately the mid-region taken at ED phase and (d) ES phase. (e) Grey-scale 17 segment polar map of thickness at ED and (f) ES phase along with the (g) thickening polar map in percentages.

Table 1

Results of global and regional analysis of thickening using Laplace.

Global Analysis	Correlation	Regional Analysis	Correlation
Summed visual score	($r=-0.8$)	Overall correlation	($r=-0.5$)
LV ejection fractions	($r=0.7$)	Basal regions	($r=-0.6$)
		Mid regions	($r=-0.6$)
		Apical regions	($r=-0.4$)