COMPUTING VENTRICULAR MYOCARDIAL THICKNESS FROM 3D MRI IMAGES

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Abstract. A method for computing the thickness of the ventricular myocardium for 3D MRI data is presented. This method involves three steps — (1) identifying the boundary of the domain based on heart geometry, (2) solving the Laplace equation in this domain given the values at the boundary and (3) computing the length of the streamlines of the solution's gradient. Unique to the heart geometry are locations where thickness may seem inherently ill-defined, however recourse to identification of the functional units allows the computation of a thickness that respects the functional organization and activity of the heart muscle. The quantification of thickness could be useful clinically to measure the health of the heart muscle.

INTRODUCTION

Computation of the thickness of the heart muscle is important because ventricular heart wall thickness is an important indicator of pathology. Traditional methods of measuring thickness from MRI data involve working from 2D cross sections of 3D data and manually deciding which point on a surface corresponds to which point on an opposite surface. These methods are therefore inaccurate and subjective. A computational method for measuring thickness of the heart muscle that works directly with 3D data would avoid these problems as well as be faster than traditional methods. Such a method is necessary in order to do quantitative analysis of thickness distribution in the large number of heart MRI images now available.

HEART GEOMETRY

The ventricular myocardium lies between three surfaces: the surface formed by the interior of left ventricle, the surface formed by the interior of the right ventricle and the exterior surface of the heart. Some part of the heart ventricle muscle lies between all possible pairs of these surfaces; the myocardial wall adjacent to the exterior of the heart lies between both ventricle interiors and the exterior of the heart and the wall of the septum lies between the two ventricle interiors. Two parts of the ventricular myocardium, where the septum joins the outer wall on either side of the heart, cannot be said to lie between any particular pair of these surfaces.

LAPLACE-EQUATION-BASED THICKNESS BETWEEN TWO SURFACES

Various methods have been proposed for calculating the thickness between two surfaces. Most of these methods produce undesirable results in common situations[1].

The method of calculating thickness between two surfaces proposed by Jones et al.[2] avoids the problems of other proposed methods. In this method, thickness at a point is defined as the length of the streamline of a vector field T that passes through that point. The vector field T is defined as $\nabla u/|\nabla u|$ with function u being the solution to the Laplace equation $\Delta u = 0$. The function u constrained to $u = 0$ at one boundary and $u = 1$ at the other and therefore it increases spatially from one surface to the other. Hence the gradient of u, which gives the vector field T, points from one surface to the other.

LAPLACE-EQUATION-BASED THICKNESS FOR HEART GEOMETRY

Input Data

The input is binary image of the heart with voxels making up the myocardium having the value 1 and background voxels having the value 0. The ventricles have been extracted by setting all voxels lying above a plane near the top of the ventricles to be part of the background. Such an image may be produced from grayscale MRI data by using a semi-automated contouring process to remove trabeculation[3].

Method for Identifying Boundaries

Before the Laplace-equation-based thickness calculation can be performed, it's necessary to find the surfaces which form the boundaries between which to solve the equation. For the heart ventricle muscles, these surfaces are the plane, call it P, above which all voxels were set to be part of the background and the borders of the ventricle walls with the interior of both ventricles and the exterior of the heart.

The first step in identifying the boundaries is to locate the plane P because other boundaries can be more easily identified once the plane P is found. A plane fitted through the centers of the voxels of this set consisting of the highest ventricular wall voxel from each vertical column of the dataset using a least-squares fit will approximate P. A better approximation can be found by refining the set by removing the furthest voxel from the fitted plane then refitting the plane. By iteratively refining the set then refitting the plane, stopping when the fitted plane passes through all voxels of the set, the plane P is located.

After computing P, the borders remaining to be found are the borders of the ventricle walls with the interior of each ventricle and the exterior of the heart. These borders are trivial to find if the heart regions they separate can be found. The volume below the plane P is separated into these regions by the voxels making up the ventricular wall, so it's only necessary to identify which contiguous set of voxels corresponds to a region. This can be done based on simple properties of these regions. The exterior of the heart is the only volume that touches the boundaries of the dataset. The left ventricle is the larger of the two other volumes, while the right ventricle is the smaller of the two.

Approaches to Extending Laplace-Equation-Based Thickness to Heart Geometry

The output of the previous step is the boundaries of the domain on which thickness is to be calculated. Included in these boundaries are the three surfaces: the border of the myocardium with each of the interior of the left ventricle, the interior of the right ventricle and the exterior of the heart. The Laplace-equation-based thickness of Jones et al.[2] is only defined between two surfaces. As a result, this method of Jones cannot be immediately applied.

A first attempt at a solution to this problem is to consider two of the surfaces to be the same surface when computing thickness. This produces computations that are correct for some regions of the ventricular wall but incorrect for others. For example, by constraining u to be 0 on both interior ventricular surfaces and 1 on the exterior surface, the calculated thickness will be correct for the ventricular wall adjacent to the exterior of the heart, but incorrect for the septum as can be seen in Fig. 1.

Another option is to constrain u to three differing values for the three surfaces instead of two at the boundaries when solving Laplace's equation. For example, the surfaces of the left and right ventricles could be constrained to $+1$ and -1 respectively while the exterior boundary of the heart was constrained to 0. This option breaks down at regions near all three surfaces where all three constants affect the value of u. This causes the streamlines of the vector field T to flow first toward one surface then veer toward another, which results in incorrectly large thicknesses as can be seen in circled areas of Fig. 2.

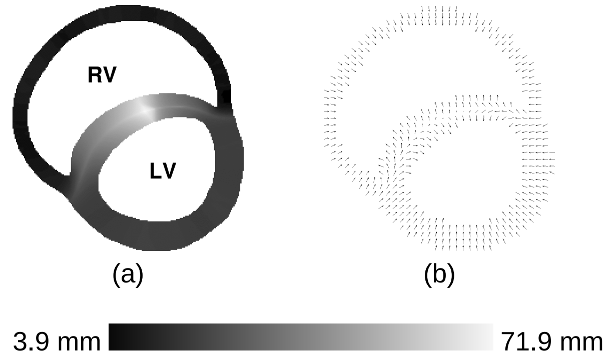

Figure 1: Cross sections of (a) calculated thickness and (b) vector field T when the borders of the interiors of both ventricles are considered to be the same surface. The direction of T along the septum is from the exterior of the heart to the ventricles rather than between the ventricles as would be correct. This results in the incorrect thickness seen along the septum in (a).

Based only on the geometry as evident in the image, it's impossible to determine how the thickness for points near all three surfaces, such as the points in the circled regions of Fig. 2(a), should be defined. To resolve this situation, it's necessary to look at the functional units of the heart. The left ventricle is the main pumping unit for the body and hence the entire wall surrounding the left ventricle is stronger and thicker than the right ventricle wall. The right ventricle wall is an appendage on the left ventricle wall. A definition of thickness should respect this functional organization of the heart. Doing so solves the problem of having three surfaces since considered separately the left and right ventricle walls are each enclosed by two only surfaces. However, this solution requires segmenting the left and right ventricles from the binary heart images.

Method for Automatic Segmentation of Left Ventricle Muscle from 3D Heart Images

Manually segmenting the left ventricle wall is tedious and prone to human error. If large numbers of heart datasets are to be processed, the segmentation must be done automatically. The method we developed for automatic segmentation is now described.

Our method of segmenting the left ventricle wall is to find the outer border of the left ventricle wall and then divide the ventricular wall into segments that lie inside and outside this border. This border is smooth so if most of the border can be found, the missing sections can be filled in by interpolation.

The majority of this border can be determined using conceptually simple and easily evaluated criteria. First, any voxel on the outer border of the heart that is closer

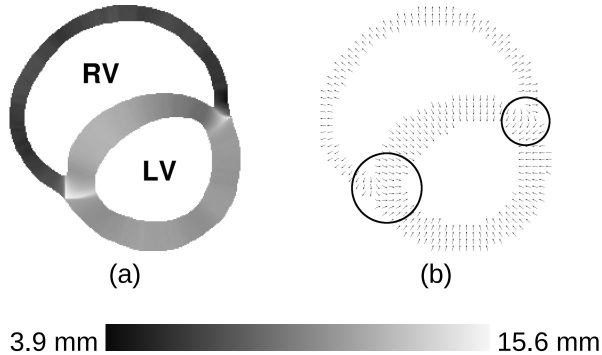

Figure 2: Cross sections of (a) calculated thickness and (b) vector field T when three constants are used to constrain u. The circled areas show where the thickness is incorrectly high due to streamlines of T flowing first toward the exterior of the heart then toward the other ventricle.

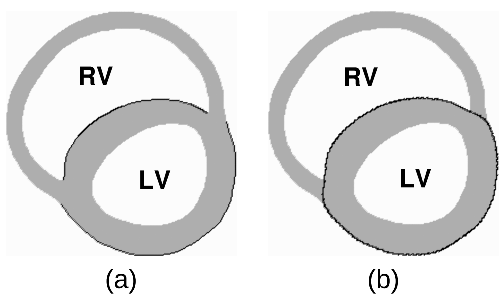

Figure 3: Cross section of the ventricular wall with sections of left ventricle border (a) as determined the two criteria and (b) as interpolated shown in black

to the nearest voxel of the left ventricle than the nearest voxel of the right ventricle is part of the border. Second, any voxel of the heart wall that is positioned such that a ray from the center of the left ventricle passes through it immediately before entering the right ventricle is part of the border. The first criterion can be evaluated quickly by using the chamfer distance transformation[4] which approximates the distance to the nearest voxel of a volume. Furthermore, since the right ventricle wall is always considerably thinner than the left, it's appropriate to multiply the distance to the right ventricle by a coefficient before comparing it. A value of 1.5 for the coefficient was found to be a good choice. Figure 3 shows a cross section of sample heart data with the sections of the left ventricle border determined by these criteria highlighted.

In order to interpolate the remainder of the border, the positions of known voxels on the border are converted to cylindrical coordinates using the center of the

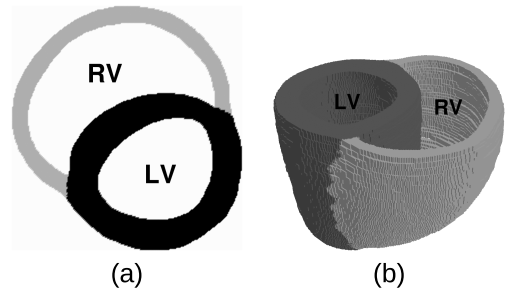

Figure 4: The results of automatic segmentation as (a) a cross section and (b) a 3D image. The left ventricle wall is lighter region.

left ventricle as the origin. A thin-plate spline[5] is then fit through these points to produce a function giving radius in term of angle and height. To account for discretization errors and other errors in the known parts of the border, smoothing is applied during the calculation of the thin-plate spline. A smoothing term in the range 10^{-6} to 10^{-7} gave the best results on test data.

Figure 4 shows a cross section of the results of this segmentation algorithm on a sample image. Compared to two manually segmented hearts, this segmentation algorithm assigned the same segment to 99.09% and 99.10% of ventricular wall voxels.

<u>Method for Thickness Calculation</u>

Having segmented the left ventricle wall, the thickness is calculated separately for the left and right ventricles then the resulting thicknesses are combined to form the complete ventricle wall thickness.

Calculating the Laplace-equation-based thickness involves two non-trivial steps: solving the Laplace Equation for u and calculating the length of the streamlines of the normalized gradient T. The solution to the Laplace equation is found by discretizing $\Delta u = 0$ to produce a system of linear equations which is solved using a multigrid method[6]. The technique described in [1] is used to calculate to length of the streamlines of the normalized gradient T. It calculates the length of the streamline passing through each voxel while avoiding the expense of actually finding these streamlines.

On a 2.4 GHz Pentium 4 processor and for an image of dimensions 256 by 256 by 130, this thickness computation takes approximately 10 minutes to perform. The automatic segmentation takes approximately 3 minutes to perform on the same data.

RESULTS

The thickness of seven ventricular heart walls was calculated and was found to range from 0.46 mm to 15.74 mm. Cross sections showing thickness of two of the

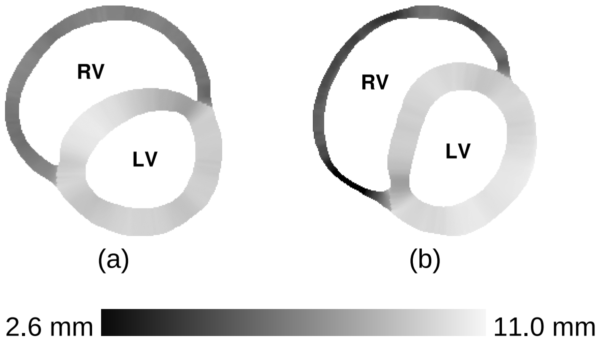

Figure 5: Cross sections showing calculated heart thickness of two hearts. In both cross sections, the left ventricular wall is thicker than the right which is consistent with shapes of the cross sections.

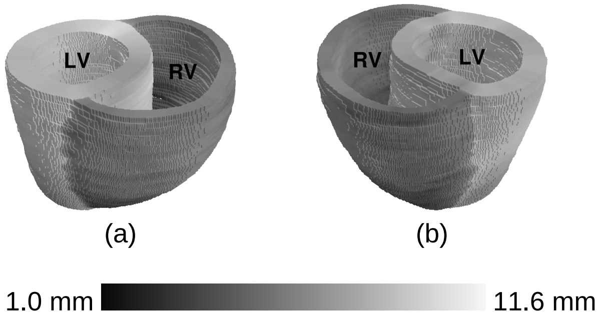

Figure 6: 3D images showing thickness at the surface of two hearts. In both images, the left ventricular wall is thicker than the right which is consistent with the shapes of the hearts.

hearts are shown in Fig. 5. The thickness at the surface of ventricular wall of the same two hearts is shown in Fig. 6. Histograms showing the distribution of thickness in all seven hearts are shown in Fig. 7.

FUTURE WORK

Future work will involve the statistical understanding of the distribution of thickness in normal and diseased hearts. We are also working on extending the Laplace-equation-based method to anisotropic data.

In conclusion, we present an automated method to quantify thickness of the heart muscle. This will allow a quantitative understanding of normal and abnormal heart wall thickness which may be useful in clinical applications.

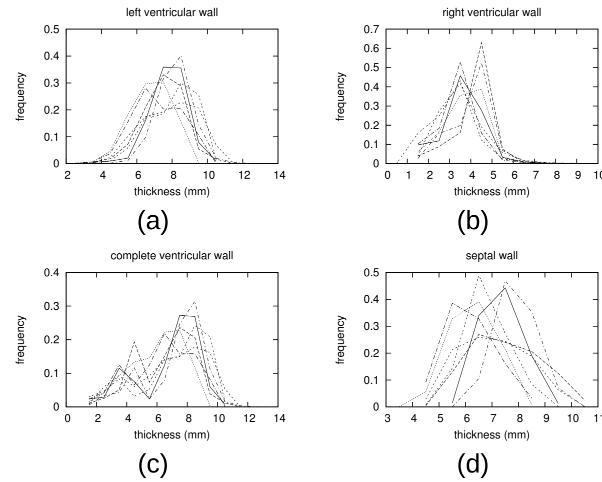

Figure 7: Normalized frequencies of thickness in (a) left ventricular wall, (b) right ventricular wall, (c) septal wall and (d) complete ventricular wall

References

[1] Anthony Yezzi and Jerry L. Prince. A PDE approach for measuring tissue thickness. In Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pages 87–92, December 2001.

[2] S. E. Jones, B. R. Buchbinder, and Itzhak Aharon. Three-dimensional mapping of the cortical thickness using Laplace's equation. Hum. Brain. Mapp., 11:12–32, 2000.

[3] D.F. Scollan, A. Holmes, J. Zhang, and R.L. Winslow. Reconstruction of cardiac ventricular geometry and fiber orientation using magnetic resonance imaging. Annals of BME, 28:934–944, 2000.

[4] G. Borgefors. Distance transformations in arbitrary dimensions. Computer Vision, Graphics and Image Processing, 27:321–345, 1984.

[5] Robin Sibson and G. Stone. Computation of thin-plate splines. SIAM J. Sci. Stat. Comput., 12:1304–1313, 1991.

[6] P. Wesseling. An Introduction to Multigrid Methods. John Wiley and Sons, Chichester, England, 1992.