Computing the Thickness of the Ventricular Heart Wall from 3D MRI Images

Gregory Golds[a] and Faisal Beg[b]

[a]School of Computing Science, Simon Fraser University, Burnaby BC, Canada;
[b]School of Engineering Science, Simon Fraser University, Burnaby BC, Canada

ABSTRACT

A method for measuring the thickness of the ventricular heart wall from 3D MRI images is presented. The quantification of thickness could be useful clinically to measure the health of the heart muscle. The method involves extending a Laplace-equation-based definition of thickness between two surfaces to the ventricular heart wall geometry. Based on the functional organization of the heart, it is proposed that the heart be segmented into two volumes, the left ventricular wall which completely encloses the left ventricle and the right ventricular wall which attaches to the left ventricular wall to enclose the right ventricle, and that the thickness of these two volumes be calculated separately. An algorithm for performing this segmentation automatically is presented. The results of the automatic segmentation algorithm were compared to the results of manual segmentations of both normal and failing hearts and an average of 99.28% of ventricular wall voxels were assigned the same label in both the automatic and the manual segmentations. The thickness of eleven hearts, seven normal and four failing was measured.

Keywords: thickness, heart, MRI, segmentation

1. 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 the 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.

2. HEART GEOMETRY

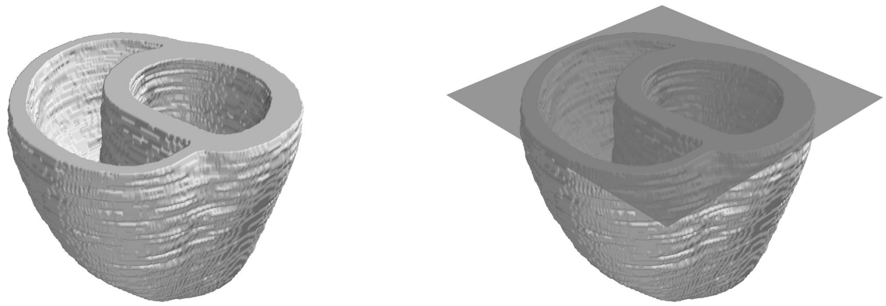
The ventricular myocardium, an example of the shape of which is shown in Fig. 1, lies between three surfaces: the surface formed by the interior of left ventricle, the surface formed by the interior of the right ventricle and the exterior surface of the heart. Some part of the heart ventricle muscle 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.

3. 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 is 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. Yezzi and Prince extended this method by proposing an efficient method of computing the streamline lengths without computing the paths of the streamlines.[1]

Medical Imaging 2005: Image Processing, edited by J. Michael Fitzpatrick,
Joseph M. Reinhardt, Proc. of SPIE Vol. 5747 (SPIE, Bellingham, WA, 2005)
1605-7422/05/$15 · doi: 10.1117/12.593948



(a) (b)

Figure 1. (a) The ventricular myocardium. (b) The plane P

4. LAPLACE-EQUATION-BASED THICKNESS FOR HEART GEOMETRY

4.1. Input Data

The input is a 3D binary image of the heart with voxels making up the myocardium having the value 1 and background voxels having the value 0. The voxels have dimensions 0.325 mm by 0.325 mm by 0.800 mm. 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 gray-scale MRI data using a semi-automated contouring process to remove trabeculation.[3]

4.2. Method For Identifying Boundaries

Before the Laplace-equation-based thickness calculation can be performed, it's necessary to locate the surfaces which form the boundaries between which to solve Laplace's equation, i.e., the boundaries of the ventricular wall. These boundaries are comprised of three surfaces: the borders of the ventricle wall with the interior of the left ventricle, with the interior of the right ventricle and with the exterior of the heart.

The first step in our method for identifying the boundaries is to locate the plane, call it P, above which all voxels have been set to be part of the background. Locating this plane, depicted in Fig.1(b), makes the domain boundaries for the heart muscle easier to find. In order to locate the plane, we calculate successively better approximations to it until these approximations converge. A plane fitted through the centers of the voxels of the set consisting of the highest ventricular wall voxel from each vertical column of the dataset using a least-squares fit is our initial approximation to P. A better approximation is 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, it remains to find the interface of the ventricle walls with the interior of each ventricle and the exterior of the heart. These interfaces are trivial to find if the heart regions they separate, i.e. the left and right ventricle interiors and the exterior of the heart, 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.

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

The output of the previous step are the boundaries of the domain on which thickness is to be calculated. Included in these boundaries are the three surfaces: the the interior surface of the left ventricle, the interior surface of the right ventricle and the exterior surface of the heart. The Laplace-equation-based thickness of Jones et al.[2] is only defined between two surfaces. As a result, the 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.

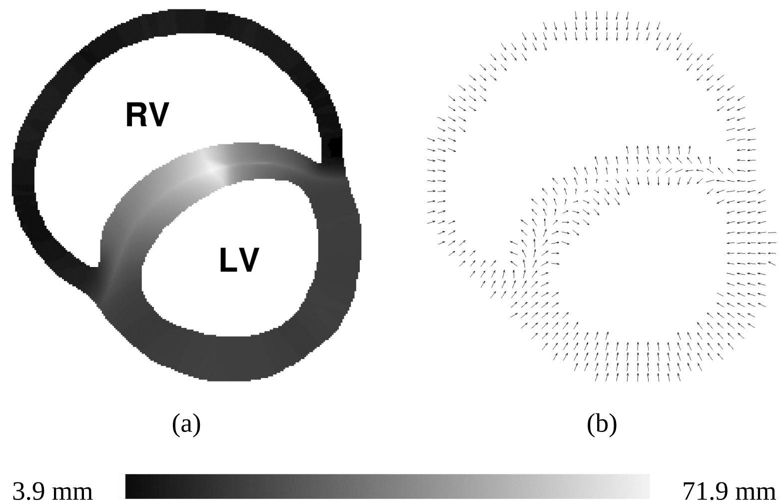


Figure 2. Cross sections of (a) calculated thickness and (b) vector field T when the borders of the interiors of both ventricles are considered to be the same surface. The direction of T along the septum is from the exterior of the heart to the ventricles rather than between the ventricles as would be correct. This results in the incorrect thickness seen along the septum in (a).

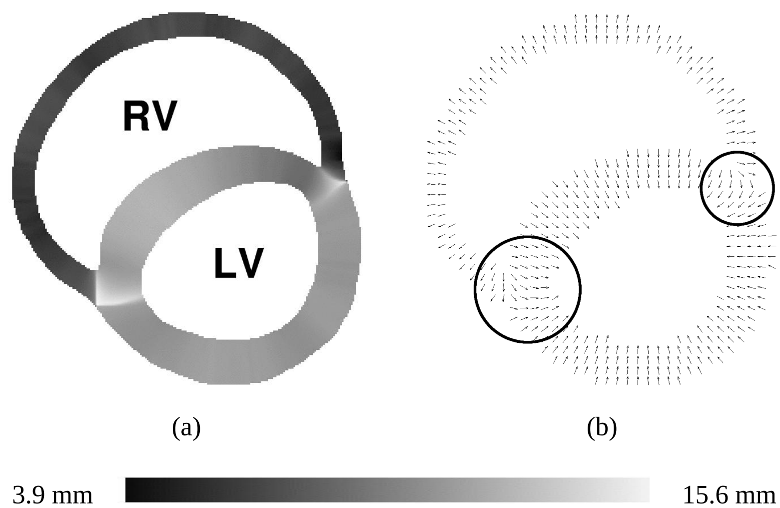
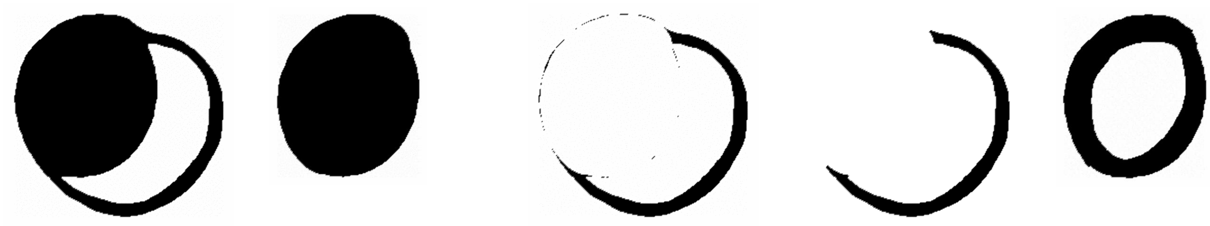


Figure 3. Cross sections of (a) calculated thickness and (b) vector field T when three constants are used to constrain u. The circled areas show where the thickness is incorrectly high due to streamlines of T flowing first toward the exterior of the heart then toward the other ventricle.

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. 2.

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. 3.



(a) (b) (c) (d) (e)

Figure 4. Cross sections of results of steps of the lv segmentation process: (a) starting image, (b) after opening, (c) voxels removed in previous step, (d) after right ventricular wall extracted, (e) segmented left ventricle.

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. 3(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.

4.3.1. 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.

We begin with a 3D binary image in which the voxels of the heart wall and the interior of the left ventricle are set to 1, and all other voxels are set to 0 (Fig. 4(a)). We wish to remove from this image the voxels belonging to the right ventricular wall. Because the right ventricular wall voxels form a much thinner volume than the combined left ventricular wall and interior, they can be removed by applying a morphological opening operator[4] to the image (Fig. 4(b)). Any spherical structuring element with a radius of at least half the maximum thickness of the right ventricular wall will remove the right ventricular wall voxels. Using higher radii increases the smoothness of the left ventricular wall at the insertion points of the right ventricular wall. A radius of roughly 7.5 mm was found to give the best results.

Applying the morpholohical opening operator removes the right ventricular wall voxels from the 3D image. However, it also removes left ventricular wall voxels in regions with high convexity. A 3D binary image in which only the voxels removed by the opening operator are set to 1 will therefore contain both the entire right ventricular wall as well as small pieces of the left ventricular wall (Fig. 4(c)). To remove these small pieces, first a morphological erosion operator with a 3 voxel by 3 voxel by 3 voxel cross as the structuring element is applied in order to disconnect from the right ventricular wall any left ventricular wall pieces adjacent to it. Any voxels not belonging to the largest connected component of the image are then zeroed. Finally, a morphological dilation operator with the same 3 voxel cross structuring element is applied to restore the right ventricular wall (Fig. 4(d)). The inverse of the resulting image is then applied as a mask to an image of the heart wall, and the largest connected component is extracted to segment the left ventricular wall (Fig. 4(e)).

The results of this automated method were compared to a segmentation performed by a human operator on two normal and two failing hearts. The automated algorithm assigned the same label as did the human operator to 99.28% of heart wall voxels on average. To demonstrate the insensitivity of this method to the choice of structuring element radius, the results of the method with the radius increased and decreased by 25% were also compared to the segmentation performed by a human operator. In these cases respectively the automated algorithm assigned the same label to 99.19% and 99.27% of heart wall voxels as the human operator on average.

4.4. Method for Thickness Calculation

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 then solving this system using Gauss-Seidel with successive over-relaxation.[5] To speed convergence, a multi-level method is used whereby the system is solved at multiple levels of coarseness with the solution at one coarseness level being interpolated to produce the initial values for the next most coarser level.

To efficiently calculate the length of the streamlines, the technique proposed by Yezzi and Prince[1] is used. 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 30 seconds to perform. The automatic segmentation takes approximately 10 seconds to perform on the same data.

5. RESULTS

We first tested our method on two phantoms of known thickness: the volume between two concentric cylinders and the volume between concentric spheres. For both phantoms, the difference between the radii of the inner and outer cylinders/spheres was 10 mm so the expected thickness was therefore also 10 mm. The calculated thickness ranged from 9.89 mm and 10.12 mm for the concentric cylinders and 9.89 mm and 10.13 mm for the concentric spheres. The difference between the expected and measured results can be accounted for by discretization errors introduced by the voxelization of the phantom volumes. Because the difference is much less than .325 mm, the value we used as the length of the side of a voxel, we consider these errors acceptable. To check the response of the thickness calculation method to changes in thickness, the two phantoms volumes were morphologically dilated by a spherical structuring element of radius 2 mm and their thicknesses were recomputed. The expected result was increase in average thickness of 4 mm. The observed increase in average thickness was 3.98 mm. Again, the difference between the computed and expected results can be accounted for by discretization error. Validating the thickness calculation on actual heart volumes was not possible because due to their irregular shape there is no standard for thickness measurement and hence no ground truth to validate against.

The thickness of seven normal and four failing ventricular heart walls was calculated and was found to range from 1.2 to 11.5 mm. Basal cross sections showing computed thickness of the hearts are shown in Fig. 5. The computed thickness at the ventricular wall surface of the hearts is shown in Fig. 6. Histograms showing the distribution of thickness in normal versus failing hearts are shown in Fig. 7.

6. CONCLUSIONS

Our results reveal that our proposed automatic segmentation algorithm is able to accurately segment binary ventricular heart wall images without requiring the careful specification of parameter values. The results also show that our method of thickness computation responds appropriately to changes in shape. Additionally, the results show that both the automatic segmentation algorithm and the method for thickness calculation produce valid results for failing hearts as well as healthy hearts.

7. FUTURE WORK

Future work will involve the statistical understanding of the distribution of thickness in normal and diseased hearts. We anticipate that histograms of such distributions, similar to the ones shown in Fig. 7 might be useful as indicators for heart diseases.

8. ACKNOLEDGEMENTS

Funding support for this research was provided through NSERC grant number 31-611387. We would like to thank Patrick Helm at the Department of Biomedical Engineering, The Johns Hopkins University for providing the heart volume datasets.

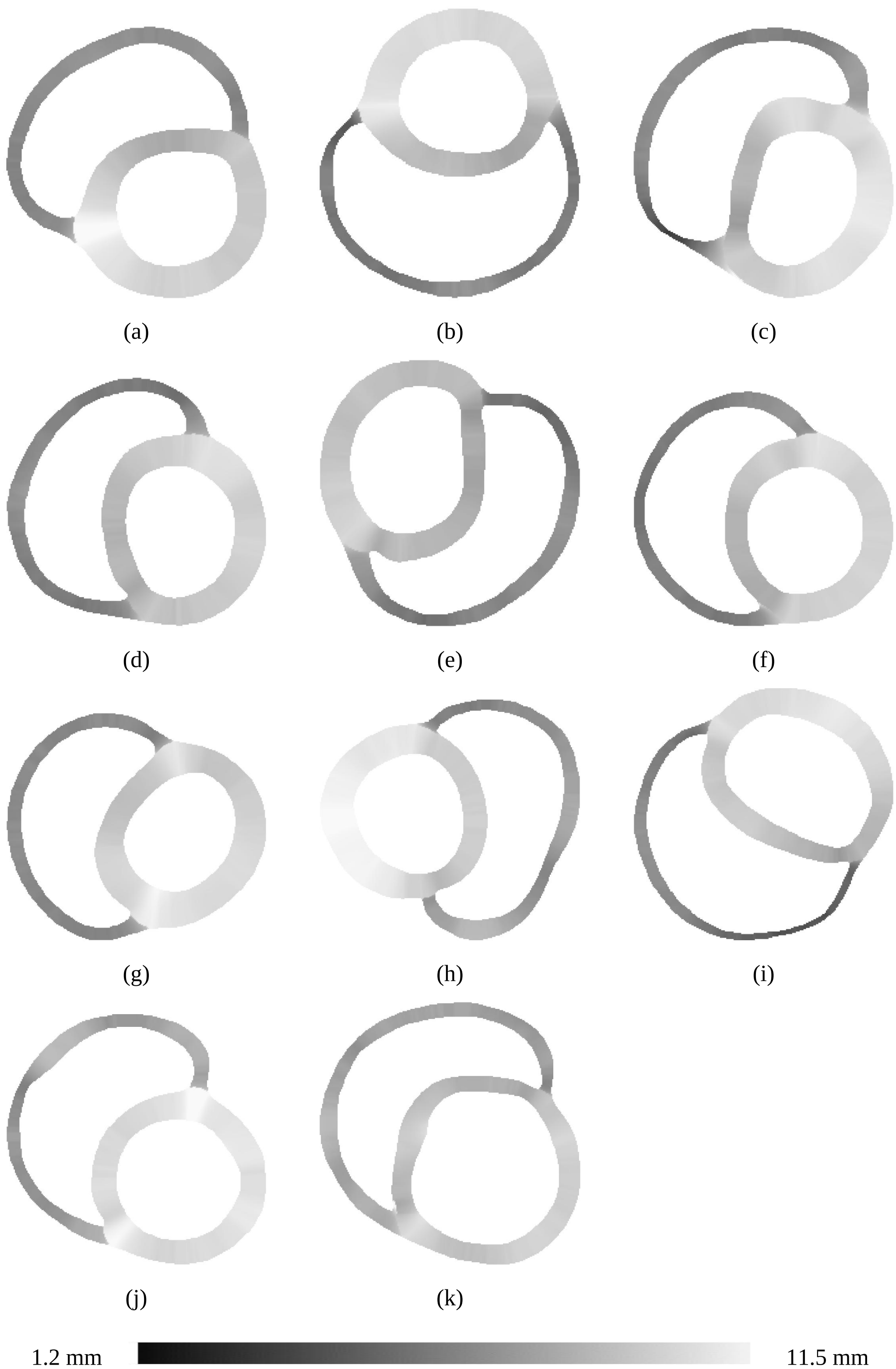


Figure 5. Basal cross sections showing thickness of normal and failing hearts. (a) through (g) are normal hearts. (h) through (k) are failing hearts.

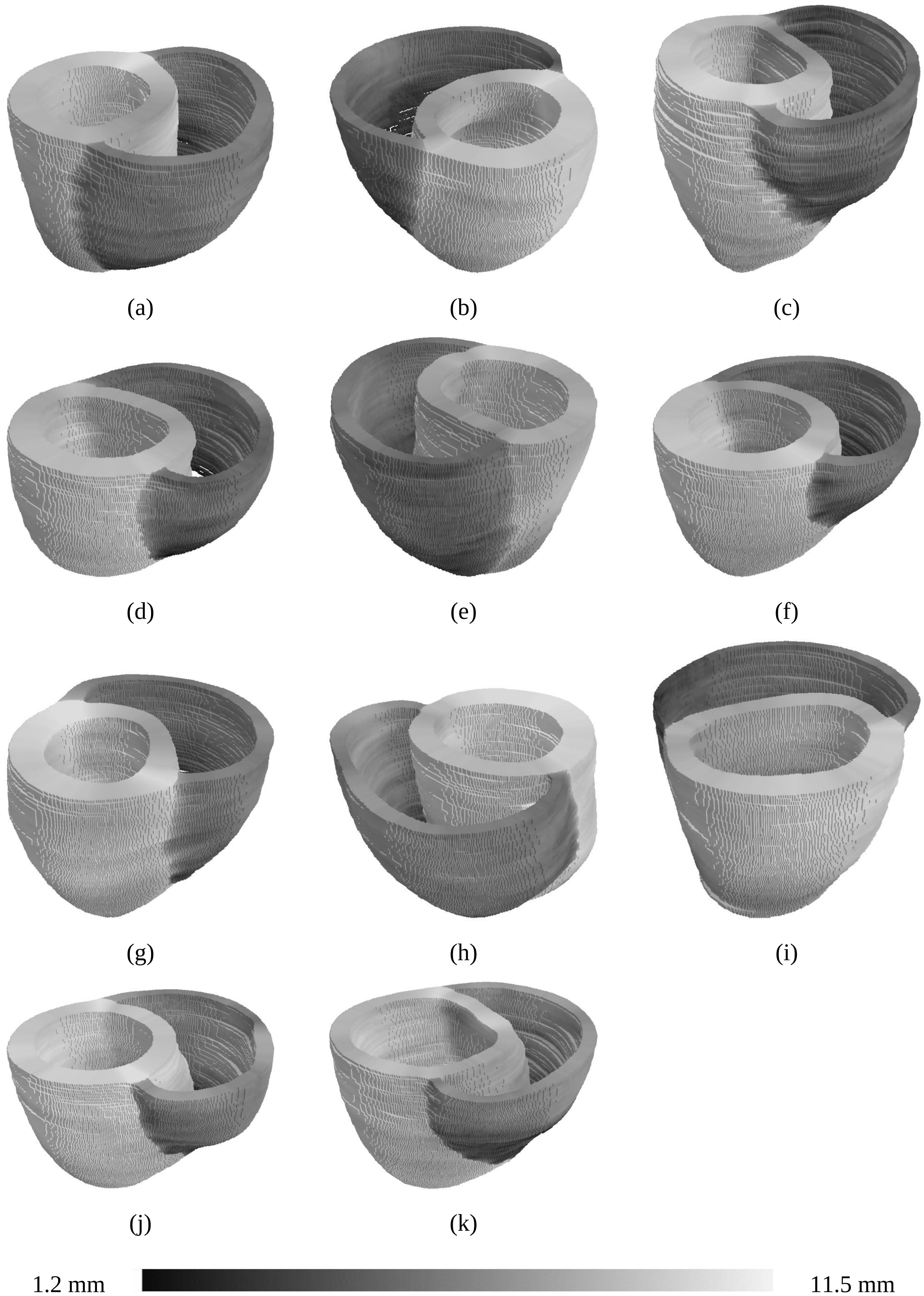


Figure 6. Thickness at the surface of normal and failing hearts. (a) through (g) are normal hearts. (h) through (k) are failing hearts.

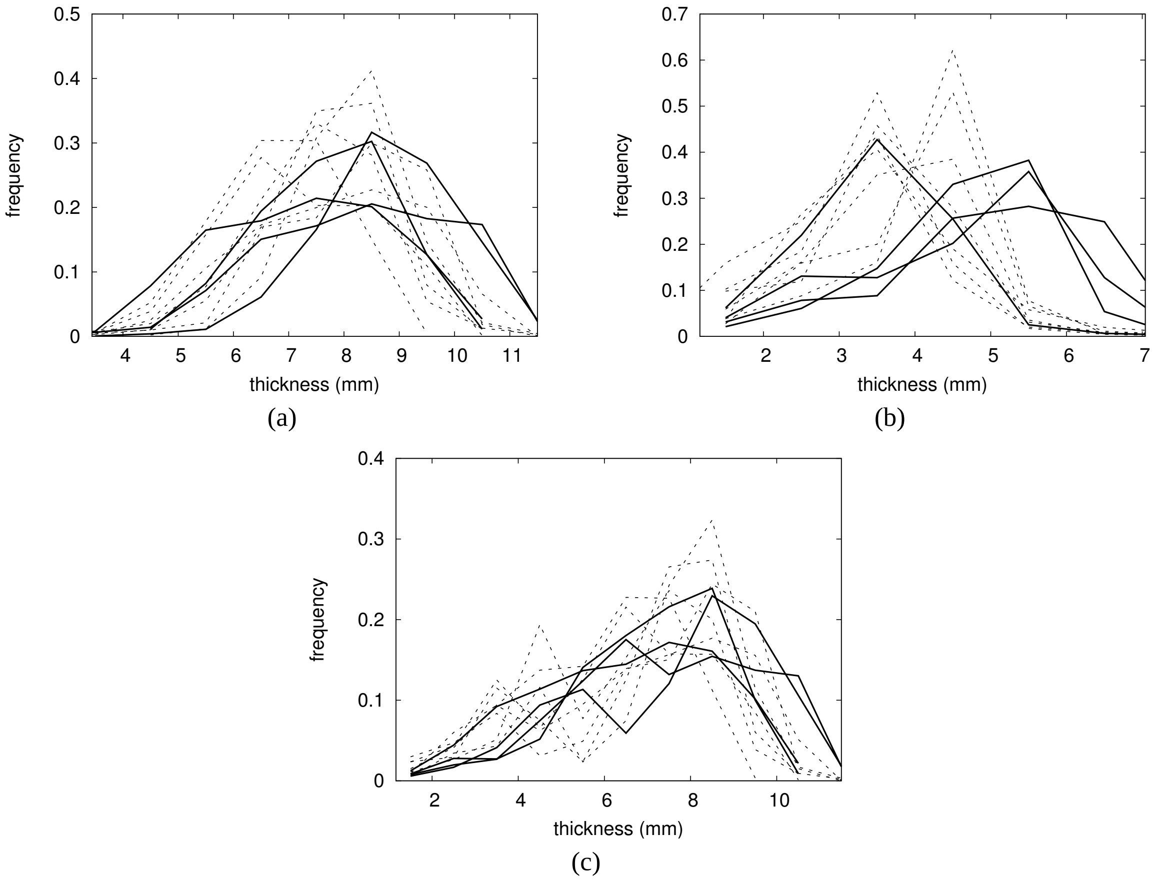


Figure 7. Normalized frequencies of thickness in (a) left ventricular wall, (b) right ventricular wall, and (c) complete ventricular wall is normal heart (dashed lines) versus failing heart (solid lines).

REFERENCES

1. A. Yezzi and J. L. Prince, "A PDE approach for measuring tissue thickness," in *Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp. 87–92, December 2001.
2. S. E. Jones, B. R. Buchbinder, and I. Aharon, "Three-dimensional mapping of the cortical thickness using Laplace's equation," *Hum. Brain. Mapp.* **11**, pp. 12–32, 2000.
3. D. Scollan, A. Holmes, J. Zhang, and R. Winslow, "Reconstruction of cardiac ventricular geometry and fiber orientation using magnetic resonance imaging," *Annals of BME* **28**, pp. 934–944, 2000.
4. J. Serra, *Image Analysis and Mathematical Morphology*, Academic Press, London, 1982.
5. R. L. Burden and J. D. Faires, *Numerical Analysis*, Brooks/Cole, Pacific Groove, CA, seventh ed., 2001.