

TWO NOVEL METHODS FOR COMPUTING THE 3D CARDIAC MIDWALL

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ABSTRACT

Computation of the cardiac midwall is an important first step in the pipeline for cardiac image analysis. In this paper, we explore two novel techniques that can give a good estimate of the cardiac midwall, and each of these techniques has certain unique advantages and limitations. Laplacian-based midwall technique measures the mid-point of the streamlines of the heat equation from the epicardium to the endocardium and uses standard MR images of the heart. The gamma-wall method measures the fiber midwall which is composed of all points where the fiber travels circumferentially about the ventricle and this is determined by exploiting color image processing techniques. This technique requires the use of diffusion tensor MR images in order to determine the fiber orientation for the entire volume. Both techniques are presented using visualizations on diseased and healthy canine dog hearts.

Index Terms— Cardiovascular system, Visualization, Biomedical computing, Heart, Midwall

1. INTRODUCTION

The cardiac midwall is an important indicator of cardiovascular health and plays an important role in the mechanical functioning. Studies have shown the effects of midwall shortening as an indicator of health and morbidity along with cardiac performance [1]. It has also been shown to be an independent predictor of cardiovascular risk in patients with hypertension [2]. Midwall shortening is used to determine contractile efficiency. In patients with hypertension those with depressed midwall shortening have more coronary impairment and exercise induced myocardial ischemia [3].

Mathematical models have shown that strain is highly related to fiber orientation and that fibers are oriented to minimize stress caused by mechanical load. Rijcken et al have shown that the structure of the left ventricle are designed for maximum homogeneity of fiber strain [4]. It is possible for the fibers to remodel due to infarction or other disease [5].

Traditional methods for determining the midwall rely on 2D slices in which the heart is placed in axial orientation i.e. with the long axis of the left ventricle oriented perpendicular to the plane in which the images are analyzed. Then, the centroid of the left ventricle is found, and from this point, a radially outward line segment is created that cuts the endocardium

and epicardium at two points as illustrated in Figures 1 and 2. The midwall is defined at the midpoint of the straight line segment cutting the inner and outer surfaces. This method has a few limitations, one that is a 2D method and ignores the 3D aspect of cardiac geometry, and secondly, the result is sensitive to the location of the centroid, and the orientation of the heart with respect to the imaging plane which leads to the radial line segment intersecting the inner and outer walls at two distinct locations. One main limitation is also that although the results can be controlled to be reasonable for the left ventricle, this straightforward approach fails to give good results for the right ventricle where the geometry is not symmetrical about the centroid.

2. METHODS

Our first method for calculation of ventricular midwall relies on solving the Laplace's-equation $\Delta u = 0$ with the endocardium surface set at $u = 0$ and the epicardial surface set at $u = 1$. The solution is a potential function u shown in Figure 3 that varies smoothly from the inside to the outside. Streamlines of this function $T = \frac{\nabla u}{|\nabla u|}$ give a bijective correspondence between the internal and outer surfaces. The length of streamlines at every point on the ventricular surfaces provides an estimate of thickness at that point [6]. In this geometric framework, we define the midwall as the set of points where $u = 0.5$ (i.e. midway along the streamlines connecting the inner and outer surfaces). The advantage of this method is that, unlike traditional methods based on defining the midpoint in 2D slices, which are prone to errors due to orientation and definition of the long axis, this method is fully 3D and invariant to orientation of the cardiac geometry in space.

The second method for determining cardiac midwall is based on the orientation of cardiac myofibers as estimated using the principle eigenvector of the diffusion tensor from diffusion tensor MRI [7]. The helical angle is the angle the principle eigenvector makes with the plane containing the local radial and circumferential vectors, i.e. perpendicular to the local long axis. The helical angle traversing the ventricular wall from inside to outside varies from $+80^\circ$ at the endocardium to -80° at the epicardium [8]. The midwall can then be defined as the set of points where the helical angle crosses 0° .

We present a simple, yet novel method to determine this

zero-crossing using a gamma-color transformation. First, each principal eigenvector $v = [v_x, v_y, v_z]$ is considered as a point in RGB color space with red= v_x , green= v_z and blue= v_y . Since cardiac fibers are locally aligned and change helical angle smoothly, contrast enhancement in the region where the helical angle is small is desired to locate the points forming the midwall based on helical angle. This is obtained by applying a color transformation that takes an input color value v_i and transforms it to a value c_i given by $c_i = 255|v_i|^\gamma$ for some value of γ . This operation is performed independently for each color channel $i = 1, 2, 3$ and serves to saturate the colors representing the xy plane leaving the z-axis component well below saturation for the midwall since at these points the z-component is negligible. Therefore, the points on the midwall, where the z-component is small (helical angle close to 0°) will appear as a distinct non-white band that can be visualized and segmented using standard image processing techniques. This method is also fully 3D, and invariant to position of the cardiac geometry in 3D space, except that the color of the midwall will be mapped to a different color in different orientations but the position will not change.

3. RESULTS

We applied our method on geometric and diffusion tensor data acquired from 11 excised dog hearts¹. We only present the results for three randomly chosen hearts due to space constraints; the method is robust and works on all the 11 volumes that were analyzed. Images were acquired with a 4-element knee phased array coil on a 1.5 T GE CV/I MRI Scanner (GE, Medical System, Wausheka, WI) using an enhanced gradient system with 40 mT/m maximum gradient amplitude and a 150 T/m/s slew rate. Each geometric heart image was first segmented manually to remove trabeculation and papillary muscles, the resultant ventricular walls were segmented automatically into left and right ventricles [6]. Diffusion tensor field over the segmented myocardium was obtained.

We processed the diffusion tensor field to extract the principal eigenvector. The eigenvectors are sign-ambiguous since both $\pm v$ are eigenvectors, hence the eigenvector field is quite noisy. We smooth this field by first locally aligning the principle eigenvector field using the monte carlo algorithm described in [9] using an initial temperature of $T = 5$ and cooling rate of $1E - 3$ and then followed by optimizing a variational cost using its gradient in a gradient descent scheme.

To compute the midwall based on Laplace's equation, we solved $\nabla^2 u = 0$ with a multi-resolution scheme to speed convergence. In order to minimize discretization errors, the Laplace's equation is solved on a up-sampled discrete mesh, and the solution u segmented for the range of values $(0.5 - \epsilon, 0.5 + \epsilon)$ for some small $\epsilon = 0.01$. The results for the Laplace's equation based midwall are shown in Figure 4 and

¹Obtained from <http://www.ccbm.jhu.edu/research/DTMRIDS.php>

5 via scalar cut planes with a white midwall inside a black ventricle via an axial and a longitudinal cut through the left ventricle. Figure 6 shows the entire Laplace's equation based midwall via an iso-surface joining the selected voxels using the VTK software toolkit.

For the gamma color transformation based midwall, we first mapped (v_x, v_y, v_z) components to the (R, B, G) channels (and not (R, G, B)). This is done so that the midwall appears a dark magenta color and not a light yellow as is the case with the standard (R, G, B) mapping making it easier to visualize. This color vector is then gamma-transformed with $\gamma = 0.15$ for each point and all datasets. The resulting midwall based on this gamma-transformation is presented in Figure 7. In the top row are shown two slices taken from each of the axial view of a healthy heart volume 080803 and a failing heart volume 082303. The second row demonstrates the midwall on evenly spaced axial slices covering nearly the entire volume for failing heart volume 050204.

4. CONCLUSIONS

In this paper, we present two methods for determining the cardiac midwall. The Laplace's equation based midwall technique is defined geometrically using the midpoint of the streamlines of the potential function. It is easy and efficient to extract the midwall from the u -field without requiring the streamlines. The gamma-wall method provides a rapid and effective way to visualize the fiber-midwall given the principle eigenvectors from a diffusion tensor MRI volume.

It is interesting to note that that midwall based on underlying fiber helical angle appears mostly near the center of the wall for the normal hearts however there are many cases where it appears much closer to the exterior. It will be important to understand if this is related to stress and load on the heart, and if this is related to the disease process.

In addition to the magenta fiber-midwall lines, there are also cyan and yellow lines. The yellow lines are barely visible due to human perception but appear very clear under the (R, G, B) channel ordering. These lines are analogous to the midwall lines where they have a very small component along a single axis. The cyan lines occur where there is a very small x-axis component and the yellow lines occur where there is a very small y-axis component.

5. REFERENCES

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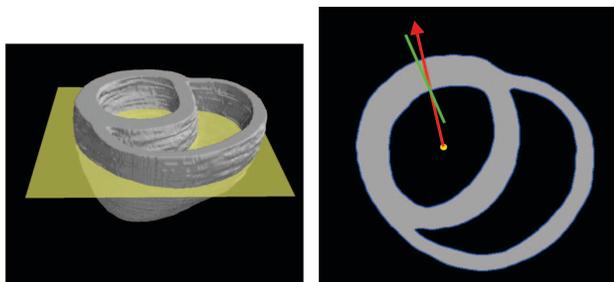


Fig. 1. Sensitivity of traditional midwall computation on orientation of the heart geometry in 3D space, as well as accurate determination of centroid and the long axis.



Fig. 2. Sensitivity of traditional midwall computation on orientation of the heart geometry in 3D space, as well as accurate determination of centroid and the long axis.

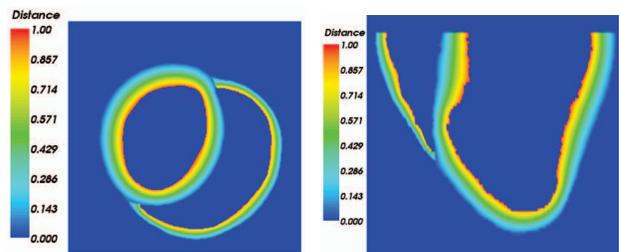


Fig. 3. Solution u of Laplace’s equation $\nabla^2 u = 0$.

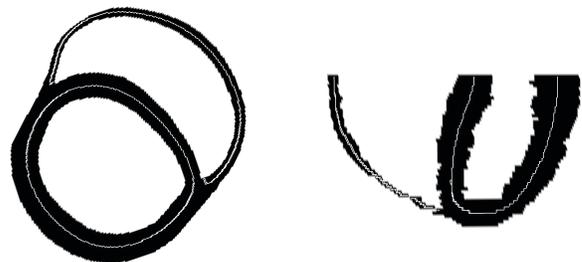


Fig. 4. Laplace’s equation based midwall. Scalar cut planes generated from the Laplace-midwall technique demonstrating the left and right ventricle midwall on heart volume 080803.

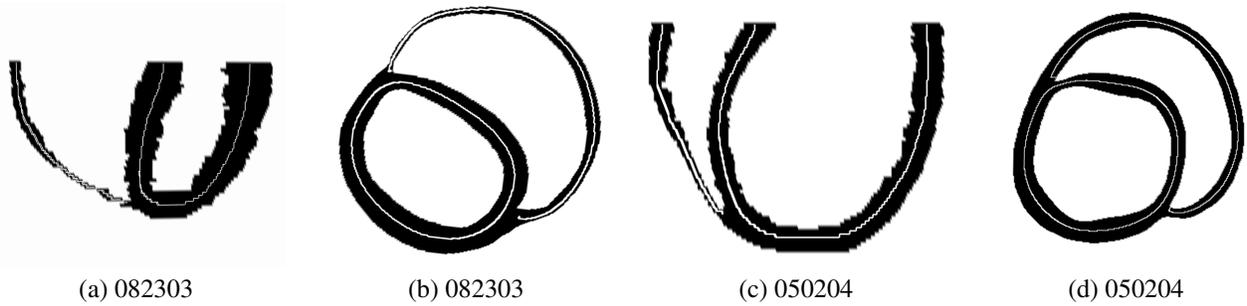


Fig. 5. Laplace's equation based midwall. Scalar cut planes generated from the Laplace-midwall technique demonstrating the left and right ventricle midwall on two heart volumes 082303 and 050204.

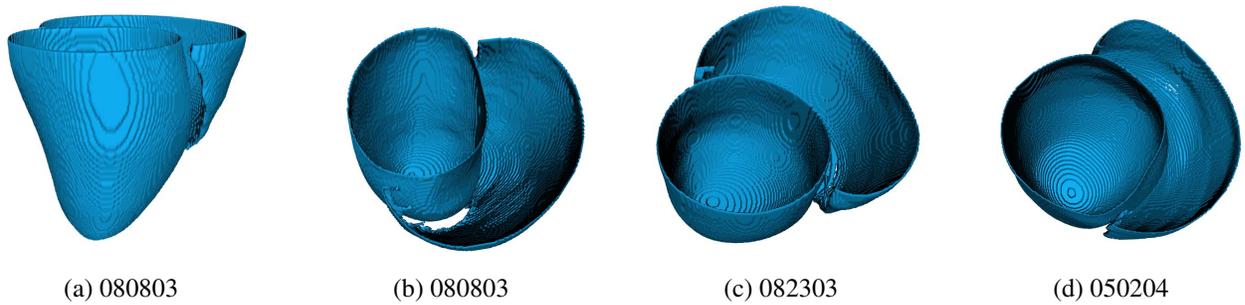


Fig. 6. Laplace's equation based midwall. Isosurface generated from the Laplace-midwall technique demonstrating the left and right ventricle midwall on heart volume 080803, 082303 and 050204.

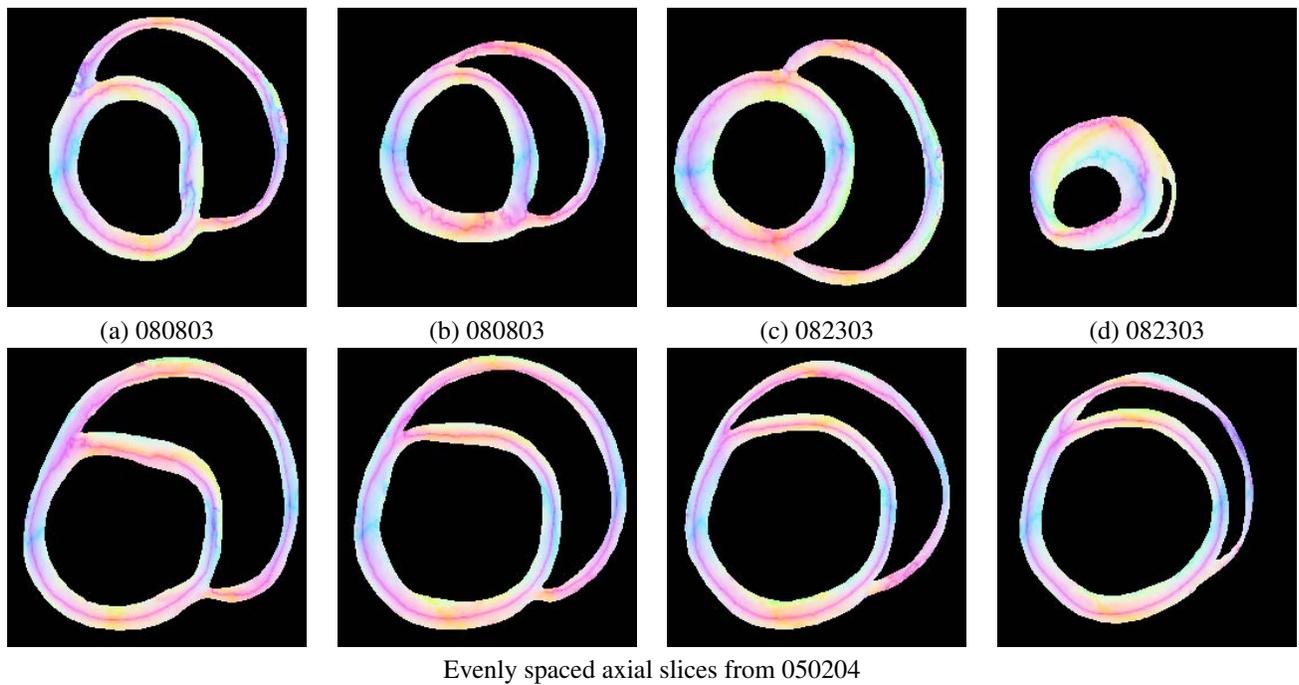


Fig. 7. Midwall visualizations obtained from the gamma-transformation method. The top row shows the midwall in two axial slices from heart 080803 and 082303, the bottom row shows four axial slices from the heart 050204.