Finding the Mitral Annular Lines From 2-D + 1-D Precordial Echocardiogram Using Graph-Search Technique

Yu-Tai Ching, *Member, IEEE*, Shyh-Jye Chen, Chew-Liang Chang, Chih-Yang Lin, and Yu-Hsian Liu

***Abstract*—The apical four-chamber view echocardiogram collected by a transthoracic transducer can be used to evaluate the left ventricle volume. In the diastole, the left ventricle and left atrium become one chamber. In this case, the left ventricle and left atrium need to be separated using a "mitral annular line" so the volume of the left ventricle can be estimated. In this paper, a nearly automatic method for identifying the mitral annular lines from two-dimensional (2-D) + one-dimensional (1-D) precordial four-chamber view echocardiogram is presented. This method employs the optical flow technique and graph-search approach. The mitral annular line sequence is found by finding the shortest path in a weighted directed graph. The vertices in the graph are candidates for the mitral annular lines. The weights on the directed edges are determined using the optical flow technique. The proposed method requires only a physician to provide a point that is always in the left ventricular chamber. Experimental results show that the average error for the left ventricle volume obtained based on the computed mitral annular lines is 3%.**

***Index Terms*—Echocardiogram, left ventricle, mitral annular line, optical flow, shortest path algorithm, signal-adaptive maximum-likelihood (SML) filter.**

I. INTRODUCTION

ECHOCARDIOGRAPHY, with the advantages of low cost and no radiation, is one of the most convenient diagnostic tools for heart diseases. Among the various echocardiograms, the apical four-chamber view collected using a transthoracic transducer is important in evaluating the left ventricle function [1]. For example, the volume of the left ventricle can be estimated from the four-chamber image views. The left ventricle ejection fraction, that is, the diastole and systole left ventricle volume ratio, can be evaluated. In this task, left ventricle segmentation is the most basic work. To segment the left ventricle, a physician can manually trace the boundary of the left ventricle in the images. This is a cumbersome and time-consuming job, especially when many images are involved. An automatic or semi-automatic method to segment the left ventricle would be a valuable diagnostic tool. Many works have discussed methods for heart chamber segmentation [2]–[9]. However, besides the wall detection problem, another problem occurs when the left ventricle is segmented in the apical four-chamber echocardiogram view. In diastole, the left ventricle and left atrium become one chamber when the mitral valve opens fully. However, in systole the left ventricle and the left atrium are separated by a virtual line connecting the mitral annulus. We call this line the *mitral annular line*. This line can be used as a reference to separate the two chambers in diastole. Thus, a convenient method to establish the mitral annular lines is needed toward designing an automatic method to calculate the left ventricle volume.

In this paper, we present a nearly automatic method to establish the mitral annular lines from a two-dimensional (2-D) + one-dimensional (1-D) precordial echocardiogram sequence. This method requires only a physician to provide a point that is always in the left ventricular chamber during the cardiac cycles.

The proposed method is presented in the next section. The proposed method consists of several steps. The related background for each step is briefly described. The results and discussion are presented in Section III.

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II. METHOD

The proposed method uses the signal-adaptive maximum-likelihood (SML) filter [10], [11], the optical flow computation [12]–[16], k-means algorithm [17], and shortest path algorithm [18]. The SML filter is for image preprocessing. To determine the mitral annular line sequence, the k-means algorithm is employed to determine a set of possible mitral annular points. Optical flow computation is then applied to estimate the velocities of the points. Finally, a weighted directed graph is established from these points and estimated velocities. The mitral annular line sequence is calculated by finding the shortest path in the graph.

A. Preprocess

The preprocessing step employs the SML filter [10], [11] to remove speckle noises. The SML filter abates noise and strengthens the signals from areas with similar intensities. The SML filter is now briefly described.

An image consists of low-frequency and high-frequency components. The low-frequency component can be estimated using a local estimator. Given a $W \times W$ window around the pixel (k, l) in an image, the original (k, l) signal can be estimated using the maximum-likelihood estimator $\hat{s}_{\mathrm{ML}}(k, l)$

based on the observations in a $W \times W$ window. The original signal estimation at (k,l), denoted $\hat{s}(k,l)$, is obtained using

$$\hat{s}(k,l) = \hat{s}_{\mathrm{ML}}(k,l) + \beta(k,l)[x(k,l) - \hat{s}_{\mathrm{ML}}(k,l)]. \quad (1)$$

In (1), $x(k,l)$ is the intensity of the pixel (k,l). $\hat{s}_{\mathrm{ML}}(k,l)$ is the maximum-likelihood estimation for the original signal at (k,l). $\beta(k,l)$ is a weighting factor that approximates the local signal-to-noise ratio (SNR) over the window. Using the multiplicative noise model, $\hat{s}_{\mathrm{ML}}(k,l)$ and $\beta(k,l)$ are formulated as the following equations:

$$\hat{s}_{\mathrm{ML}}(k,l) = \frac{\sqrt{\pi}}{2}\sqrt{\frac{1}{N}\sum_{W} x^2(k-i, l-j)} \quad (2)$$

and

$$\beta(k,l) = 1 - \left(\frac{4-\pi}{4}\right)\frac{Ew[x^2]}{Ew[(x-\hat{s}_{\mathrm{ML}})^2]} \quad (3)$$

where $Ew[x^2] = 1/N\sum_W x^2(i,j)$. The value of $\beta(k,l)$ ranges over $[0,1]$. If $\beta(k,l)$ is small, (k,l) is considered a noise point and its intensity is altered by the maximum-likelihood estimation.

B. Computing the Mitral Annular Lines

In this step, a point that exists in the left ventricular chamber interior and separates the left and right attachments of mitral annular lines at all times in a cardiac cycle must be provided. There are four tasks in this step, namely, identifying the set of possible mitral annular points, estimating the velocities of the mitral annular points, establishing a weighted directed graph, and finally computing the mitral annular lines.

Identify the Mitral Annular Points: The mitral annular points on fat and muscle demarcation have higher echogenecity. Thus, these mitral annular points will be in the brighter areas in the image. A 3-means algorithm is applied to divide the intensity into three clusters. The cluster, S, consisting of the highest intensity pixels contains the mitral annular points. Since a mitral annular line is formed by a pair of boundary points in S, only the boundary points are considered the possible mitral annular points in the later computation.

Estimate the Velocities: The velocities of these points are needed to determine the weights associated with edges in the graph. Because the true velocities are not available, the estimated velocities are calculated using the optical flow technique. This method is briefly stated next. For details, please refer to [16].

Optical flow is a technique used to estimate the velocities of points from a pair of consecutive images. The velocities are estimated using the conservation and neighborhood information. The estimated velocities $U_{cc} = (u_{cc}, v_{cc})$ are computed using the conservation information. Errors exist between the estimated and true velocities. Assume that these errors have zero mean and are independent. A covariance matrix S_{cc} is used for the estimated velocity U_{cc}. The estimated velocities $\overline{U} = (\overline{u}, \overline{v})$ are obtained from the neighborhood information. The covariance matrix with the estimate is S_n. The conservation and neighborhood errors are respectively

$$(U - U_{cc})^T S_{cc}^{-1}(U - U_{cc}) \quad (4)$$

and

$$(U - \overline{U})^T S_n^{-1}(U - \overline{U}). \quad (5)$$

By minimizing the sum of the conservation and neighborhood errors

$$\int\int \left[(U - U_{cc})^T S_{cc}^{-1}(U - U_{cc}) + (U - \overline{U})^T S_n^{-1}(U - \overline{U})\right] \quad (6)$$

the true velocity can be estimated. Minimizing (6) is carried out by applying an iteration method. The velocity of the $(n+1)$th iteration is calculated using

$$U^{n+1} = \left[S_{cc}^{-1} + S_n^{-1}\right]\left[S_{cc}^{-1}U_{cc} + S_n^{-1}\overline{U}^n\right]. \quad (7)$$

The boundary condition is $U^0 = U_{cc}$. The iteration stops when the difference between the velocities of two successive iterations is smaller than a given threshold value.

Finding the Mitral Annular Lines: Let the image sequence be denoted I_i, $i = 1, \ldots, r$. Each I_i is preprocessed using the 3-means algorithm to identify those points that could be the mitral annular points. Let the user input a selected point denoted O so that a vertical line passing through O divides the point set into two subsets L_i and R_i. A mitral annular line is formed by a pair of points (p,q) that $p \in L_i$ and $q \in R_i$. Each line segment, $\overline{p_j, q_k}$, $p_j \in L_i$, $q_k \in R_i$ is a *candidate* for the mitral annular line.

Let v_{L_i} and v_{R_i} be the average velocities of the points in L_i and R_i. If $\overline{p_i, q_i}$ and $\overline{p_{i+1}, q_{i+1}}$ are the mitral annular lines in I_i and I_{i+1}

$$|(\overrightarrow{p_i, p_{i+1}} - v_{L_i})| + |(\overrightarrow{q_i, q_{i+1}} - v_{R_i})|$$

should be small. Based on this observation, a method to identify the mitral annular line sequence from I_1 to I_r was designed using the graph-search approach.

A weighted directed graph $G = (V, E)$ is constructed. V is the set of vertices that $V = \cup V_i$, $i = 1, \ldots, r$. $V_i = \{v_{(i,j)} | j = 1, \ldots, m_i\}$ where $v_{(i,j)}$ is the jth candidate for the mitral annular line in I_i and m_i is the number of candidates in I_i. E is the set of directed edges

$$\{\langle v_{(i,j)}, v_{(i+1,k)}\rangle | i = 1, \ldots, r-1, \quad j = 1, \ldots, m_i, k = 1, \ldots, m_{i+1}\}.$$

There is a weight, $w_{(i,j,k)}$, associated with an edge $\langle v_{(i,j)}, v_{(i+1,k)}\rangle$. Let $v_{(i,j)}$ represent a candidate $\overline{p_i, q_i}$ and $v_{(i+1,k)}$ represent a candidate $\overline{p_{(i+1)}, q_{(i+1)}}$. Given the velocities v_{L_i} and v_{R_i}, the weight $w_{(i,j,k)}$ is defined using (8)

$$w_{(i,j,k)} = |(\overrightarrow{p_i, p_{i+1}} - v_{L_i})| + |(\overrightarrow{q_i, q_{i+1}} - v_{R_i})|. \quad (8)$$

Suppose that $\overline{p_i, q_i}$, $i = 1, \ldots, r$, are the sequence of mitral annular lines in I_i. The sum of the weights w_i, $i = 1, \ldots, r-1$ should be the minimum. Thus, given the weighted graph G, the shortest path from a vertex in V_1 to a vertex in V_r corresponds to the mitral annular line sequence.

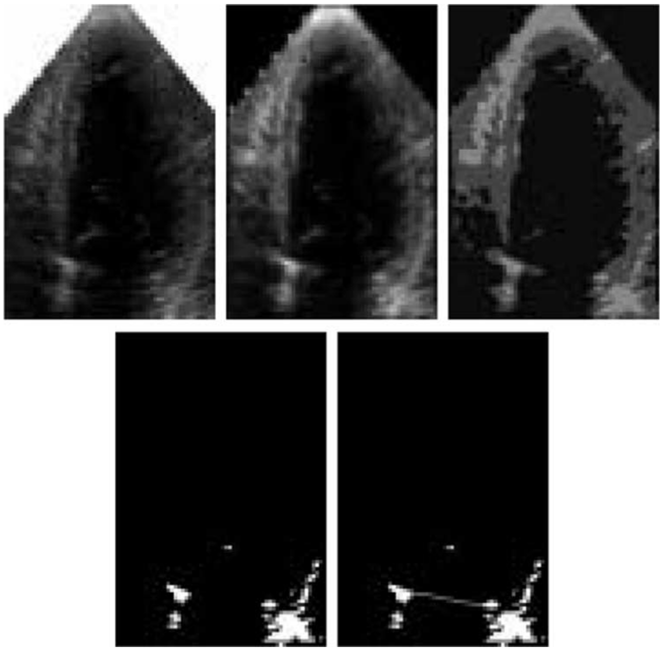

Fig. 1. The images before (upper left) and after (upper middle) the SM filter application. The image after applying the 3-means clustering method is shown in the upper right-most image. The lower left image shows the selected point O and the points in the highest intensity cluster. Only the boundary points are the possible mitral annular points. The lower right image shows the superimposed mitral annular line.

To implement the shortest path algorithm, there are two fields, $c_{(i,j)}$ and $f_{(i,j)}$, associated with each vertex $v_{(i,j)}$. $c_{(i,j)}$ maintains the least path cost from a vertex in V_1 to $v_{(i,j)}$. $f_{(i,j)}$ records the vertex in V_{i-1} on that path. The algorithm is presented in the following pseudocode.

```
set v_(1,j) = 0, j = 1,...,m_1;
set v_(i,j) = a large number for all i ≠ 1, for all j;
for (i = 2 to r) {
 for (j = 1 to m_i) {
  for (k = 1 to m_(i-1)) {
   if (c_(i,j) > w_(i-1,k,j) + c_(i-1,k)) {
    c_(i,j) = w_(i-1,k,j) + c_(i-1,k);
    f_(i,j) = v_(i-1,k);
   }
  }
 }
}
```

III. Results and Discussion

The experimental results are presented in this section. The image resulting from the SML filter application is presented in Fig. 1. The image after 3-means clustering is also shown in Fig. 1. The cluster that has the largest intensity contains the possible mitral annular points. Only the points below the selected point O are considered to be the possible mitral annular points.

Fig. 2 shows a sequence of identified mitral annular lines obtained using the proposed method. The computing time for processing a sequence of 20 images is shown in Table I. The computation time was recorded using an AMD Athlon (TM) XP 1500+ personal computer. The computation time required by the first and the second step depends on the image size. The image size was 140 by 210 in our experiment. The computation time required for Step 3 depends on the number of mitral annular line candidates. This was the most time-consuming step. The time complexity for the algorithm in Step 3 is $O(r \cdot m^2)$ where m is the number of candidates in each image and r is the number of

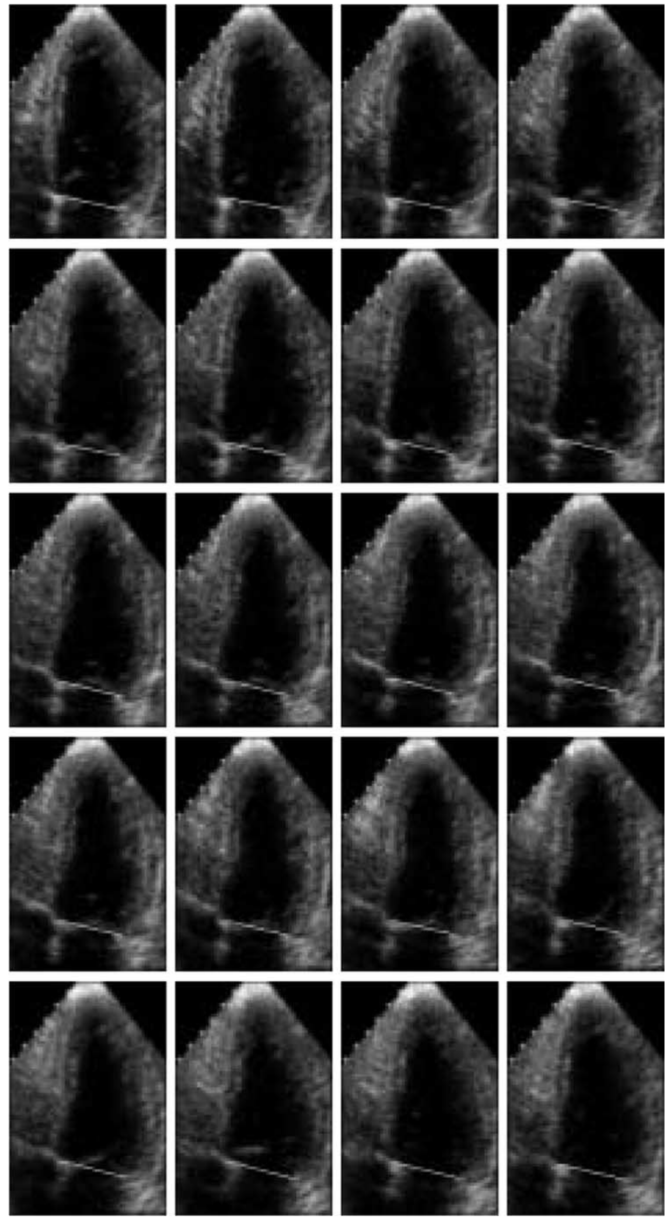

Fig. 2. Sequential precordial echocardiographic images in long axis view of an adult healthy volunteer within a cardiac cycle. The white line separating the left ventricle and left atrium is the mitral annular line created by the proposed method.

TABLE I
COMPUTATION TIME REQUIRED IN EACH STEP. THE TIME WAS OBTAINED USING AN AMD ATHLON (TM) XP 1500+ CPU

SML Filtering	25 sec.
Optical flow computing	67 sec.
Shortest Path Computation	123 sec.

TABLE II
ERROR DISTRIBUTION FOR THE 148 IMAGES

Error	Number of Images
0.01	33
0.02	24
0.03	25
0.04	18
0.05	16
0.06	16
0.07	7
0.08	3
0.09	4
0.1	2

images in the sequence. The run time was recorded when the number of candidates was 4225, i.e., we restricted the number of candidates for mitral annular points to 65 points on each side. These 65 points are below the point O and they are the 65 closest points to O horizontally.

To test the accuracy of the proposed method, the method was applied to seven mitral annular lines sequence cases. These seven cases were chosen because the junctions between the left atrium and the left ventricle were anatomically obvious. The endocardial wall of the left ventricle was traced and the volume of the heart chamber was calculated based on the mitral annular lines obtained using the computer and by a physician. There were seven cases consisting of 148 images. The volume was obtained using the proposed method V_c and a physician tracing V_p. We computed the difference $d = V_c - V_p$. The error was evaluated using $|d|/V_p$. Our results show that the averaged error was 0.03. Table II shows the error distribution for the 148 images.

A nearly automatic method for calculating the mitral annular lines from a 2-D + 1-D precordial echocardiogram four-chamber view was presented. The proposed method needs only a physician to provide a point in the left ventricular chamber. The average error was 3% which is clinically acceptable. The proposed method saves much clinician time, allowing a shift from machine to patient care.

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