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Left Ventricle Function Quantification in Two Dimensional Echocardiography Image Sequence Using Temporal Hybrid Level Set Method

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Abstract: Identifying left ventricle area is highly important in the process of evaluating cardiac function. It also plays crucial role in quantification and measurement of cardiac parameters, such as ejection fraction. Since echocardiography is real time and the object moves in a periodic pattern, we applied temporal priors in segmentation considering segmentation as a spatio-temporal process. This approach is expected to deal with motion through estimation as a part of the segmentation process directly via a temporal prior in to the Level Set Method. Also with using temporal and regional information from neighbouring frames solves leakage problem in border detection process. The proposed method is evaluated on forty-four patients. The results are quantitatively evaluated using different metrics, in comparison with contours manually segmented by a specialist. Experimental results validate the advantages of the proposed method for the intended task and regression between all measured parameters are over r=0.96. We show how our temporal-based hybrid algorithm helps to provides accurate cardiac function analysis.

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Key words: Echocardiography, Segmentation, End-Systole, End-Diastole, Level Set Method, Ejection Fraction, Cardiac Output

1. Introduction

Cardiac function assessment has constantly been an area of interest in medicine. This domain pertains to heart function embracing pumping chambers which regulates systemic and pulmonary circulation systems by delivering blood to areas. As far as subjective evaluation of cardiac function is concerned, it is rather important to fully realize the diagnostic role of contour extraction, as it not only encompasses stroke volume calculation and ejection fraction, but also quantitative assessment of Left Ventricle (LV) motion dynamics in pathology [1].

To typify universal cardiac functions, a significant number of parameters have been investigated to measure End Systole (ES) and End Diastole (ED) volumes, Stroke Volume(SV), Ejection Fraction (EF) ratio, Cardiac Output(CO) and wall thickening, all of which are essential parameters for heart function assessment [2-4]

Generally, contours have been used in important researches aiming at finding an approach to treat echocardiographic endocardial segmentation. On the other hand, studies indicate that more sophisticated techniques are required for LV boundary identification in 2DE images which necessitates proper a priori assumptions and domain knowledge about standard echo images including heart anatomy, morphology, intensity, spatial or temporal information, and even noise features, all of which must be integrated with the system.

Since Echocardiography are often of poor image quality, the boundary dropout is a typical image degradation. The contour is leaked out from the gaps on the boundary, If a boundary is weakened. Dropouts are prone to causing the leakage of the level set curve.

Various complicated algorithms have been proposed for Two Dimensional Echocardiography (2DE) image analysis as in Markov Random Field [5], Optical Flow [6,7],Morphological Filters [8,9], Artificial Neural Networks [10],Multiple Active Contour Model [11-14], and Fuzzy Logic [15].

Accurate Left Ventricle (LV) segmentation during a cardiac cycle provides not only useful quantitative parameters, e.g. ejection fraction, but also qualitative information for certain heart conditions diagnosis.

The proposed method is semi-automatic demanding a single-user intervention to identify the position of Endocardial borders in the first temporal frame of the video sequence. Most of the early work merely focused on single frame segmentation, although what a cardiologist conducts is spotting maximum expansion of LV, named End Diastole, and its maximum contraction. If the ventricular boundary is disrupted by the signal dropout in the current frame, it is possible to reconstruct the missing part by temporal information from neighbouring frames. That way, leakage problem of the Level Set Method can be prevented and no off-line training process is needed [16].

The results are quantitatively assessed using different metrics, compared with contours manually segmented by a specialist and with alternative methods from the literature review.

In addition to End Systole frames, in a whole cardiac cycle, to compute parameters such as ejection fraction, segmented LV boundaries can also be helpful for further quantitative analysis. Eventually, the results of the suggested method were compared with that of a echocardiographic expert.

The order of presenting the paper will include Section II, introducing basic principles of the Level Set Method; Section III, elaborating the proposed method in details as it incorporates the temporal and regional information into the speed term of the Level Set function. Experimental results and concluding remarks are given in Sections IV and V, respectively.

2. Materials & Methods

2.1 Cardiac Cycle

A cardiac cycle encompasses every single event that occurs during a heartbeat. Figure 1 illustrates a typical cardiac cycle. This cycle is of two separate stages, i.e. diastole and systole [17,18].

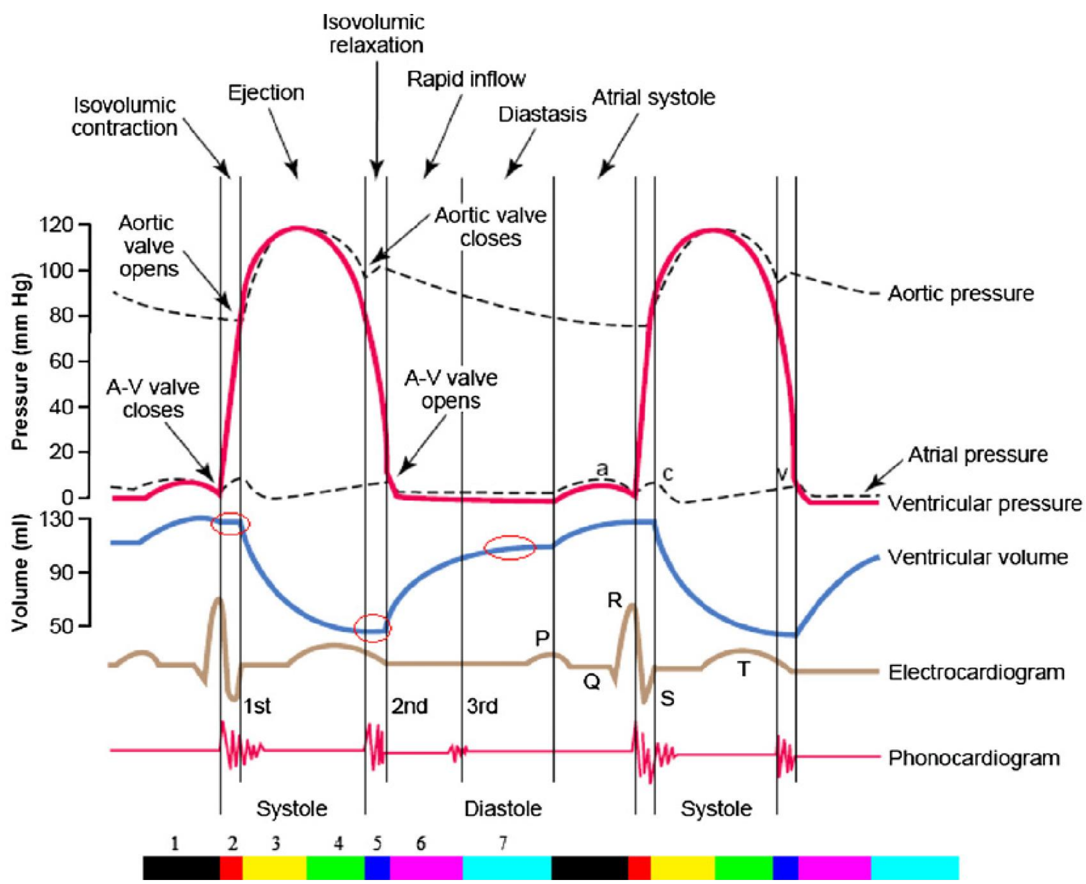


Fig 1 The entire two cardiac cycle diagram, which contains information on aortic, left ventricular and left atrial pressures, along with ventricular volume, heart sounds and the electrocardiogram. Three isovolumic intervals are emphasized by circles in the ventricular volume diagram. The color bar illustrates seven phases of the cardiac cycle (first phase: black, second: red, third: yellow, fourth: green, fifth: blue, sixth: magenta, seventh: cyan) [17].

When the ventricular volume is at its maximum volume- known as the End-Diastolic Volume (EDV)- in the third phase, rapid ejection, blood flows into the aorta and pulmonary arteries rapidly. When the closure of aortic and pulmonic valves occurs and successively ends with the opening of AV valves, this volume is called End-Systolic Volume. On the other hand, there are two steps in a cardiac cycle which has minimum and maximum of ventricular volume diagram in Figure2 [17]

2.2 Data Acquisition

As far as cardiac function assessment by ultrasound is concerned, there are different types of 2D diagnostic views known as Parasternal Short Axis (SAX), Apical Four Chamber (4C), Apical Two Chamber (2C), and Apical Three Chamber (3C). These three views are also called Apical Long Axis (LAX). The quality of images and, hence, the methods of segmentation vary and, mainly, depend on the data set view owing to the angle of ultrasound probe positioning for image acquisition.

The GE Vivid 7 Ultrasound Machinary provided apical two-dimensional gray scale sequences of patients. These data sets are stored in format of AVI, and the Two Chamber Long Axis views were used.

To evaluate the suggested method, the image sequences were visually analyzed by an experienced echo cardiologist and the End-Systolic and End-Diastolic Frames were visually determined, for each of the views.

2.3 Level Set Method

The main steps of the proposed approach are shown in Figure 2. Defining Formula (1), as in Figure 3 a group of closed contours is generated [19] by moving an initial contour towards its Euclidean normal inward vector N.

$$C(p,t)=\{x(p,t),y(p,t)\} \qquad (1)$$

Considering scalar function F and speed of curve movement of curvature, the equation will be as follows:

$$\begin{cases} C_t(p,t)=F(k)N \\ C(p,0)=C_o(p) \end{cases} \qquad (2)$$

In order to solve the partial differential equation, the Level Set Method was innovated by Sethian and Colleagues [20,21] to signify the contour, merely because the zero level set of a flat continuous scalar function is the level set function, where x, y ∈ R2.

At any time t, a contour is calculated as follows:

$$\{C(p,t)=\{x,y|\phi(x,y,t)=0\} \qquad (3)$$

Concerning time and space, derivative of is obtained as follows:

$$\begin{cases} \phi_t=-F(k)|\nabla\phi| \\ \phi(C_o(p),0)=0 \end{cases} \qquad (4)$$

where is a gradient operator and denotes the gradient norm. As a consequence, a group of moving curves is recognized corresponding with the group of evolving level set surfaces. The scalar function is defined based on some image information such as edge or region information.

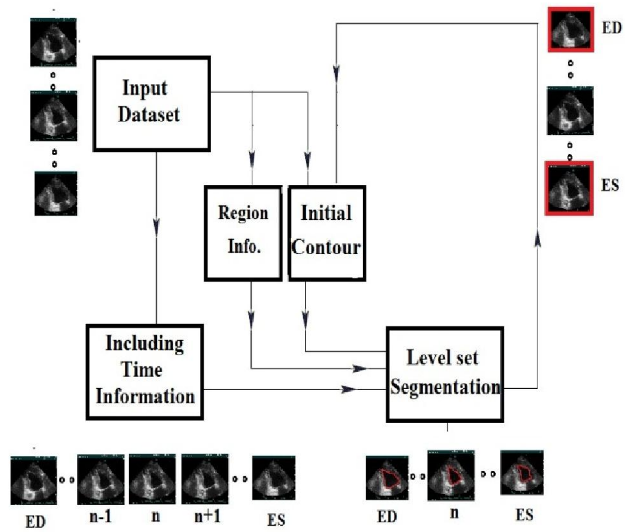


Fig 2 the block diagram of the proposed method

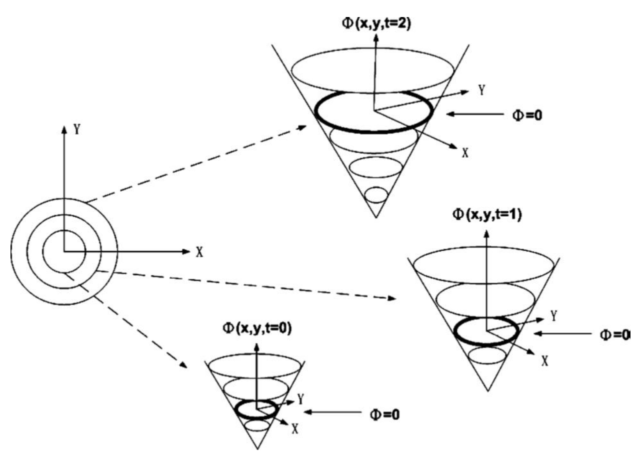


Fig 3 Level set formulation of front motion: the curve γ and the corresponding surface Φ(x,y,t) at different time t [20,21].

2.4 Proposed Method

The proposed method is the combination of region and edge-based information. The Edge-Based Level Set can be expressed as follows [19]:

$$\frac{\partial \phi}{\partial t} = E(x)(\kappa + V_0)|\nabla \phi| + (\nabla E \cdot \nabla \phi) \quad (5)$$

is a stopping term that is obtained from the gradient of the image. Generally, one can assume two different types for this term; and.

We adopted the first one as the stopping term. is the input image and is the Gaussian Filter with variance; besides, is the curvature of the boundary.

The first term in Edge-based Level Set reach zero at the boundary of the LV, while preventing the growth of the boundary length. The second term was included to avoid passing the boundary.

To find the region-based Level Set Model, the energy function should be defined and minimized. Using forces and initial contour, an algorithm is defined iteratively and the final contour is extracted. Suppose boundary divides the space into two regions. The two regions should have uniform intensity while the boundary length should be minimized [20]. The energy function that should be minimized will be described as follows

$$\begin{aligned} &F(c_1, c_2, c) = \mu length c) + \\ &\lambda_I \int_{indide(C)} |I_0(x,y) - c_1|^2 \, dxdy \quad (6) \\ &+ \lambda_I \int_{outdide(C)} |I_0(x,y) - c_2|^2 \, dxdy \end{aligned}$$

c_1 and c_2 are the mean of intensity in inner and outer regions of the contour and $I_0(x,y)$ is the intensity of the image. Contour C is defined by the higher-dimensional function ϕ that has the value of $\phi > 0$ for the inner region and $\phi < 0$ for the outer region. The function ϕ evolves in time by the following differential equation

$$\frac{\partial \phi}{\partial t} = \delta(\phi)\left[\begin{array}{l} \mu div\left(\frac{\nabla \phi}{|\nabla \phi|}\right) - \lambda_1 (I_0 - c_1)^2 + \\ \lambda_2 (I_0 - c_2)^2 \end{array}\right] \quad (7)$$

is the gradient of Level Set Function. is the narrow band around the boundary and the parameters are constant during the iterative method. In each iteration, the value of and is computed using the mean of intensity of pixel in inner and outer region. This method is applied where there are no strong boundaries and, especially when the image has lots of noise.

To obtain better segmentation results and use both edge and region information of the image, the final Level Set Equation is defined as the combination of the equations (5) and (8) which is described as follows

$$\frac{\partial \phi}{\partial t} = \delta(\phi)\left[\begin{array}{l} \mu div\left(\frac{\nabla \phi}{|\nabla \phi|}\right) - \lambda_1 (I_n - c_1)^2 + \\ \lambda_2 (I_n - c_2)^2 \end{array}\right] + \quad (8)$$

$$\alpha\left(\begin{array}{l} E(I_{n-2}, I_{n-1}, I_n, I_{n+1}, I_{n+2}) \\ (\kappa + V_0(I_n))|\nabla \phi| + (\nabla E \cdot \nabla \phi) \end{array}\right)$$

Parameter defines the effect of the Edge-based term. Constant velocity is obtained adaptively using the nth frame of a cardiac cycle. This value is positive when the initial contour is in the inner region of the desired LV boundary and negative when the initial contour is in the outer region of the desired LV boundary.

Moreover, the Block Matching Technique is incorporated to modify the initial contour [21]. To achieve this, a search window is defined around each pixel on the initial contour. All pixels in this window are investigated to find the best match to the central pixel using Mean Squared Error (MSE) criterion.

We extend the method proposed by [21,22] to calculate. The value of it is calculated using the information of previous phases and next phases of the current phase. It regularizes the Level Set Curve to stop at the weak segments instead of leaking out. The steps for computing are as follow:

1- Identifying strong and weak edges; the following steps are performed to identify strong and weak edges:
   a- A region around the initial contour is defined in Figure 5 (a).
   b- The histogram of pixel intensity in the region is computed and a Gaussian Mixture Model (GMM) is fitted to this histogram. As depicted in Figure 4, two thresholds and are extracted [22]. The edge pixels with the intensity between and are the weak edges and the edge pixels with the intensity more than are the strong edges. Figure 5 (b) displays the weak edges of the initial contour.

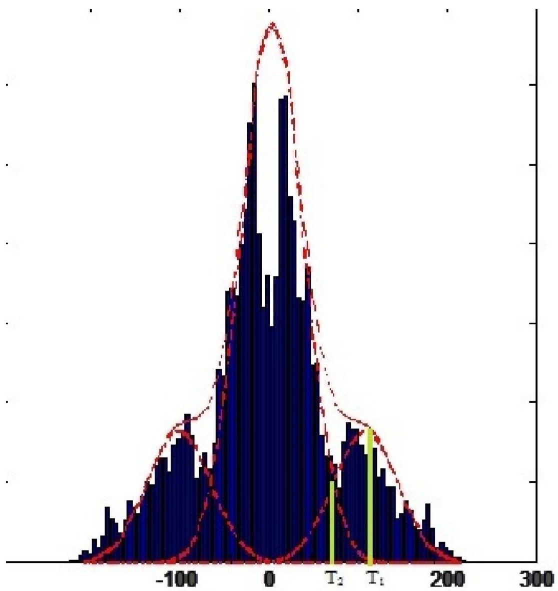


Fig. 4. Histogram of image gradient values and the estimated Gaussian Mixture Model. The Values of T_1 and T_2 is defined on the GMM

2- Incorporating temporal information: The information about the two previous and next frames is utilized to compute for the weak edge pixels, as follows

$$E(x) = \exp\left[-\alpha\begin{pmatrix}\delta_1 E_{image} + \\ (1-\delta_1)E_{temporal}\end{pmatrix}\right] \quad (9)$$

The values of and are defined like the equations presented in [22]. The value of is equal to and the value of is defined as follows

$$E_{temporal} = \left|\nabla\left[\frac{I_{n-2} + 2I_{n-1} + 2I_{n+1} + I_{n+2}}{6}\right]\right| \quad (10)$$

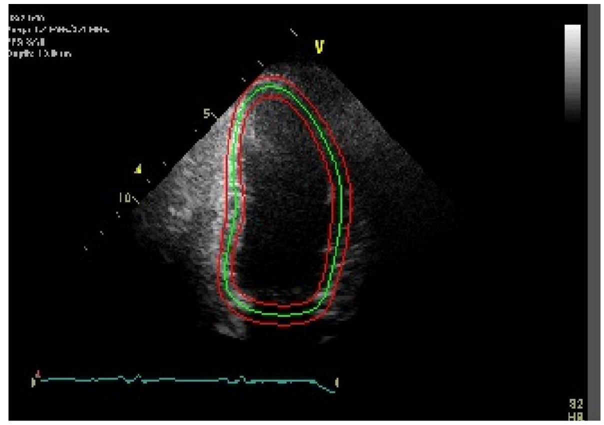


Fig. 5. (a) The points between two red contours are chosen as training data for computing GMM and thresholds T_1 and T_2.

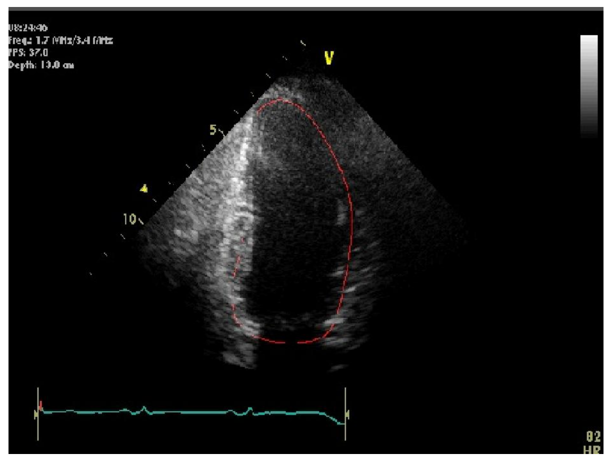


Fig. 5. (b) Red Points in the images are the weak segments on the boundary that need to be reinforced by temporal information

2.5 Proposed Method

In physiology, ejection fraction represents the volumetric fraction of blood pumped out of the ventricle with every heartbeat [23]. Worldwide, echocardiography or cardiac imaging greatly contributes to the thorough study of cardiac performance that can be economically reproduced.

Accurate calculation of CO is indispensable for abnormality diagnosis and well-organized management, as far as clinical method is concerned.

In other words, exact and non-invasive CO measurement must be carried out in every clinical examination which underlines its significance in research in the domain of cardiovascular remedy [24-25].

Stroke Volume (SV) = EDV – ESV

Ejection Fraction (EF) = (SV / EDV) × 100%

Cardiac Output (CO) = SV × HR
12
Heart Rate (HR)= BPM (Beats Per Minute)

Increase or decrease in CO often leads to cardiovascular diseases, hypertension and heart failure, in particular. To assess the accuracy of results, a number of metrics are applied, the first of which is absolute error and relative absolute error that compute errors of parameters from the extracted boundary and the ground truth.

Given the certain value and its approximation, an absolute error is calculated as follows:

$$\varepsilon = \left|\upsilon - \upsilon_{approx}\right| \qquad (11)$$

If $\upsilon \neq 0$, then a relative error is

$$\eta = \frac{\left|\upsilon - \upsilon_{approx}\right|}{\left|\upsilon\right|} = \frac{\left|\upsilon - \upsilon_{approx}\right|}{\upsilon} = \left|1 - \frac{\left|\upsilon_{approx}\right|}{\upsilon}\right| \qquad (12)$$

Statistically speaking, the Mean Squared Error (MSE) is one way to assess the differences among values cited by an estimator and the true values of the quantity being estimated [25]. An error is the amount by which the value quoted by an estimator differs from the quantity to be estimated. Such differences occur due to random selection.

The MSE of an estimator concerning the estimated parameter is defined as

$$MSE(\hat{\theta}) = E\left[(\theta - \theta)^2\right] \qquad (13)$$

The Mean Absolute Error (MAE) is a criterion for precise predictions of final results. In fact, MAE is the average of absolute errors [26]. It is a common measure to predict errors in time series analysis which is computed as

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|f_i - y_i\right| = \frac{1}{n}\sum_{i=1}^{n}\left|e_i\right| \qquad (14)$$

3. Results

To implement the suggested method on each case, three cardiac cycles were considered. Figure 6 illustrates the results of the study during heart contraction and relaxation period, respectively.

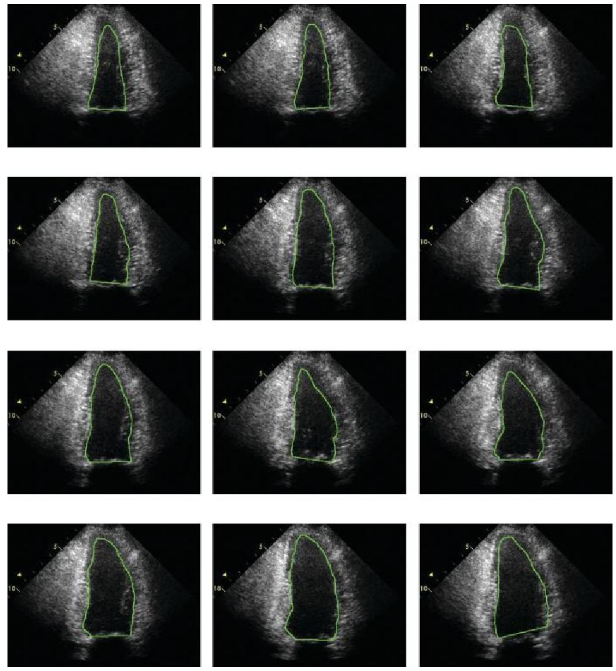


Fig 6 show the results of our proposed method for a one cardiac cycle for a random case in the heart contraction and relaxation period

In addition, figuring out how LV evolves throughout an entire cardiac cycle permits physicians to determine the health of myocardial muscles. Left Ventricle volume change during a cardiac cycle which is illustrated in Figure 7 using proposed method for segment all frames in one cardiac cycle.

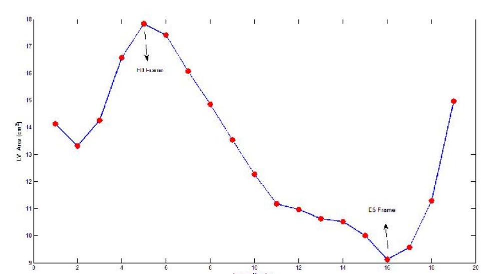
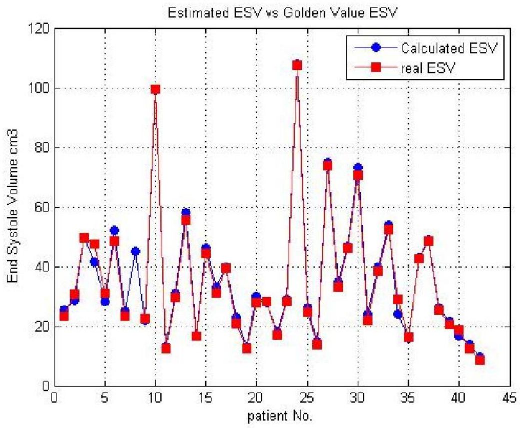


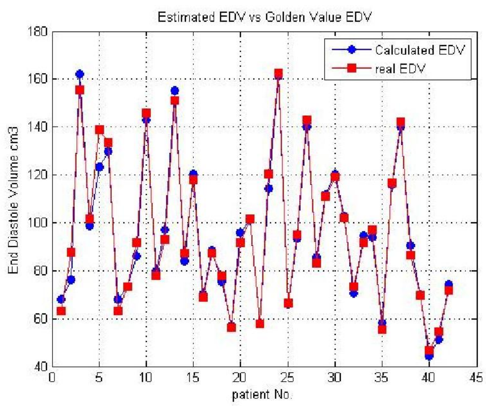
Fig 7 left ventricle volume changes for all frames in cardiac cycle of a random case using proposed method

The results obtained from this method were validated with that of experienced echo cardiologist (Golden Standard) on 44 patients. To conduct statistical analysis, Regression and P-value was calculated using EF obtained with the reference to visual reading, and that of automatically estimated using the suggested method. The results depict the usefulness of the presented method.

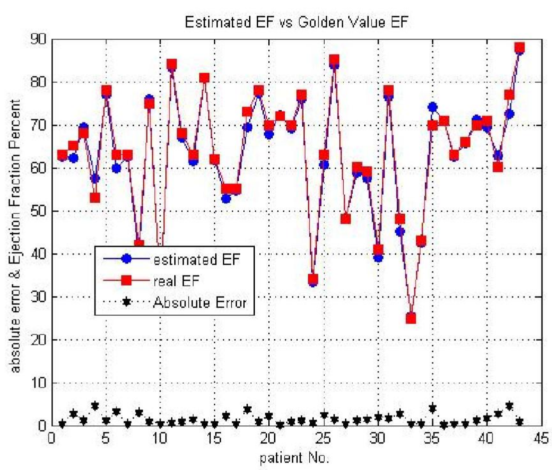
In Figure 8 all measured parameters compared with ground truth and related error for EF measurements are displayed. Figure 9 indicates the mean absolute error, Euclidean distance between estimated EF and ground truth EF.



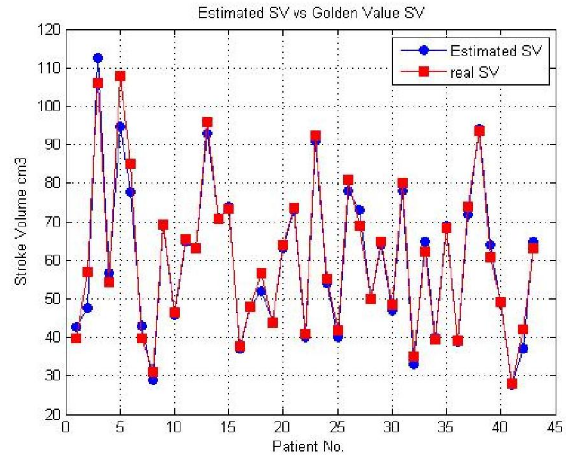
1) EF



2) EDV



3) ESV



4) SV

Fig 8 comparison for all measured parameters and ground truth for all cases.1) EF, 2) EDV, 3) ESV, 4) SV.

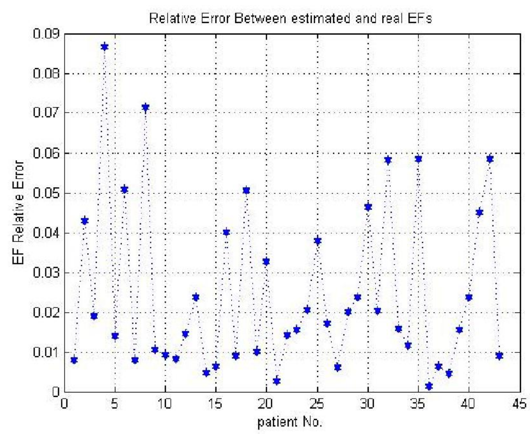


Fig 9 (a) Relative error between estimated EF and ground truth EF for all examined cases.

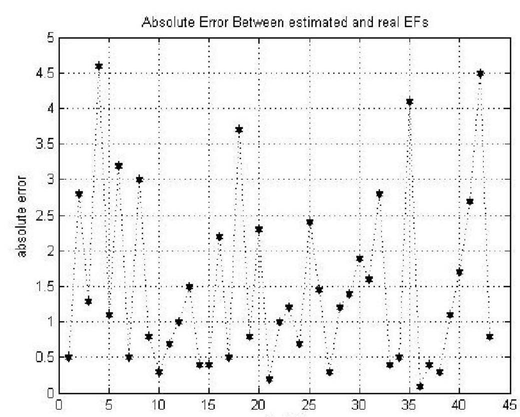


Fig 9 (b) absolute error between estimated EF and ground truth EF for all examined cases.

4. Discussion

Having experiments carried out while comparing the results with the ground truth, it was proven the suggested method effectively prevents automatic detection of cardiac borders and contributes to more efficient detection in comparison with other approaches without imposing the burden of calculation.

This method is not only cost effective, but also effortlessly applied in such a way that any ambiguity resulted from the human assessment is fortunately overcomed. Consequently, this method has its potentials and efficient for the intended tasks.

Due to noisy temperament of echocardiography images, the assessement of cardiac function via other analogous methods is truly problematic. Similarly, the results indicate that the suggested method is applicable for normal and abnormal cases.

It has been observed that such a method provides far more accurate segmentations during shorter period of time compared with other approaches, especially once the observed data are of limited quality.

We should evaluate our tasks based on all cardiac echocardiography views within all age range of patients. There is no limitation to extent proposed method and develop an approach based on 3D echocardiography that has lately been warmly welcomed by the Cardiology Community.

5. Conclusion

The results of the suggested method demonstrate its strong potential in analyzing data in sets of echocardiography images. Adopting this method, we reduce the time of segmention process while attaining more accurate results.We maintain that the dedicated segmentation approaches will open a new horizon in analyzing the medical images and echocardiography images, in particular.

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