A Novel Model-Based Approach to Left Ventricle Segmentation

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Abstract

In this paper a parametric model of the left ventricle is presented, whose task is to improve the segmentation results obtained by the use of standard algorithms. An individual model is built on the basis of properly designated sections. Incorrectly designated sections should be replaced with ellipses evaluated using the presented model. While elaborating the model a database has been used consisting of cardiac images delineated by experts. The model is based on parametric curves and regression analysis. A segmentation algorithm based on the Kernelized Weighted C-Means clustering and automatic segmentation correctness coefficients has been proposed. Eventually the model should also work with other segmentation algorithm. By improving the segmentation results with the model, the error has been reduced from a clinically unacceptable to the interobserver variability. The model is most useful while assessing the epicardium at end-systole and the heart weight.

1. Introduction

An important and difficult step of image diagnostics is the segmentation of anatomical structures and pathological lesions. A frequent problem occurring in dynamic tests are hazy outlines of individual structures. This phenomenon, observed among others in heart diagnostics, reduces the probability of or even prevents proper outlining the entire organ.

Magnetic resonance imaging enables the assessment of cardiac functions in a noninvasive manner [1]. In contrast to echocardiography or computed tomography it is not dependent on the axis along which the following sections of the organ are registered. Due to this it is a source of accurate data on the volume and mass of the left ventricle [2, 3].

Popular segmentation algorithms tend to oversegment cardiac magnetic resonance images. Trying to avoid this problem, however, results in the appearance of undersegmented areas. Methods adapted to a particular type of data do not often yield good results if any of the images parameters changes (e.g. a different imaging camera). The methods, usually used and evaluated in practical heart segmentation applications, are nowadays semi-automatic.

The methods commonly used in image processing are mathematical morphology operations. They are used among others in [4]. A semi-automatic method based on regions of interest hyperplasia is presented in [5]. Other examples of semi-automatic algorithms, in which mathematical morphology methods have been used to determine the contours of the left ventricle, can be found in [6–8]. Automatic segmentation of the left ventricle can also be based on active contours [9, 10].

Experts are not unanimous about the fact whether when calculating the volume of the heart ventricle, the papillary muscles should be considered or the ventricle volume occupied by them should be subtracted from the total volume. In response to this apparent dilemma a segmentation method of the left ventricle is proposed in [11], treating the papillary muscles dependently on the user's preferences.

Another group of algorithms is a set of methods, in which on the basis of previous image analysis of healthy and pathological organs a model of the whole heart or just of the left ventricle is constructed. An important issue here is the problem of selecting the algorithm, which best fits the model to the segmented structures. Considering methods of structures segmentation from medical images developed so far, it should be noticed that they comprise two main tasks: locating the elements of the object and determining its contours. The algorithms using predefined models perform both these tasks simultaneously by minimizing the energy function, containing the internal force (recognition) and external force components(contour).

Such a model is presented in [12]. The user's task is to preliminary fit the model to the data (properly but not necessarily absolutely exactly). Then, the model is stretched from the inside towards the edge of the image. Using the Finite Element Method the steady-state model is calculated, which is being pursued at the moment the energy of the model is minimized. A developement of [12] is [13] in which a non-linear model was introduced, called Deformable Elastic Template (DET).

A very popular technique of heart shape modelling is the so-called Point Distribution Model (PDM) also known as Active Shape Models (ASM) [14, 15]. Another yet similar approach is the Active Appearance Model (AAM) [16, 17].

It is worth noticing that methods completely free of the need of medical intervention, hence better from the user's point of view, usually segment the desired structures with less accuracy than methods initialized or even fully supervised by a specialist, which is a source of relevant errors, affecting the diagnosis [18]. The solution to this problem can be a model of the left ventricle, described in this paper, whose task is to estimate the shape of the heart muscle where the segmentation algorithm incorrectly sketched the outline of the structure. Replacing the improperly designated shape by an ellipse, whose parameters and position are calculated using the model, results in the improvement of the quality of cardiac health condition assessment. Using the model on incorrectly segmented sections should improve the accuracy of the calculated haemodynamic parameters of the heart. The proposed model will work with any segmentation algorithm.

2. Methods

In this paper a parametric model of the left ventricle is presented. The task of the model is to improve the segmentation results, obtained using standard algorithms. First, the correctly evaluated sections should be selected and they should serve as a basis for building the individual model of the left ventricle. Secondly, the improperly outlined sections should be replaced with ellipses calculated using the presented model.

While constructing the model, a database of images delineated by experts has been used. Into expert outlines ellipses have been inscribed and analysed. First, dependencies between the parameters of these ellipses have been found and then approximated using Bézier curves of degree 2 or linear regression. As a result a set of parameters, describing ellipses dedicated to each slice, common for the whole training series, is obtained.

To assess the usefulness of the model, first the left ventricle segmentation algorithm had to be chosen. The proposed segmentation algorithm is based on the Kernelized Weighted C-Means clustering (KWCM, [19]). The KWCM clustering is a space dividing method, defined by distribution matrix U which is the fixed point of a particular transformation under certain assumptions. The number of groups can be either fixed or each time assessed based on special conditions. The developed segmentation algorithm is fully automatic [20]. It enables the automation of heart condition assessment. Four combinations of the heart walls (epicardium and endocardium) and the phases of the cardiac cycle (end-diastole and end-systole) are computed separately. Nevertheless, the presented model of the left ventricle works with any method determining the contours of myocardium.

The automation of the segmentation of left ventricular structures entails the possibility of occuring errors. Often there are oversegmented or undersegmented elements. Endocardium and epicardium segmentation correctness coefficients have been defined, whose values determine the need to replace particular heart contours. The proposed segmentation correctness coefficients enable the selection (without user intervention) of sections incorrectly delineated by the algorithm. The areas of the contours on consecutive sections have been compared (Fig. 1). If the area of the segmented structure, which did not appear on the previous section, exceeded a threshold value, the contour was classified as incorrect. All sections are therefore divided in terms of the correctness of the carried out segmentation.

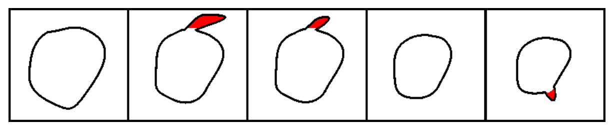

Figure 1. The segmentation correctness coefficients are calculated on the basis of the areas marked in red

The improperly segmented contours are replaced with ellipses, whose parameters are calculated on the basis of the previously obtained set.

The results improvement is achieved through the inclusion of real data. All estimated values are interpolated and extrapolated on the basis of the coefficients of ellipses, inscribed in the correctly outlined contours, independently of the described algorithm . The values of ellipses rotation angles are obtained only by interpolation and extrapolation. The final values of the ellipses parameters are affine combinations of the values obtained using the proposed model and the interpolated and extrapolated values.

3. Results

The parameters of the described model were chosen on the basis of a series of cardiac 4D MR images. To estimate the model parameters, images from Cedars-Sinai Medical Center (CSMC, Los Angeles, CA, containing 2 series of cardiac magnetic resonance images with expert outlines) and a web-accessible database ([21], containing series of cardiac magnetic resonance images of 18 people) were used. The outlines of the left ventricle from the internet base were made by two independent experts. 10 studies (2 from CSMC and 8 from the internet base) formed the training set, while the remaining 10 studies served as a test base. Each series belonging to the test set consisted of 22 or 25 3D images, on which at least one full cardiac cycle has been recorded. The number of heart sections in the series ranged from 24 to 44, which yielded a total of 312 sections. Ellipses have been inscribed into the designated areas. Their analysis has lead to determining the values of the model parameters. The model verification was performed using the test database.

The choice of threshold values of the segmentation correctness coefficients has been performed on the basis of the comparison of the areas outlined by the experts and resulting from the segmentation. A consultation with a specialist helped establish that the difference of these areas at the level of 10% has no diagnostic significance in the analysis of cardiac haemodynamic parameters; this value has been therefore the basis for defining the boundary between the sections with correct and incorrect segmentation.

While examining the usefulness and the accuracy of the model, the surface areas of endocardium and epicardium at end-diastole and end-systole obtained only by using the segmentation algorithm and with the improvement contributed by the model have been compared with the results calculated for the expert contours.

Linear correlation coefficients between the results obtained with different methods (first expert, second expert, segmentation, model-improved segmentation) have been studied and the relative error, expressed in percents, has been calculated referring to both experts. Furthermore, the interobserver variability for the two specialists has also been calculated.

The use of the model has improved the results of determining the contours of epicardium to a large extent. In case of the endocardium the results diferrences arising from the use of the model have been smaller. The reason for this is the fact that because of the high-contrast between the ventricle interior and the myocardium the segmentation of the endocardium usually has not required any correction. The issue of designation of the contours of the myocardial outer wall is not well realized by common segmentation algorithms, therefore, through the use of the model the epicardium outlines have undergone significant improvement (Fig. 2-3). In case of the epicardium the relative error has not exceeded 10%, while the segmentation error for the epicardium at end-diastole corrected by using the model was less than 6%. Besides the endocardium at end-systole the obtained relative errors are comparable to the interobserver variability.

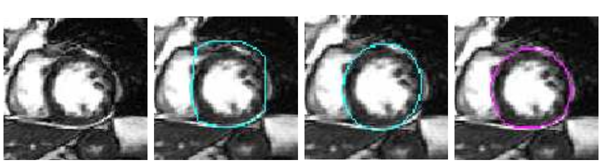

Figure 2. Epicardium at end-diastole: a) original image b) segmentation result c) model-improved segmentation result d) expert's outline

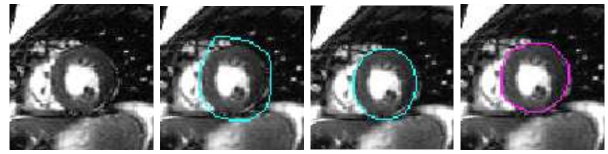

Figure 3. Epicardium at end-systole: a) original image b) segmentation result c) model-improved segmentation result d) expert's outline

The haemodynamic parameters and the heart weight have been compared with the golden standard obtained from the expert delineations. The estimation of heart mass has significantly improved after the application of the model — the relative error has decreased from 28% to 10% and from 23% to 11%, respectively, for the two experts. The ejection fraction and the stroke volume have not been corrected to a comparably high extent. In case of stroke volume estimation the average interobserver error was 8%, whereas the algorithm relative errors were 13.5% and 16%, respectively, for the first and second expert. The interobserver ejection fraction error was 7% while the relative errors for both experts were 12.5% and 15.5%, respectively. Nevertheless, despite the fact that there has been noimprovement for all of the studies, the average relative error has been raised by no more than 0.1%. The reasons for this are, as before, very good segmentation of the endocardium and correction requiring epicardium segmentation. Regardless of the myocardium wall the results of proposed segmentation supported by the model have not differed significantly from the expert ones.

It should be emphasized that in those cases where the application of the model has not improved the segmentation results, it has not worsened them significantly (the maximum deterioration is the increase of the relative error from 5% to 7%).

The number of sections replaced using the model referred to the number of correctly segmented contours of the left ventricle has also been evaluated. In case of endocardium only a few contours have been substituted — less than 2% and less than 4% of all sections at end-diastole and end-systole, respectively. For the epicardium the adequate values are 28.2% at end-diastole and 38.5% at end-systole.

4. Discussion and conclusions

On the basis of the training set the model parameters have been determined. Having at the disposal the endocardium and epicardium contours delineated by two independent experts, the segmentation results and cardiac haemodynamic parameters obtained using the pure segmentation algorithm and the model-corrected segmentation have been compared. The usefulness of the model is the greatest when calculating the epicardium and the heart weight. The error of heart parameters estimation, calculated for the segmentation revised using the proposed model, is clinically acceptable, whereas, without the use of the model, the errors exceed the accepted limits for the epicardium at end-systole and the heart weight. The presented model can operate with any segmentation algorithm.

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