MYOCARDIAL BORDER TRACKING IN M-MODE ECHOCARDIOGRAMS USING JOINT PROCESS ESTIMATION

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A sequential approach for the detection of myocardial borders in M-mode echocardiograms is introduced. Initial border estimates are obtained from a cross-correlation detector. They are then improved by an adaptive lattice form joint process predictor. Alternatively, a physiological constraint is used to improve the detection of the endocardium during systole. A least squares algorithm is proposed to update recursively the correlation templates in order to track their temporal variations.

Introduction

M-mode echography refers to a time sequence of one-dimensional signals locating anatomic structures from their echoes along a fixed axis of emission. Various computer-assisted procedures have been proposed to detect automatically left ventricular structures in M-mode echocardiography [1,2]. Recently, we have proposed a robust procedure (DPA)[3] based on template matching and dynamic programming which determines optimal trajectories according to global cost criterion.

A new sequential approach is presented in this paper. The essential feature of this new approach is that the border templates are modified adaptively after each estimation and correlative information is used to improve the estimation of certain borders difficult to detect correctly.

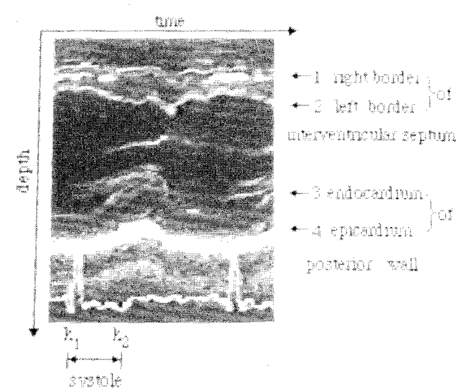

Fig. 1 : Example of M-mode echocardiogram with the definition of myocardial structures.

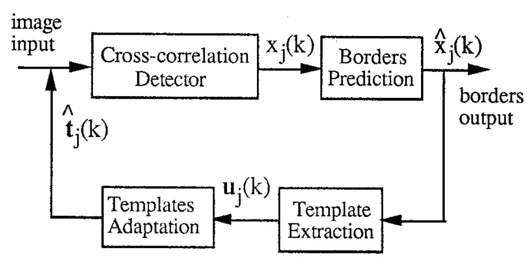

Fig. 2 : Sequential cardiac border detection system for M-mode echocardiograms.

The system is summarized by the block diagram in Fig. 2. The starting points of the myocardial borders are specified initially and serve to initialize the templates used for matched filtering. The border point in a time frame is determined from the local maximum of cross-correlation coefficients between this time frame and the border template in a region around the predicted border point. These preliminary position observations are then filtered

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adaptively by a joint process filter. A physiological constraint is also used in detecting the endocardium during systolic phase to reduce the influence of irrelevant echoes. The correlation templates are modified with the corresponding border profiles in this time frame in order to track their temporal variations. The final estimation of the border position is then used as the starting point for the next time frame and the whole procedure is repeated sequentially.

Corrections of Borders Estimation

The initial border points extracted by template matching are often inaccurate. It is therefore highly desirable to improve their location, not only to have a good estimation of border positions, but also to have a good starting point for the detection in the remaining time frames. Obviously, there is a dependance between the movements of the four cardiac borders, especially for the septum border pair and posterior wall border pair. So we have proposed the following models of the displacement of the borders:

A) Correlative model

$$x_j(k)=\sum_{i=1}^{N_j} a_j(i)x_{j+1}(k-i)+n_j(k), \qquad (j=1,3)$$

$$x_j(k)=\sum_{i=1}^{N_j} a_j(i)x_j(k-i)+n_j(k), \qquad (j=2,4)$$

where N is the model order, $n_j(k)$ the additive noise, and a_j are the model parameters to be estimated. The positions of the myocardial borders are denoted by $\{xj(k),k=1,...K\},j=1...4$. The subscript j sequences correspond to the right and left borders of the interventricular septum, the endocardium, and the epicardium, respectively (c.f. Fig. 1). Generally, the epicardium and the left septal border are easier to detect [2,3]. So we take them as the reference inputs and we use the others two borders as the principal inputs. This model use the past border estimations to predict the actual border position under the assumption that the residual noises have zero mean. Considering the non-stationarity of the signal processes, an adaptive lattice form joint process filter was applied to the processing of the septum and the wall border pairs simultaneously[4,5]. The filter predicts two signals at the same time and the parameters concerning their structures propagate within the filter recursively. The criterion autoregressive transfer (CAT) function which minimizes the difference between the true prediction error filter and the estimated filter was used to select an adequate order for the signal models[6].

B. Wall thickness/cavity diameter relationship

During systole, the detection of the endocardium is made more difficult due to the presence of others uninteresting structures in its vicinity. We have to introduce some *a priori* knowledges about the anatomy of the left ventricle. Fortunately, a good linearity between the ventricular diameter and the posterior wall thickness was found during systole[7,8]. Defining T as the wall thickness and D as the ventricular diameter, the following linear relationship was found during systolic phase

$$T(k) \cong \alpha D(k)+\beta, \quad (k=k_1,....k_2)$$

where k_1 and k_2 are the time indices corresponding to the beginning (telediastole) and end (telesystole) of the contraction. Unlike the correlative model, this model is time-invariant but is only valid in systole. The model parameters α,β are determined using a standard linear least squares procedure. Supposing that the corrected estimations of the left septal border and the epicardium are sufficiently accurate, we use them for the prediction of the endocardium with the following predictor:

$$\hat{x}_3(k) = \frac{\alpha\hat{x}_2(k)+\hat{x}_4(k)-\beta}{\alpha+1}, \quad (k=k_1,....k_2)$$

Adaptive Template Modification

The pattern of the cardiac structures visualized in echocardiograms is unstable during a cardiac cycle. To account for their variation, we have designed an adaptive algorithm which modifies the border templates in terms of the actual pattern in the current time frame.

Let $\mathbf{u}(k)$ denote the M-dimensional template vector obtained from the border profile centered on the currently detected border position and $\hat{\mathbf{t}}(k-1)$ the template used for the previous detection. The new template vector $\hat{\mathbf{t}}(k)$ is computed from the linear combination :

$$\hat{\mathbf{t}}(k)=\gamma\,\hat{\mathbf{t}}(k-1) + (1-\gamma)\,\mathbf{u}(k)$$

where the weighting coefficient (or forgetting factor) γ is determined as

$$\gamma= \frac{M\sigma^2}{||\mathbf{u}(k) - \hat{\mathbf{t}}(k-1)||^2}$$

and where σ^2 is the noise variance. The principle underlying this procedure is to minimize the error between the template estimate $\hat{\mathbf{t}}(k)$ and an hypothetical noise free template $\mathbf{t}(k)$. This updated template will then be cross-correlated with the next time frame to provide an initial estimate of the border position.

Results

Fig. 3 show some results of the cardiac borders tracking. Fig. 3-a displays the myocardial borders that were manually traced by an experienced cardiologist and that we used as the reference to evaluate the border detection algorithms. Fig. 3-b presents the results of borders detection using DPA. Below are the results corresponding to the sequential adaptive approaches. On the left, the border templates are fixed, so they do not track myocardial pattern variations. And on the right, we update the border templates recursively to account for their temporal variations. We can find that the template adaptation improves the detection quality, especially for the two borders difficult to detect.

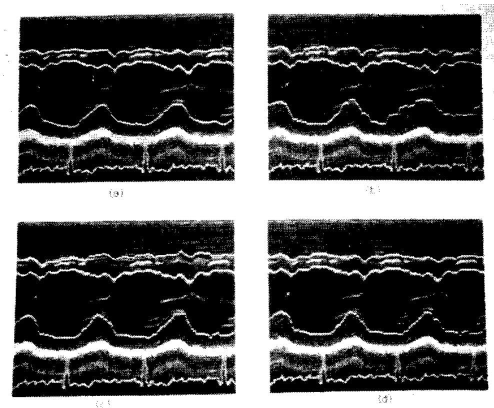

Fig. 3 : Processing example. (a) M-mode echocardiogram with borders traced by a cardiologist; (b) results of border detection using the DPA; (c) results of border detection using the present method without template adaptation; (d) results of border detection using the present method with template adaptation.

The detection of left septal border and epicardium is relatively easy and the improvement obtained by lattice filtering is not very important. On the other hand, this adaptive filter does have an obvious effect on the detection of the two others cardiac borders. For instance, there is sometimes a bright line near the right septal border between the left and right septal borders, it seriously disturbs the DPA detection of the latter structure. With the joint process filter, the influence of this bright line is almost eliminated. The detection procedure used in figure 3-c and 3-d makes use of some *a priori* knowledge (i.e. the linearity between the cavity diameter and wall thickness) and is capable of delineating correctly the endocardium during systole.

Table I presents an index *e* which evaluates the performance of the different algorithms by reference to the tracing of the cardiologist and it validates what we do in our algorithm.

Algorithm description	Right Septal Edge	Left Septal Edge	Endocardial Edge	Epicardial Edge
Dynamic programming border detection :				
($\underline{a}$, $\underline{b}$, $\underline{c}$)	e=1.363	e=0.866	e=6.472	e=1.170
Sequential border detection :				
($\underline{a}$, $\underline{b}$, $\underline{c}$)	e=2.944	e=1.811	e=13.46	e=1.648
($\underline{a}$, $\underline{b}$, c)	"	"	e=0.559	"
(a, $\underline{b}$, $\underline{c}$)	e=1.619	e=0.851	e=7.432	e=1.175
($\underline{a}$, b, $\underline{c}$)	e=1.708	e=0.859	e=6.204	e=1.324
(a, b, c)	e=0.711	e=0.794	e=0.262	e=1.749

Processing options :
- a : adaptive templates — $\underline{a}$: fixed templates
- b : joint process — $\underline{b}$: no joint process
- c : physiological constraints — $\underline{c}$: no physiological constraints

Conclusion

A sequential approach for the automatic detection of cardiac structures in M-mode echocardiograms has been presented. Our results are quite encouraging and we believe that this method could be useful in other signal processing applications.

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