EXAMINATION OF LEFT HEART VENTRICLE'S CONTRACTILITY BY ANALYSIS OF ITS SHAPE COEFFICIENTS

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Abstract: A method of left heart ventricles' contractility assessment based on computer aided analysis of sequences of *USG* cardiac images is presented. It is based on a formal model of left heart ventricle's shape time-variations given in the form of double trigonometric series with time-dependent coefficients called decremental shape coefficients. The decremental shape coefficients are automatically extracted from the sequence of cardiac images under consideration. The behaviour of decremental shape coefficients as time-series is then examined. The aim of examination is detection of typical left heart ventricle's contractility disorders like cardiac akinesis, hypokinesis or diskinesis. There are presented the results of experiments showing the distances between the time-series of decremental shape coefficients in normal patients and in patients with different types of left cardiac ventricle's contractility disorders. The results have shown that the decremental shape coefficients contain, in general, information which can be used effectively in this type of cardiac diagnosis.

Introduction

The left heart ventricle's (*LHV*) contraction is a dynamic process of composite bio-chemo-electro-mechanical nature whose kinetic effects are observable in the time-sequences of cardiac images. Modern medical imaging methods make it possible to observe living heart in real time and to analyze various aspects of its action in quasi-real time. In particular, the *ultrasonographic* (*USG*) imaging modality gives us an opportunity of registering series of imaging snapshots showing heart in consecutive states of its evolution cycle and then using them for a deep examination of heart ventricles' contraction process. The *USG* cardiac imaging modality can be preferred due to its low cost and non-invasiveness. Technical aspects of such examination have been described in several publications [2,3,98]. In the present paper the problems of using of so earned information in cardiac diagnosis is described, special attention being paid to the left heart ventricle's contractility in norm and in pathology. At any fixed time-instant a current form of the *LHV* can be approximately represented by contours corresponding to several projections [6]. In practice, very often a single *2D* (planar four chamber apical) projection for hemodynamical parameters assessment is used. A formal model used in our works in three points differs from the *LHV* shape models described in literature [1,4,9]: 1st at any fixed time-instant it can be better adjusted to the real *LHV*'s form, 2nd it describes the *LHV*'s contraction process within a full heart evolution cycle, and 3rd it can be used in the case of a single or of several *2D* heart projections being available for examination. Till now, the last point is of low importance in medical practice, because reconstruction of a *3D LHV*'s shape on the basis of several *2D* projections needs more effort from the medical staff. However, a deep examination of *LHV*'s contractility disorders should be based on a more complete *3D* information about the heart contraction process, not only the one obtained by an extrapolation of single *2D* projections.

The model used in our works has the form of a function describing the length of a vector plotted between a fixed center and current points on the ventricle's inner surface. This function, represented by a trigonometric series, is periodic with respect to the azimuth and elevation angles; the coefficients of the series, called *shape coefficients*, contain full information about the current shape of the ventricle under examination. It is assumed that the shape coefficients are time-varying within the heart evolution cycle and those variations can be examined due to the fact that the captured *USG* images correspond to consecutive heart evolution states (this would be not possible if the images are reconstructed on the basis of data collected within longer time-intervals). For heart contractility examination a series of images covering at least one heart evolution cycle is needed. In fact, not absolute values but the differences between the current shapes and the extreme diastolic shape of the ventricle are taken into account. So defined, a *decremental function* is also periodic with respect to the azimuth and elevation angles and it is represented by a series of *decremental shape coefficients*. In addition, its time-periodicity corresponding to the heart evolution cycles is also assumed and, thus, any decremental shape coefficient is represented by a periodic time series. The set of such time series contain full information about the time-variations of the ventricle's form. In practice, taking into account of no more than 6 – 12 shape coefficients is sufficient for examination of the left heart ventricle's contractility process. Each of the basic (i.e.

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lower level) shape coefficients has an easy interpretable geometrical sense. In particular, they make us able to detect such contraction abnormalities as cardiac *akinesis*, *diskinesis* or *hypokinesis* with their anatomic localization on the ventricle's wall and in the phase of the heart cycle. In order to make the results of contractility analysis independent on the ventricle's volume the time-series can be normalized, as it will be shown below. The possibility of discrimination between normal and pathological *LHV*'s contraction was observed on real clinical data and the correctness of this discrimination has been proven by comparison with the statements of medical specialists.

The aim of this paper is presentation of a *LHV*'s contractility assessment method based on sequences of cardiac *USG* images analyzed using the corresponding formal model and software tools.

Materials and Methods

A. Experimental data

There were used, in our investigations, sequences of cardiac *USG* images in standard 2- and 4-chamber apical projections. Each sequence consisted of at least 22 snapshots covering a full heart evolution cycle. The images were acquired by experienced radiologists within routine examinations of patients with various cardiac disorders, 22 of them being diagnosed as suffering from *LHV*'s contractility abnormalities. The images were delivered in digital form with medical description. They were entered into an image processing system based on a standard PC equipped with Image Pro Plus (Media Cybernetics) software for basic image processing and a library of original procedures for advanced image processing written in C++. The library is, in fact, an extension of a former DIAVENT system implementing the method of *LHV*'s action assessment based on functional models describing *LHV*'s shape and its time-variations [4]. A kinetic version of the model has been adapted to the purposes of examination of *LHV*'s contractility disorders, as will be shown below.

B. Model properties

The time-variations of the *LHV*'s shape can be represented by a difference between the extreme diastolic and a current shape. Assuming that each sequence of images starts from the extreme diastole, it will be taken into consideration a *decrement function*:

$$\Delta r[P(\alpha, \varepsilon);t] \equiv \Delta(\alpha, \varepsilon; t) \equiv \equiv r[P_0(\alpha, \varepsilon);0] - r[P(\alpha, \varepsilon);t] \qquad (1)$$

representing current decrements of the point $P(\alpha, \varepsilon)$ distance to the center of co-ordinates O with respect to this in the initial position $P_0(\alpha,\varepsilon)$.

Here α denotes the azimuth angle and ε - the elevation angle in polar coordinates, as shown in Fig. 1. The direction $\alpha = 0$ indicates on the center of mitral valve, while $\alpha = \pi$ is directed to the heart apex. The value $\varepsilon = 0$ fixes a basic plane corresponding to the four-chamber cardiac projection. The current time t is assumed to be discrete; in practice it is identified with a current snapshot's number starting from $t = 0$ for the extreme diastolic heart state. Therefore, the sequences of values $\Delta(\alpha, \varepsilon; t)$ for $t = 1,2,\ldots,T$ form finite time-series, where T denotes the length of a heart cycle: for most cases it is $T \cong 22$.

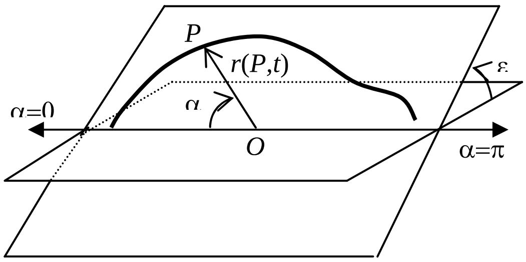

Figure 1: The system of polar coordinates

The decrement function is then represented in the form of a double trigonometric series:

$$\Delta(\alpha,\varepsilon;t) = \sum_{m=0}^{M}\sum_{n=0}^{N}[\Delta a_{m,n}(t)\cdot \sin m\alpha \cdot \sin n\varepsilon + \Delta b_{m,n}(t)\cdot \sin m\alpha \cdot \cos n\varepsilon + \Delta d_{m,n}(t)\cdot \cos m\alpha \cdot \cos n\varepsilon] \qquad (2)$$

within the angular intervals $0 \le \alpha < 2\pi$, $-\pi/2 \le \varepsilon < \pi/2$, where

$$\begin{aligned}\Delta a_{m,n}(t) &\equiv a_{m,n}(0) - a_{m,n}(t),\\ \Delta b_{m,n}(t) &\equiv b_{m,n}(0) - b_{m,n}(t),\\ \Delta d_{m,n}(t) &\equiv d_{m,n}(0) - d_{m,n}(t),\end{aligned} \qquad (3)$$

and $a_{m,n}(t)$, $b_{m,n}(t)$, $d_{m,n}(t)$ denote the primary shape coefficients obtained as a result of computer analysis of cardiac image sequences (see [8]).

The decrement function $\Delta(\alpha,\varepsilon;t)$ should satisfy several sets of formal constraints (similar to those imposed on the primary static model described in [6]:

1) due to the properties of trigonometric functions it should be $\Delta a_{0,n}(t) = \Delta a_{m,0}(t) = \Delta b_{0,n}(t) \equiv 0$ for any m, n, y;

2) due to the requirement that for any fixed t the length of the ventricle can not depend on ε, there should be $\Delta d_{m,n}(t) \equiv 0$ for any $n > 0$; for similar reason no terms of the type $\cos m\alpha{\cdot}\sin n\varepsilon$ occur in expression (2);

3) a continuity requirement that for any α, t and $\delta > 0$ it should be

$$\Delta(\alpha,\pi/2-\delta; t) \cong \Delta(2\pi-\alpha,\delta-\pi/2; t), \qquad (4)$$

4) the equality becoming strong when $\delta \to 0$, leads to the condition that all terms of the type $\sin m\alpha\cdot \cos n\varepsilon$ should vanish for any even n;

5) according to the expressions (3) there should be $\Delta(\alpha, \varepsilon; 0) = \Delta a_{m,n}(0) = \Delta b_{m,n}(0) = \Delta d_m(0) \equiv 0$.

The model coefficients $\Delta a_{m,n}(t)$, $\Delta b_{m,n}(t)$, $\Delta d_m(t)$ (where $\Delta d_m(t)$ stands for $\Delta d_{m,0}(t)$) satisfying the above-given constraints are called *decremental shape coefficients*. Like in the former case, the sequences of decremental shape coefficients constitute some time-

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series denoted, respectively, by $\Delta\boldsymbol{A}_{m,n}$, $\Delta\boldsymbol{B}_{m,n}$ and $\Delta\boldsymbol{D}_m$. However, it should be remarked that the above-defined time-series play different roles in *LHV*'s action description. The $\Delta\boldsymbol{A}_{m,n}$ time-series, as being connected in (2) with the $\sin n\varepsilon$ terms, characterize an asymmetry of ventricle's contraction with respect to the basic plane ($\varepsilon = 0$). On the other hand, the $\Delta\boldsymbol{B}_{m,n}$ time-series carry information about symmetrical deformations of the ventricle with respect to the basic plane. The basic effect of such deformations is flattening of the left ventricle. In a simplified examination of heart action it is often assumed that the *LHV*'s shape can be described by an ellipsoid in which the ratio of their two shorter axes is approximately 1 : 0.85 [3]. Such effect of shape flattening can be reached by putting

$$b_{m,1}(t) = \lambda\cdot b_{m,0}(t), \quad (5a)$$
$$d_{m,1}(t) = \lambda\cdot d_{m,0}(t), \quad (5b)$$

where $\lambda = 0.08$. However, such approximate relationships hold in regular, symmetrical with respect to the plane $\varepsilon = 0$, shapes only; in fact, they contain no information about possible *LHV*'s shape irregularities occurring in the third dimension. Therefore, if such information plays a substantial role in medical diagnosis, the values of primary shape coefficients $b_{m,1}(t)$, $d_{m,1}(t)$ as well as the corresponding decremental shape coefficients should be evaluated on the basis of real images rather than by calculations.

The main *LHV*'s contractility disorders are manifested by occurrence, within the heart cycle, of low or negative values of the decrement function in selected regions of α and ε. The region of *LHV*'s wall delimited by the azimuths $0 < \alpha_{\min} \le \alpha \le \alpha_{\max} < \pi$ for some fixed values $\alpha_{\min}$, $\alpha_{\max}$ is of particular interest, the *LHV*'s contraction outside this angular interval being, in principle, moderate or small.

C. *LHV*'s contractility assessment

In *LHV*'s contractility assessment the time-series of decremental shape coefficients can be analyzed, in general, using a direct or a Fourier spectra based approach. The first approach is presented below.

The method consists in comparison of normalized time-series of basic decremental shape coefficients to the corresponding reference time-series. Normalization should take into account: 1st that only patients with similar age, sexuality, weight, etc. can be compared, and 2nd only time-series of equal lengths can be compared. The first problem, of reference groups of patients selection, arises in many other areas of medical investigations; however, it is here not considered. The second problem is also typical in experimental data processing. If any two finite experimental time-series:

$$\boldsymbol{f}^{\,0} = [f^0_1, f^0_2, f^0_3, \ldots, f^0_T]\,, \quad (6a)$$
$$\boldsymbol{f} = [f_1, f_2, f_3, \ldots, f_S] \quad (6b)$$

are to be compared using a standard mathematical approach then the following conditions should be satisfied: 1st they should consist of components represented in the same scale of physical units, 2nd they should be described on similar time-scales with harmonised starting points, 3rd a distance-measure can be calculated only for time-series of equal lengths ($S = T$). In such case the Euclidean distance-measure between the time-series is given by the formula:

$$\rho(f^0, f) = \sqrt{\sum_{t=1}^{T} (f_t^0 - f_t)^2} \quad (7)$$

Otherwise, if $S \neq T$, the larger time-series should be cancelled to min(S,T) or the components of one of time-series should be recalculated by interpolation. In the last case it is assumed that both time-series have been embedded into the same continuous time-interval of a given length θ. If, for example, $\boldsymbol{f}$ is to be represented by an equivalent time-series consisting of T (instead of S) components in order to be compared with $\boldsymbol{f}^{\,0}$, and $\varphi(\tau)$, called an *envelope* of $\boldsymbol{f}$, is a continuous function such that

$$\varphi(t) \equiv f_t \ \text{ for } t = 1,2,\ldots,S \quad (8)$$

then the components of the recalculated time-series $\boldsymbol{f'}$ will be given by the formula:

$$f'_t = \varphi(\mu\cdot t), \text{ for } t = 1,2,3,\ldots,T, \quad (9)$$

where $\mu = S/T$.

When the distance measure $\rho(\boldsymbol{f}^{\,0}, \boldsymbol{f})$ is used for an analysis of the experimental time-series $\boldsymbol{f}$ then its calculated values should be considered as instances of a random value. This means that its mean value and standard deviation should be calculated (using standard statistical methods, [6]) in order to evaluate the statistical error.

Results

The utility of selected decremental shape coefficients as carriers of diagnostic information has been proven by examination of several their time-series. There were examined only *2D* four-chamber apical cardiac images, for which the model equation (2) preserves only terms depending on the shape coefficients $b_{m,n}(t)$ and $b_{m,n}(t)$. In the first experiment the coefficients Δd_2, Δd_4, and Δd_6 have been taken into consideration, each of them being responsible for *LHV*'s contraction in the azimuth region where $\cos m\alpha$ takes extreme (maximum or minimum) values:

$\cos 2\alpha$ at $\alpha = 0, \pi/2, \pi$, etc.
$\cos 4\alpha$ at $\alpha = 0, \pi/4, \pi/2, 3\pi/4, \pi$, etc.
$\cos 6\alpha$ at $\alpha = 0, \pi/6, \pi/3, \pi/2, 2\pi/3, 5\pi/6, \pi$, etc.

In Figs. 2 and 3 there are plotted the time-series of the corresponding time-series: primary (a), decremental (b) and decremental normalised (divided by d_0 in order to make the results independent on the total size of the ventricle) (c). Fig. 2 corresponds to a normal patient (a one, indicated by physicians as having normal *LHV*'s contractility but, possibly, suffering from other types of heart disorders), while Fig. 3 corresponds to a patient with clinically diagnosed *LHV*'s contractility disorder.

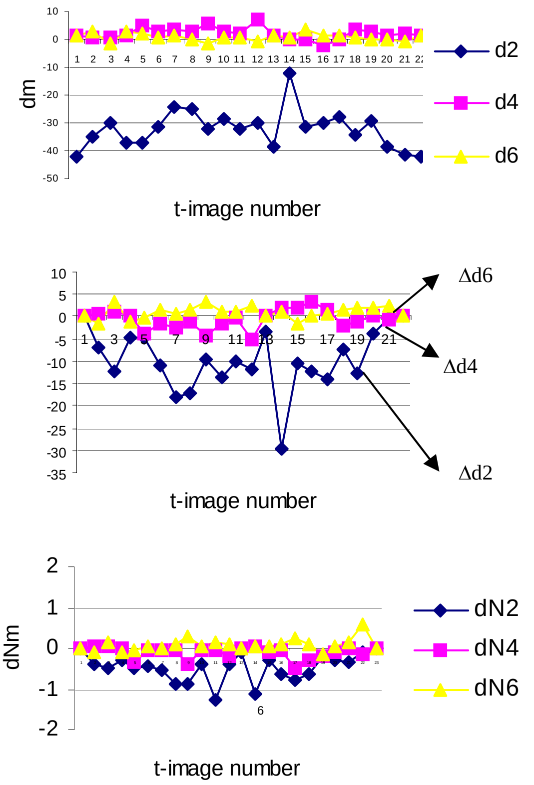

Figure 2: Shape coefficients in a normal patient

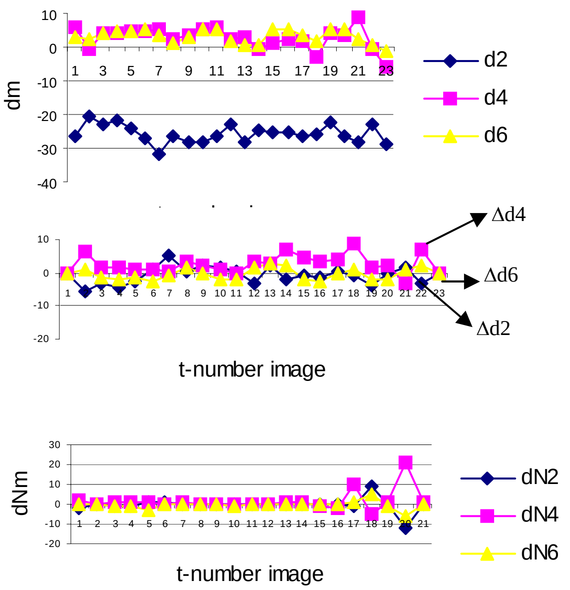

Figure 3: Shape coefficients in contractility disorders

Similar time-series of decremental shape coefficients have been obtained from the records of 22 sequences of cardiac images in patients with clinically diagnosed *LHV*'s contractility disorders. The next step of investigation consisted in calculation of distances between the normalised time-series of decremental shape coefficients of a normal patients and of the patients with contractility disorders. The results are shown in Fig. 4. As it have been mentioned above, for any coefficient they are considered as instances of a random value. In this experiment all patients classified as "abnormal" have been considered as representing one statistical ensemble, no discrimination between different types of contractility disorders being taken into account.

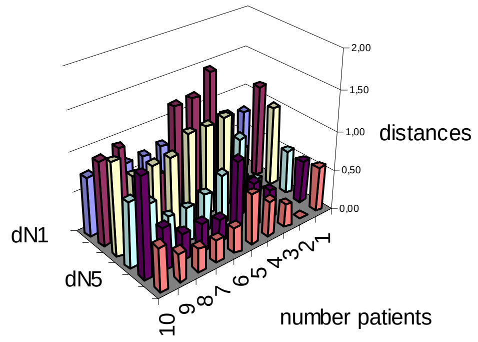

Figure 4: Distances between shape coefficients

For this set of data mean values and standard deviations have been calculated, calculations being performed for six normalised decremental shape coefficients. The results are shown in Fig. 5.

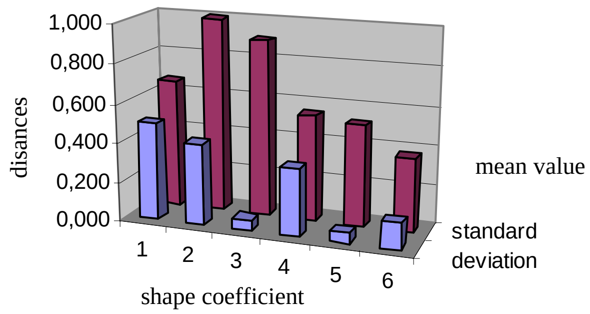

Figure 5: Mean values and standard deviations of distances

At last, in similar way the distances between the time-series of normalised decremental shape coefficients in two patients with different types of *LHV*'s contractility disorders (akinesis and hypokinesis) and in a normal and pathological patient have been calculated. The results are shown in Fig. 6.

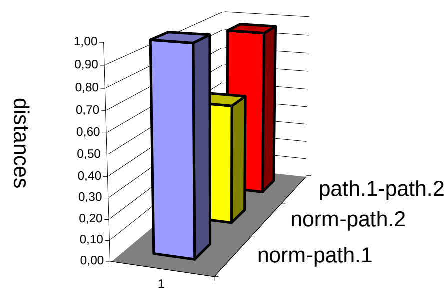

Figure 6: Distances in different contractility disorders

Discussion

A rough comparison of the corresponding time-series plotted in Fig. 2 and Fig. 3 shows that the differences between the norm and pathology, in particular, in lower-level shape coefficients may be essential. This observation justifies deeper examination of the time-series of decremental shape coefficients in larger groups of patients. However, it arose a problem of selection of a representative group of normal patients as a reference set for the detection of *LHV*'s contractility disorders. Among more than a hundred available cases there were no patients healthy in a common sense (such patients are not recommended for deep cardiac examinations). The more, it was also not possible to form reference sets for different age, sexuality or any other physical parameters of the patients. This problems needs to be solved in the future.

Examination of the time-series have also shown that informational values of different decremental shape coefficients are different. They also may be different in various cases of *LHV*'s contractility disorders. The data shown in Fig. 6 lead to the conclusion that the distance-measure based approach to examination of decremental shape coefficients may be used not only to a general detection of contractility disorders but also to a discrimination between various types of disorders. In any case, in medical diagnosis it seems necessary to evaluate the distances of several shape coefficients to the norm, abnormalities being possible to occur in some of them only. This point needs further examination, as well.

The distance measure between time-series of decremental shape coefficients leads to a general contractility disorders detection and evaluation. It also gives a possibility of rough localisation of the region of contractility disorders. However, in several patients there were observed temporal contractility disorders during a part of heart cycle. In such case the distance measure extended on the full heart evolution cycle may lead to a loss of substantial information.

Conclusions

Examination of *LHV*'s contraction process within a full cardiac cycle leads to more complete diagnostic information than a comparison of cardiac images corresponding to the extreme diastolic and systolic states.

For this type of examination sequences of echocardiographic images due to their low invasiveness and possibility of capturing images in real time are particularly useful.

The process of *LCV*'s shape time-variations can be described using a formal model presented in the paper.

Basic information useful in *LCV*'s contractility assessment is contained in decremental shape coefficients of the model.

The decremental shape coefficients can be evaluated automatically by analysis of sequences of cardiac images covering full heart evolution cycle.

The time-series of decremental shape coefficients in normal patients and in patients with *LCV*'s contractility disorders are substantially different.

A comparison of the time-series of several basic decremental shape coefficients of a patient under examination and of a normal one can be used for detection and assessment of *LCV*'s contractility disorders, like: cardiac akinesis, diskinesis and/or hypokinesis.

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