COMPUTER-AIDED INTERPRETATION OF SERIAL USG CARDIAC IMAGES

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ABSTRACT

It is presented an approach to computer-aided interpretation of serial USG images describing the left cardiac ventricle’s evolution process. The method is based on a formal model describing the class of admitted shapes’ variations within the cardiac evolution period. The model has the form of functional trigonometric series with constraints imposed on their time-varying coefficients. Image interpretation consists in following a decision-tree whose nodes evoke logical tests concerning the properties of the heart contractility process under examination. The responses are based on an analysis of the values of auxiliary coefficients calculated from the extracted model coefficients.

KEY WORDS
image processing, cardiac image analysis, shape’s time variation analysis

1. INTRODUCTION

Image interpretation can be defined as an art of image content description within an assumed ontological system and of logically founded answering questions concerning the type, properties, physical state, behaviour, etc. of the visualized objects. It can be considered as a higher step in computer-aided image analysis, the lower ones consisting of image enhancement, segmentation, local patterns recognition, extraction of parameters, etc. Image interpretation supplies the user with information necessary for decision making based on image analysis. In less-advanced image processing systems based on human-computer interaction image interpretation is an immanent part of image processing that is performed by the man together with final decision making. In advanced image processing systems a great deal of image interpretation can be performed by the computer. This, in particular, concerns computer-aided analysis of images in medical diagnosis and supervision of treatment. In this kind of applications they may arise questions concerning existence or non-existence of abnormalities or of specific details, not in the image but in the object under observation, of their localization, type, size, characteristic parameters, level of similarity to some reference objects, physical, geometrical or statistical characteristics of the objects, their evolution state, and any other statements that can be deduced from the image.

Ontological system is here considered as a system of concepts and rules describing a part of physical world, of its possible states, ways of behaviour, and explaining the way of their manifestation in observed images. It is thus a result of long-term observations of the world, our deliberations about it and of its understanding. A basic scheme of image interpretation is shown in Fig. 1. The aim of this paper is showing how this general image interpretation scheme works in the case of a sort of cardiac images interpretation. We refer to a series of former papers [1,2,3] where special attention has been paid to the left cardiac ventricle’s contractility investigation.

2. ONTOLOGICAL ASSUMPTIONS

The assumed ontological system consists of a set of basic concepts referred to cardiac anatomy and physiology and of a formal model describing the processes of investigated objects’ shapes evolution in time. It is assumed that:

- heart is an anatomic organ in which a left and a right part separated by a septum can be distinguished,
each part consisting of a pair of the corresponding chambers: an atrium and a ventricle connected by valves;
- heart’s physiological function consists in stimulation of blood circulation caused by a quasi-periodical process of ordered heart chambers’ contractions (heart-beating);
- each quasi-period of the process is a time-interval contained between two consecutive maximum diastole states of the given heart chamber;

- the process of chamber’s contraction considered within a selected quasi-period is called a heart-evolution process;
- a heart-evolution process can be normal or abnormal, i.e. disturbed by pathological or physiological reasons;
- the main types of heart evolution abnormality are: a/ chamber’s akinesis, i.e. its low contractility level, b/ chamber’s diskinesis, i.e. its local expansion instead of contraction;
- a great deal of cardiac disorders is manifested by abnormality of left cardiac ventricle evolution process;
- the cardiac chambers’ evolution processes can be observed due to various cardiac imaging modalities; among them the echo-cardiac (ultrasound, USG) imaging offers a low-cost, non-invasive, and real-time method of cardiac examination.

A typical example of an USG cardiac image in a standard apex 4-chamber projection is shown in Fig. 2. A left ventricle with its shape reconstructed automatically within a preliminary image processing is also visible there.

![Fig. 2. Example of an USG cardiac image in apex 4-chamber projection.](image)

3. FORMAL MODEL DESCRIPTION

An extension of the ontological system is a formal model describing the class of shapes of cardiac ventricles that are expected to occur in cardiac examinations. This is given in a functional form:

\[ r[P,t] = F[P(\alpha,\epsilon),t] \]  \hspace{1cm} (1)

Here \( r[P,t] \) denotes a distance between a fixed centre \( O \) of polar co-ordinates system and a point \( P \) located on the surface of the chamber, \( t \) denotes a current time taking values between 0 and \( T \), \( T \) being the length of quasi-period; \( \alpha \) and \( \epsilon \) stand for polar co-ordinates, correspondingly azimuth and elevation angles, of the point \( P \), as shown in Fig. 3, and \( F \) is a function, periodic with respect to \( \alpha \) (with period \( 2\pi \)) and to \( \epsilon \) (with period \( \pi \)).

![Fig. 3. Polar co-ordinates used in heart ventricle’s shape.](image)

It is assumed that \( F \) has the form of a double trigonometric series:

\[ F[P(\alpha,\epsilon),t] = \sum_{m=0}^{M} \sum_{n=0}^{N} \left[ a_{mn}(t) \cdot \sin m \alpha \cdot \sin n \epsilon + b_{mn}(t) \cdot \sin m \alpha \cdot \cos n \epsilon + d_{m}(t) \cdot \cos m \alpha \right] \]  \hspace{1cm} (2)

\( M \) and \( N \) being positive integers limiting the shape description accuracy. In the formula \( a_{mn}(t), b_{mn}(t) \) and \( d_{m}(t) \) are time-varying model parameters (shape coefficients) which should be experimentally evaluated. It can be shown that due to some formal properties of trigonometric functions as well as to the shape continuity requirements it should be \( a_{00} = a_{00} = 0 \) for any \( m, n \), as well as \( b_{mn} = 0 \) for \( m = 0 \) or for any even \( n \); in similar way no terms of the type \( \cos m \alpha \sin n \epsilon \) or \( \cos m \alpha \cos n \epsilon \) for \( n > 0 \) in formula (2) may occur. If a 2D model of the heart ventricle is considered, we put \( \epsilon = 0 \) and the model takes a simpler form:

\[ F[P(\alpha),t] = \sum_{m=0}^{M} \left[ b_{m}(t) \cdot \sin m \alpha + d_{m}(t) \cdot \cos m \alpha \right] \]  \hspace{1cm} (3)

where \( b_0 = 0 \).

The shape coefficients \( [a_{mn}(t), b_{mn}(t), d_{m}(t)] \) for \( 0 \leq m \leq M, \ 0 \leq n \leq N \) in formula (2) and \( [b_{m}(t), d_{m}(t)] \) for \( 0 \leq m \leq M \) in formula (3) are assumed to be periodic time-functions of period \( T \). Their form can be evaluated by analysis of series of cardiac images in the way that has been described in [3]. Typical shape coefficients’ time-variations for a 2D model are shown in Fig. 4. A continuous time-axis is here replaced by a discrete one with a time-unit corresponding to a time-interval between the captures of two consecutive images. A typical heart evolution period is represented by about 25 images.

In heart contractility investigations we are interested in the difference between maximum diastolic and current shapes as functions of time:
i = 1,2,...,I, where \( g_i \) are some real or Boolean functions of the primary model parameters. The secondary parameters are some numerical or logical characteristics of the model corresponding to a real object. We shall denote by \( \Gamma \) an \( I \)-component string of the secondary parameters, and by \( G \) an \( I \)-dimensional space of such strings. The secondary parameters can be directly used to the interpretation of images being taken as a source of model parameters; they also can be used as a basis of logical inference concerning objects’ properties. A logical scheme of image interpretation thus takes the below-given form:

\[
\Delta[P(\alpha, \varepsilon), t] = F[P(\alpha, \varepsilon), 0] - F[P(\alpha, \varepsilon), t] \tag{4}
\]

where it has been assumed that \( t = 0 \) corresponds to the maximum diastolic state. According to the former assumptions it also can be given by a trigonometric series, analogous to (2):

\[
\Delta[P(\alpha, \varepsilon), t] = \sum_{m=-0}^{M} \sum_{n=0}^{N} \left[ a_{mn}^*(t) \cdot \sin m\alpha \cdot \sin n\varepsilon + b_{mn}^*(t) \cdot \sin m\alpha \cdot \cos n\varepsilon + d_{mn}^*(t) \cdot \cos m\alpha \right] \tag{5}
\]

where

\[
a_{mn}^*(t) = a_{mn}(0) - a_{mn}(t), \tag{5a}
\]

\[
b_{mn}^*(t) = b_{mn}(0) - b_{mn}(t), \tag{5b}
\]

\[
d_{mn}^*(t) = d_{mn}(0) - d_{mn}(t). \tag{5c}
\]

So defined shape- and decrease-models constitute a “bridge” between the above-given ontological system assumptions and a reality given in the form of a series of images representing an observed real object.

4. IMAGE INTERPRETATION

Computer-aided image interpretation puts some constraints on the class of questions that can be answered on the basis of image analysis. In fact, the questions should be limited only to: 1/ the properties of the model adjusted, as close as possible, to the observed reality, and 2/ to the statements that can be logically inferred on the basis of model properties and of the ontological system’s assumptions. This emphasizes the role of the model which should reflect all substantial properties of the objects under observation. On the other hand, all information concerning any individual observed object is contained in the primary shape parameters \( a_{mn}(t) \), \( b_{mn}(t) \), \( d_{mn}(t) \) evaluated on the basis of image analysis, and in the decrement-model parameters \( a_{mn}^*(t) \), \( b_{mn}^*(t) \), \( d_{mn}^*(t) \). Let us denote the corresponding vectors of parameters by \( A(t) \), \( B(t) \), \( D(t) \), and by \( A^*(t) \), \( B^*(t) \), \( D^*(t) \). For image interpretation it has been defined a set of secondary parameters of a general form:

\[
\gamma_i = g_i[A^*(t), B^*(t), D^*(t)]. \tag{6}
\]
Fig. 6. Admissible logical order of giving responses to image interpreting questions.

secondary parameters divided into sub-groups: \( I_1 \) consisting of calculated distances \( F[P(\alpha, \varepsilon), t] \), \( I_2 \) of decrements \( \Delta[P(\alpha, \varepsilon), t] \), \( I_3 \) of hemodynamical parameters, etc., can be calculated.

The values of distances \( r[P(\alpha, \varepsilon), t] \) are obtained from the formula (2), while the decrements \( \Delta[P(\alpha, \varepsilon), t] \) for any \( \alpha, \varepsilon \) and discrete \( t \) - from (4). The decrement-model parameters \( A^{*}(t), B^{*}(t), \) and \( D^{*}(t) \) can be calculated from the formulae (5 a, b, c). Let us focus our attention on the right branch of the graph in Fig. 6.

5. MODEL-BASED LOGICAL INFERENCE

The time-series of decrements will be denoted as:

\[
C_{ij} = [\Delta_{ij}(k)],
\]

where \( \Delta_{ij}(k) \equiv \Delta[P(\alpha_i, \varepsilon_j), t_k] \) for \( i = 1,2,\ldots,I, \, j = 1,2,\ldots,J, \) \( k = 1,2,\ldots,K \), \( k \) being interpreted as a current image-number a single heart-cycle.

For answering \( Q_3 \) a test of heart evolution normality can be used. According to the ontological assumptions a heart evolution process is normal if all time-series \( C_{ij} \) it consists of are normal. We define the criteria of decrement time-processes normality in the form of logical functions:

\[
g_n(i,j) : G \rightarrow \{\text{true, false}\}
\]

and it is assumed that, by definition,

\[
g_n \equiv \bigwedge_{i,j} g_n(i,j),
\]

where \( \bigwedge_{i,j} \) denotes a multiple logical alternative. The value of \( g_n(i,j) \) should be true if the components of \( C_{ij} \) for the given \( i, j, \) and \( k \) are not lower than admissible. For proving it a system of normalised threshold coefficients \( \beta_n(k) \) such that

\[
0 \leq \beta_n(k) \leq 1 \quad \text{for} \quad 1 \leq i \leq I, \, 1 \leq j \leq J, \, 0 \leq k \leq K.
\]

can be introduced. Let us denote

\[
h_{ij} = \max_{k} [\Delta_{ij}(k)] \quad \text{for} \quad 1 \leq i \leq I, \, 1 \leq j \leq J.
\]

The admissible thresholds will be given in the form:

\[
B_\beta(k) = \beta_\beta(k) \cdot h_{ij}.
\]

Finally, the criterion of normality of a left heart ventricle’s contractility takes the form (10), where

\[
g_n(i,j) = \text{true} \quad \text{if} \quad \Delta_{ij}(k) > B_\beta(k) \quad \text{for} \quad 0 \leq k \leq K,
\]

\[
= \text{false} \quad \text{otherwise}.
\]

Let us remark that if this criterion is satisfied, diskinesis is also excluded. However, if \( g_n = \text{false} \), then additional test for answering the question \( Q_4 \) is necessary. For this purpose a criterion excluding diskinesis can be established in the form of a logical function:

\[
g^*_n(i,j) = \text{true} \quad \text{if} \quad \Delta_{ij}(k) \geq 0 \quad \text{for} \quad 0 \leq k \leq K,
\]

\[
= \text{false} \quad \text{otherwise}.
\]

6. CONCLUSIONS

It has been shown that computer-aided interpretation of medical images can be realized on the basis of a set of ontological assumptions and of a formal model of the objects under observation. In particular, responses to some questions concerning the objects can be reached by calculations performed on model parameters obtained as a result of image analysis. The quality of so realized image interpretation depends on the correctness of ontological assumptions and on the model quality.

REFERENCES