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# Analysis of Dynamical Interrelations of Electrocardiogram Parameters

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## Introduction

Mathematical modeling of human physiology is a tremendously ambitious task. It encompasses the modeling of most diverse compartments such as the cardiovascular, respiratory, skeletal and nervous systems, as well as the mechanical and biochemical interaction between blood flow and arterial walls, and electric processes and electric conduction in biological tissues [1].

The heart is a complex system in itself, where electrical phenomena are functionally related to wall deformation [2]. In its turn, electrical activity is related to heart physiology. Electrocardiology deals with description of both intracardiac bioelectric phenomena and extracardiac electric field generated in the body [1].

All the fields of mathematics have a role to play in this context. Mathematical analysis, fluid and solid dynamics, stochastic analysis is used to set up the differential models and predict uncertainty [3]. Numerical analysis and high performance computing are needed to solve the complex differential models numerically. Methods from stochastic and statistical analysis are exploited for the analyzing and interpretation of space – time patterns. Indeed, the complexity of the problems often stimulates the use of innovative mathematical techniques that are able to capture accurately processes that occur at multiple scales in time and space, and that are governed by heterogeneous physical laws [1],[3].

So the main purpose of this paper was to present the analytical method for the analysis of dynamical interrelations of electrocardiogram parameters.

## Theoretical Background

Suppose we have two synchronous numeric time series $(x_n; n = 0,1,2,...)$ and $(y_n; n = 0,1,2,...)$, that elements $x_n$ and $y_n$ are determined. For the cointegration of two time series a series of second order matrixes can be constructed as follows:

$$A_n := \begin{bmatrix} x_n & x_{n-1} - y_{n-1} \\ x_{n+1} - y_{n+1} & y_n \end{bmatrix}.$$

Some numerical parameters of second order matrices $A_n$ can be introduced:

Trace of matrix $A_n$: $\mathrm{Tr}A_n := x_n + y_n$;

Difference of matrix $A_n$: $\mathrm{dfr}A_n := x_n - y_n$;

Co – diagonal product of matrix $A_n$:
$\mathrm{cdp}\,A_n := (x_{n-1} - y_{n-1}) \cdot (x_{n+1} - y_{n+1})$.

From these initial parameters follow characteristic which have more applicative sense discriminant of matrix $A_n$ :

$$\mathrm{dsk}\,A_n = (\mathrm{dfr}A_n)^2 + 4\,\mathrm{cdp}\,A_n .$$

According to these expressions hypothesis can be formulated: if discriminants of matrixes $A_n$ become close to zero, then numeric time series $(x_n; n = 0,1,2,...)$ and

$(y_n; n = 0,1,2,...)$ become similar, that means that their cohesion is high [4].

Cohesion of time series can be labeled as $x \circ y$. According to previous expressions value of cohesion can be defined as follows [5]:

$$\varepsilon(x_n \circ y_n) = \frac{1}{k \cdot dsk\, A_n},$$

where $k$ – real number coefficient, $\varepsilon$ - value of $x_n$ and $y_n$ cohesion.

For the three synchronous numeric time series $(x_n; n = 0,1,2,...)$, $(y_n; n = 0,1,2,...)$ and $(z_n; n = 0,1,2,...)$, that elements $x_n$, $y_n$, $z_n$ are determined a series of third order matrixes $B_n$ can be constructed and dynamical cohesion can be defined in the similar way [4].

**Results and discussion**

For the synchronous registered ECG parameters series the matrix analysis was applied. The automated ECG analysis system "Kaunas – Load W01", developed at the Institute of Cardiology was used [6]. From ECG signals some parameters during every cardio – cycle were calculated: RR interval in ms (RR), JT interval duration in ms (DJT), R wave amplitude in µV (AR), QRS complex duration in ms (DQRS) and T wave amplitude in µV (AT).

Data of ECG parameters series of 30 persons were analyzed. All persons were divided into three groups: healthy persons (N=10, 40-60 years old, average age 43,16±1,17), 2 groups of patients with acute myocardial infarction (one group patients of 30-60 years old, N=9, average age 42,44±3,91; another group patients of 60-90 years old, N=11, average age 72,55±3,78). For all patients the coronary angiography was performed and occlusion of at least of the one coronary artery was diagnosed. For all of them percutanies transluminal coronary angioplasty reconstructing TIMI3 flow in damaged artery was successfully performed [7],[8].

For the dynamical interrelations of ECG parameters all possible pairs of parameters series were analyzed: $RR \circ DJT$, $RR \circ AR$, $RR \circ DQRS$, $RR \circ AT$, $DJT \circ AR$, $DJT \circ DQRS$, $DJT \circ AT$, $AR \circ DQRS$, $AR \circ AT$ and $DQRS \circ AT$. For the analysis of different complexity levels [8] some triad were selected: $RR \circ DJT \circ AR$ for the system level, $RR \circ DJT \circ DQRS$ for the subsystem (heart regulation) level and $RR \circ DJT \circ AT$ for the subsystem (heart metabolism) level. For the correct interrelations analysis and comparison all the data were normalized to interval [0; 1] as follows:

$$x = \frac{x_0 - x_{\min}}{x_{\max} - x_{\min}},$$

where $x_0$ – the original value, x – normalized value, $x_{\min}$ and $x_{\max}$ – minimal and maximal physiological value [4].

Assuming that, k = 1, the dynamical interrelation of each cardio - cycle was calculated as cohesion function for two parameters series $\varepsilon(x_n \circ y_n) = \frac{1}{dsk\, A_n}$ and $\varepsilon(x_n \circ y_n \circ z_n) = \frac{1}{dsk\, B_n}$ for three parameters series.

Non-invasive diagnosis of ischemic heart disease (IHD) is the main objective of cardiologists. However at rest accuracy of usual ECG, using only common, widely used diagnostic parameters is only about 45%. It increases using stress test [10], but also in this case accuracy and specificity is too low. If to take human organism as a complex system [1],[11], important features of its complex function is assessment of dynamical interrelations between investigative parameters. There is still unknown the form of changes of any ECG parameters, during coronary artery revascularization procedures, when there is changing ischemic situation in the heart [12].

In this work it was hypothesized, that if person is healthy, ECG parameters cohesion values are high, if an ischemic heart disease is diagnosed – values are low [4]. All possible dynamical interrelations for each person were calculated and analyzed individually. The examples of one patient with acute myocardial infarction initial ECG parameters and their dynamical interrelation before, during and after coronary angiography are given in the Fig. 1 - 4. The results confirm the hypothesis and illustrate, that dynamical interrelations are more informative for clinical practice than initial ECG parameters series [4],[13].

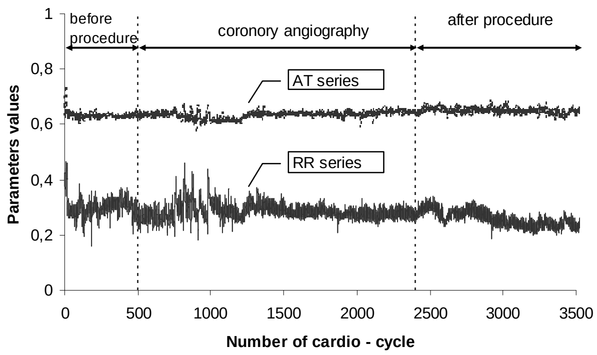


**Fig. 1.** An example of one investigation, initial ECG parameters RR and AT time series

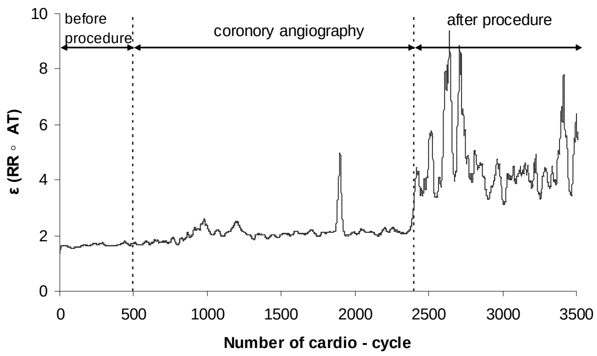


**Fig. 2**. An example of one investigative ECG parameters RR and AT dynamical interrelations

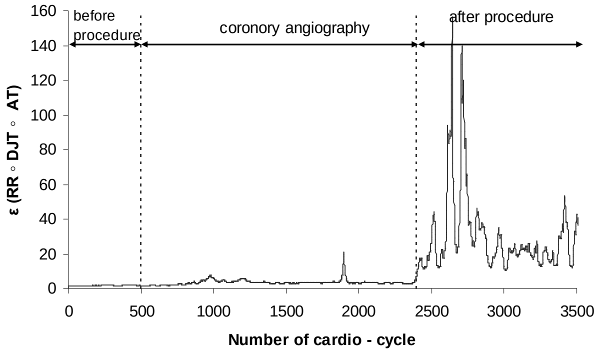


**Fig. 3.** An example of one investigative ECG parameters RR, DJT and AT dynamical interrelations

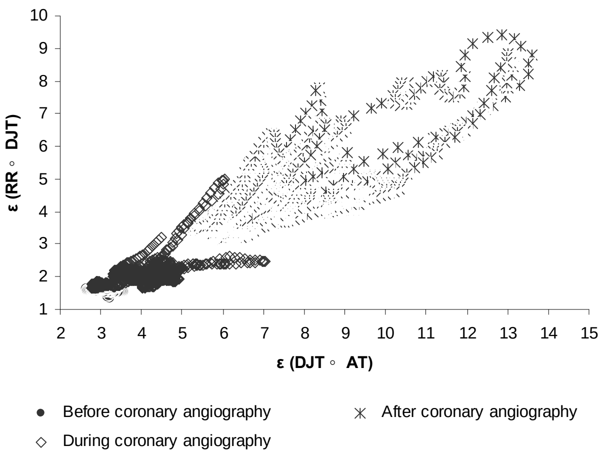


**Fig. 4.** An example of one investigative ECG parameters dynamical interrelations at different complexity levels: *ε (RR◦DJT)* and *ε (DJT ◦ AT)*

For the results comparison the average value of $\varepsilon$ was calculated. Non – parametric Man – Whitney – U test for the independent samples was applied. For the comparison of results before and after coronary angiography for ischemic patients non – parametric Wilcoxon test for two related samples was applied. The significance level 95 % was selected. The comparison between groups is given in Fig. 5.

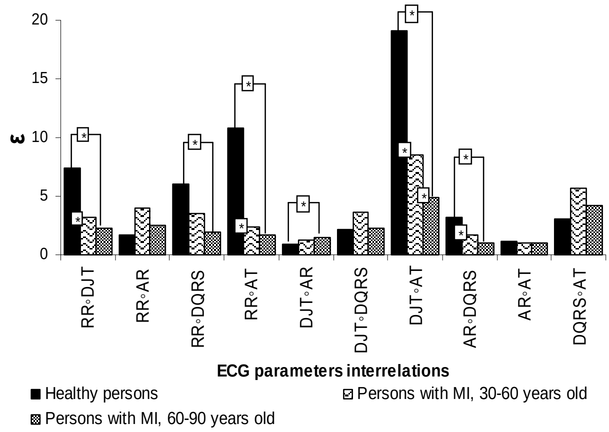


**Fig. 5.** Comparison of different ECG parameters dynamical interrelations average values for between different groups (* – the difference is statistically significant, p<0,05)

The results, given in Fig. 5 confirm, that if person is healthy, ECG parameters cohesion values are higher, if an ischemic heart disease is diagnosed – values are lower - six out of ten cohesion values were significantly higher (5 of them significantly), than in groups with MI. For elder persons ECG parameters average cohesion values are lower.

The comparisons between average cohesion values before and after coronary angiography procedure for different groups are given in Fig.6 and Fig. 7.

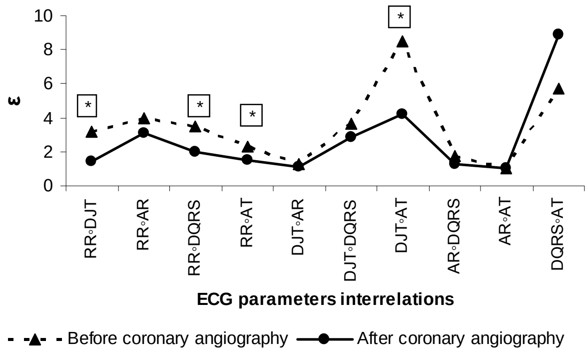


**Fig. 6.** Comparison of average interrelation values between ECG parameters before and after coronary angiography for patients with MI, 30-60 years old (* – the difference is statistically significant, p<0,05)

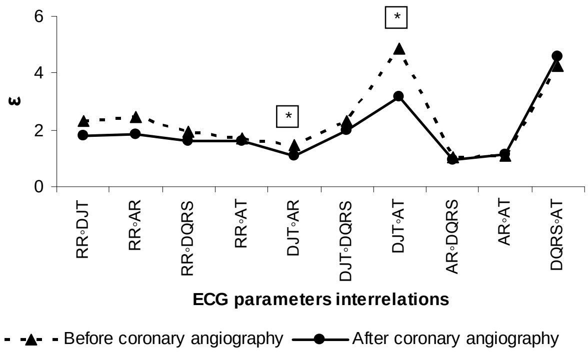


**Fig. 7.** Comparison of average interrelation values between ECG parameters before and after coronary angiography for patients with MI, 60-90 years old (* – the difference is statistically significant, p<0,05)

An interesting phenomena was discovered after restoration of blood flow in damaged heart muscle. Most of cohesion values were lower after coronary angiography – well known in clinical practice so called "stunned heart" mode was demonstrated.

## Conclusions

The results indicated that ECG signal parameters dynamical interrelations, calculated for each cardio – cycle are more informative in clinical practice than initial data. It was observed, that dynamical interrelations are different to each person and it is better to analyze them individually. ECG parameters cohesion values should be checked by future analysis. All results should be tested with more data from ECG signals, registered for different age, gender and functional state persons.

## Acknowledgement

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Mathematical modeling of human physiology is a tremendously ambitious task. The complexity of the problems often stimulates the use of innovative mathematical techniques that are able to capture accurately processes that occur at multiple scales in time and space. The main purpose was to present the analytical method for the analysis of dynamical interrelations of electrocardiogram parameters, cointegrating numeric time series to matrixes by each cardio-cycle. The dynamical interrelations were compared between healthy persons and persons with acute myocardial infarction, also during coronary angiography. The results indicated that ECG signal parameters dynamical interrelations, calculated for each cardio-cycle bring new clinical information, that is not visible in the initial data. Ill. 7, bibl. 13 (in English; summaries in English, Russian and Lithuanian).

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Математическое моделирование физиологии человека является чрезвычайно амбициозной задачей. Сложность проблемы зачастую стимулирует применение инновационных математических методов, способных детально анализировать процессы, происходящие в различных масштабах во времени и в пространстве. Основная цель – представить аналитический метод анализа динамических взаимоотношений для параметров электрокардиограммы. Создана методика коинтеграции числовых временных рядов строя матрицы для каждого сердечного цикла. Сравнивались динамики взаимосвязей между здоровыми людьми и лицами с острым инфарктом миокарда, а также во время коронарной ангиографии. Результаты исследований показали, что динамика взаимосвязей параметров ЭКГ сигнала, рассчитанных для каждого сердечного цикла, является новой клинической информацией, которая не видна в исходных данных при обычном подходе. Ил. 7, библ. 13 (на английском языке; рефераты на английском, русском и литовском яз.).

**K. Berškienė, A. Lukoševičius, G. Jaruševičius, V. Jurkonis, Z. Navickas, A. Vainoras, A. Daunoravičienė. Elektrokardiogramos parametrų dinaminių sąsajų analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – No. 7(95). – P. 95–98.**

Žmogaus fiziologijos modeliavimas tebėra labai ambicingas uždavinys. Dėl problemos sudėtingumo dažnai pravartu naudoti novatoriškus matematinius metodus, kurie leistų analizuoti procesus, vykstančius erdvėje ir laike. Pagrindinis tikslas – pateikti analizinį metodą, skirtą elektrokardiogramos parametrų dinaminėms sąsajoms vertinti, kointegruojant pradines duomenų eilutes į matricas kiekvieno kardiociklo metu. Buvo palygintos sveikų asmenų ir sergančių ūmiu miokardo infarktu, taip pat atliekant angioplastikos procedūrą gautų dinaminės elektrokardiogramos parametrų sąsajos. Rezultatai parodė, kad EKG signalo parametrų dinaminės sąsajos, apskaičiuotos kiekvienam kardiociklui atskleidžia naują, klinikinėje praktikoje svarbią informaciją, kurios negalima gauti analizuojant EKG signalus. Il. 7, bibl. 13 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).