FRACTAL DIMENSIONS IN EVALUATION OF HEART FUNCTION PARAMETERS DURING PHYSICAL INVESTIGATIONS

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Alfonsas Vainoras. Habil. Doctor, Professor, the head of the Department of Kinesiology and Sports Medicine in Kaunas University of Medicine. The field of scientific research — the creation of computer-aided evaluation methodologies for human functional state analysis using the theory of complex systems, the methodologies of non-linear processes' analysis and chaos theories.

ABSTRACT

In last two decades the theory of complex systems made big steps in its development. The new methods for integral situations' evaluations were created. Beginning from F. Hausdorff in 1919, the set of fractal dimensions was proposed to evaluate systems' complexity. Now F. Hausdorff's dimension, A. Kolmogorov's integral correlation dimension, information dimension, correlation dimension and many others are widely used. They are used in physics, medicine, biology, astronomy and all other sciences. The question still exists which, when to use and what additional information it will provide. The aim of this work was to explore the behavior of a few well known fractal dimensions during physical investigations of healthy persons, sportsmen and ischemic heart diseased patients with the aim to evaluate the heart function. The studied fractal dimensions can be used for the evaluation of a sportsman's functional state. The endurance-trained sportsman has the highest values of fractal dimensions. Information dimension detects new unstudied information in sport and clinical medicine. It separates out the investigated persons according to gender, disease and physical activity. But information dimension does not depend on age in the investigated groups of asymptomatic persons (men and women).

Keywords: *cardiovascular system, functional state, complexity, fractal dimensions.*

INTRODUCTION

The idea of complexity must be understood in the context of processes in nature generating systems with more parts and special relations between various kinds of parts. The fractal dimension can be viewed as a relative measure of complexity, or as an index of the scale-dependency of a pattern (Kenkel, Walker, 1996). The fractal dimension could be understood as a summary statistic measure of overall "complexity". The term "fractal" was introduced by B. B. Mandelbrott (1977) to characterize spatial or temporal phenomena that are continuous but not differentiable.

The human body can be evaluated as a complex system (Baranger, 1994) which consists of, at least, three holistic systems, and they where indicated by A. Vesalius in 1548. But, even in today sport and clinical medicine, we can hardly find parameters to evaluate the complexity of human organism. More convenient in medicine are investigations of processes in depth, than the study of systems' relation. The relations between systems in human organism usually are nonlinear and their formalization is quite a difficult task. There is well known fact that human health, harmonic development of human organism strongly depends on that relations between systems, on the complexity of all organism. Decrease of complexity in human organism leads to disintegration of human organism's functions. The pathology can rise up in any scale it will happen. Evaluating the changes in electrocorticograms with A. Kolmogorov's integral correlation influenced by microwaves (Sidorenko, 2004), have shown decrease of complexity in brain function when the pathogenic influence of microwaves appears.

The aim of this work was to explore the behavior of a few well known fractal dimensions during physical investigations. We evaluated capacity, information and correlation dimensions for the parameters of an integrated health evaluation model (those parameters reflect different human physiological functions). We tried to evaluate the behavior of chosen dimensions in various investigated groups of persons (sportsmen, healthy persons and patients with ischemic heart disease).

MATERIAL AND METHODS

Two investigations were made.

The first investigation. The investigated contingent consisted of three groups: 15 endurance-trained sportsmen, 10 non-athletes and 12 sprint-trained sportsmen. Sportsmen had had their training experience for more than 7 years. All the participants underwent three exercise tests: 1) bicycle ergometry — every one minute stepwise increase in workload; 2) Roufier's test — 30 squats per 45 s; 3) 30 s vertical jump test. The computer system "Kaunas Load" was employed for the registration and analysis of the 12-lead electrocardiogram (ECG). Dynamics of heart rate (HR), and ratio of JT and RR intervals (JT / RR) were investigated. To avoid influence, in calculation, of different range of parameters, the HR and JT / RR were normalized according to their physiological (max-min) scale of changes.

The three widely used fractal dimensions were investigated — F. Hausdorff's, or capacity dimension (CD), information dimension (ID) and correlation dimensions (CoD).

The formula for dimensions' calculations was:

$$D_q = -\lim_{\varepsilon \to 0} \frac{I_q(\varepsilon)}{\ln \varepsilon},$$

when q = 0, we have F. Hausdorff's (capacity) dimension (CD)

$$I_q(\varepsilon) = \ln N_\varepsilon \,;$$

q = 1, we have information dimension (ID)

$$I_q(\varepsilon) = -\sum_{i=1}^{N_\varepsilon} P_i(\varepsilon) \ln P_i(\varepsilon) \,;$$

q = 2, we have correlation dimension (CoD)

$$I_q(\varepsilon) = -\ln \sum_{i=1}^{N_\varepsilon} (P_i(\varepsilon))^2 \,;$$

Iq (ε) — information function;
G — fixed parameter;
ε — square grid box size;
N — the total number of points in the set;
Pi (ε) — probability that element is normalized, i. e.

$$\sum_{i=1}^{N_\varepsilon} (P_i(\varepsilon) = 1;$$

Nε — the number of occupied boxes;
n_i — the number of points counted in the box.

The number of filled boxes is Nε, calculations were made for fixed ε values. Comparison of means was made for different groups of investigated persons.

The second investigation. The investigated contingent consisted of three groups: sportsmen (159 tests of men, 53 tests of women), asymptomatic persons (113 tests of men, 210 tests of women) and patients with ischemic heart disease (61 tests of men). Asymptomatic persons were divided into 6 groups according to gender (male and female) and age (20—30, 30—40 and 40—50 years old). Groups of investigated persons and the means of their age are given in Table 1 (M stands for the mean of age; SEM stands for standard error of the mean).

The physical load was performed by provocative incremental bicycle ergometry (modified Brooce's protocol). The bicycle ergometry was started with 50 W intensity and the power was increased every minute by 50 W for men and by 25 W for women, and the cycling frequency of 60 cycles per minute was used. The loading was performed till the submaximal heart rate or appearance of clinical symptoms indicating the test. A computerized 12-lead ECG analysis system "Kaunas-Load", developed at the Institute of Cardiology, Kaunas University of Medicine, was used (Vainoras et al., 1999).

We used the model of integral health evaluation (Poderys, 2004), which integrates changes of three functional elements: P — periphery system, R — regulation system (brain), S — supplying system (heart, blood-vessel system) (Fig. 1). Relation between these systems

Table 1. **The number and age of investigated groups (M ± SEM)**

Group	Number	Age (M ± SEM)
Sportsmen	159	23.56 ± 0.40
Sportswomen	53	24.88 ± 0.65
Men	113	36.05 ± 0.60
20—30	27	28.37 ± 0.56
30—40	55	35.36 ± 0.35
40—50	31	43.97 ± 0.60
Women	210	33.97 ± 0.53
20—30	66	25.17 ± 0.44
30—40	100	35.14 ± 0.28
40—50	44	44.52 ± 0.50
Patients with ischemic heart disease	61	52.44 ± 1.56

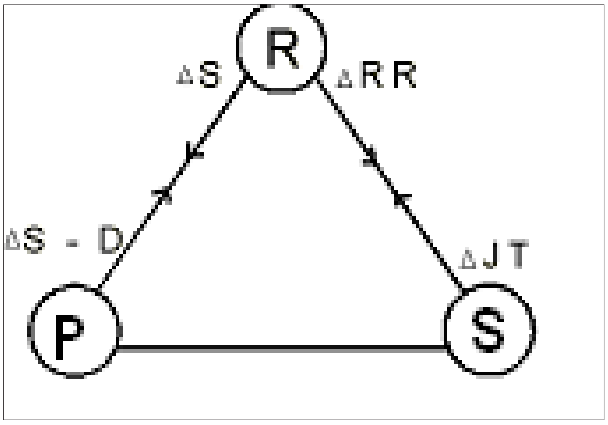

Fig. 1. **Integrated model for functional state evaluation**

can be specified by several parameters, but we used the simplest and easier calculated ECG and ABP parameters: heart rate (HR), JT interval, systolic (S) and diastolic (D) blood pressure.

Also we studied proportions between parameters: $\frac{S-D}{S}, \frac{JT}{RR}$, where $RR = 60 / HR$.

Initial data was the discrete values of all discussed parameters at each level of load and during rest.

For calculation of information dimension at first discrete points we interpolated with cubic interpolation spline (Plukas, 2001). Then we calculated function values in step h (h = 0.01). During the research we found out that information dimension depended on particular parameters' values of physiological interval (max-min), so according the interval of possible changes, we normalized the initial data (for example, heart rate can be from 50 to 220 beats per minute, JT interval can be from 0.15 to 0.36 seconds). Then the return map using calculated function values was made. After that, the information dimension for this map was calculated. The algorithm for calculating information dimension was taken from literature (*Internet link*).

Consider a square grid (box size ε) superimposed on an observed point pattern. Within each occupied grid unit, the number of points n_i is counted. Each count is then expressed as a proportional value:

$$P_i(\varepsilon) = \frac{n_i}{N},$$

when N is the total number of points in the set. The "information function" is defined as

$$I \equiv -\sum_{i=1}^{N_\varepsilon} P_i(\varepsilon)\ln[P_i(\varepsilon)],$$

when N_ε is the number of occupied boxes (squares) of size ε. $P_i(\varepsilon)$ is the natural measure, or probability that element *i* is populated, normalized so that: $\sum_{i=1}^{N_\varepsilon} P_i(\varepsilon) = 1$

The information dimension is then defined as:

$$ID = -\lim_{\varepsilon \to 0} \frac{I}{\ln(\varepsilon)} = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N_\varepsilon} P_i(\varepsilon)\ln[P_i(\varepsilon)]}{\ln(\varepsilon)}$$

For the comparison of calculated information dimension, we compared the means of the studied groups. We assumed that the distribution of information dimensions is normal, so we used a two-sample t-test for the significant differences of the means (Čekanavičius, Murauskas, 2001):

$$\begin{cases} H_0 : \mu_X = \mu_Y \\ H_1 : \mu_X \neq \mu_Y \end{cases}$$

RESULTS

Results of the first investigation. The results obtained during the first investigation are presented in Figure 2. Significant differences among the studied groups were found during 30 s jump test for HR in CD (among endurance sportsmen, non-athletes and sprint athletes) and ID calculations (between sportsmen and non-sportsmen). Differences in dimensions for parameter JT / RR were more expressed, especially for Roufier's and 30 s jump tests. Significant differences were between the athlete and non-athlete groups and non-athletes have all the smallest dimensions' values.

For more detailed analysis we chose

Table 2. **Means ± SD of information dimension for investigated men groups**

Parameters	Patients with ischemic heart disease	Asymptomatic men of different age	Sportsmen
(S—D) / S	0.48 ± 0.12	0.65 ± 0.14	0.77 ± 0.13
JT / RR	0.54 ± 0.13	0.62 ± 0.11	0.64 ± 0.11
RR	0.56 ± 0.12	0.61 ± 0.10	0.68 ± 0.12
JT	0.56 ± 0.12	0.62 ± 0.11	0.67 ± 0.10
S	0.70 ± 0.12	0.73 ± 0.11	0.77 ± 0.08
S—D	0.55 ± 0.13	0.65 ± 0.13	0.81 ± 0.12

Table 3. **Means ± SD for investigated women groups**

Parameters	Asymptomatic women of different age	Sportswomen
(S—D) / S	0.58 ± 0.14	0.70 ± 0.15
JT / RR	0.63 ± 0.12	0.68 ± 0.11
RR	0.58 ± 0.09	0.72 ± 0.12
JT	0.61 ± 0.11	0.72 ± 0.09
S	0.61 ± 0.11	0.71 ± 0.11
S—D	0.53 ± 0.14	0.69 ± 0.15

Table 4. **Two-sample t-test for means results for RR interval**

Compared groups		t	p
Patients with ischemic heart disease	Asymptomatic men of different age	3.185	0.002
Patients with ischemic heart disease	Sportsmen	6.596	< 0.001
Asymptomatic men of different age	Sportsmen	4.802	< 0.001
Asymptomatic women of different age	Sportswomen	5.905	< 0.001

Table 5. **Two-sample t-test for means results for RR interval in different age groups**

Compared groups		t	p
Men 20—30	Men 30—40	0.521	0.604
Men 20—30	Men 40—-50	0.573	0.569
Men 30—40	Men 40—50	0.502	0.599
Women 20—30	Women 30—40	0.870	0.386
Women 20—30	Women 40—50	1.056	0.295
Women 30—40	Women 40—50	0.529	0.598

information dimension (ID). It shows quite big differences in our studied groups and is sensitive to the person's functional state.

Results of the second investigation. In Table 2 and Table 3 the means of information dimension for all parameters (mean ± standard deviation) are presented:

The means of information dimension of different investigated parameters for all studied groups of men are shown in the diagram form (Fig. 3).

In Figure 2 we can see, that means for all parameters differs — the means of information dimension for patients with ischemic heart disease are smaller than the means in sportsmen group. For some parameters ($\frac{S-D}{S}, S-D$) we can see even different tendencies compared with other parameters.

The two-sample t-test for the means showed that in most cases the means of information dimension significantly differs ($p < 0.05$) between investigated groups of men, the same for women. For example, for RR interval significant differences you can see in Table 4:

The means of information dimensions don't differ between groups of different age, the same for men and women (Table 5).

Existing difference between the groups with different physical activity and absence of it in the

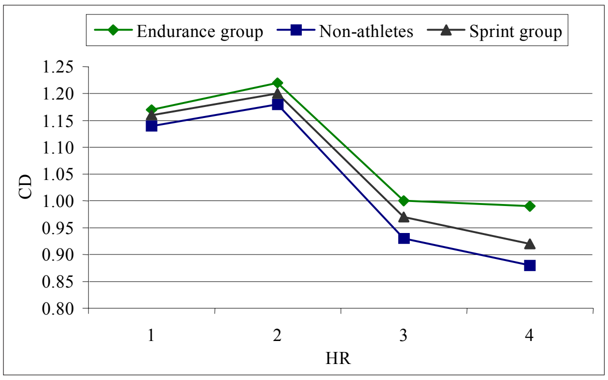

Fig. 2, A. **F. Hausdorff's dimension (CD) for heart rate (HR)**

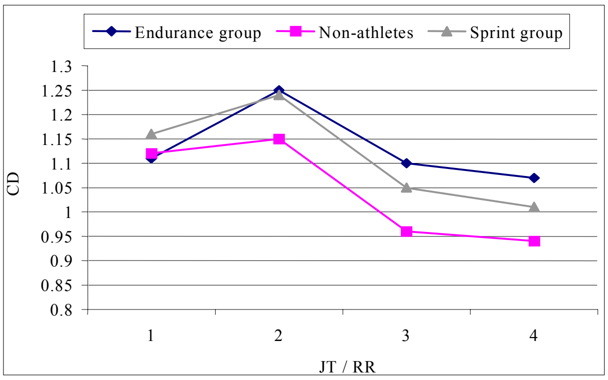

Fig. 2, B. **F. Hausdorff's dimension (CD) for heart parameter (JT / RR)**

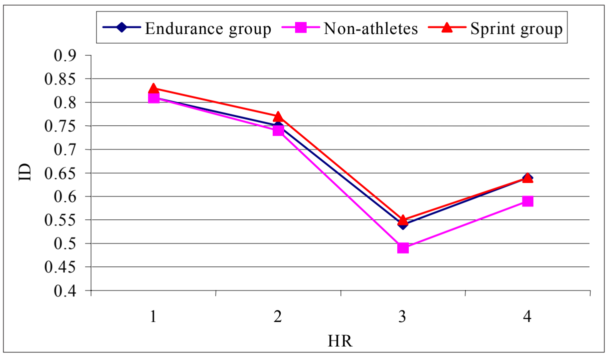

Fig. 2, C. **Information dimension (ID) for heart rate (HR)**

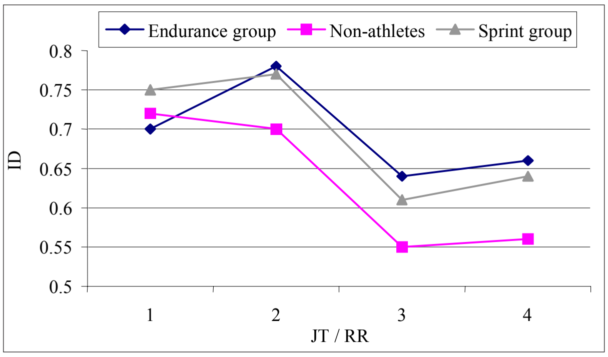

Fig. 2, D. **Information dimension (ID) for heart parameter (JT / RR)**

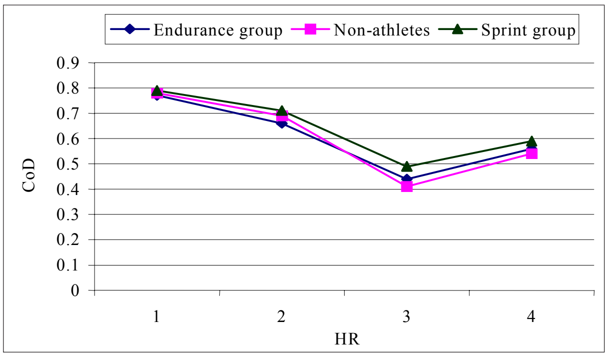

Fig. 2, E. **Correlation dimension (CoD) for heart rate (HR)**

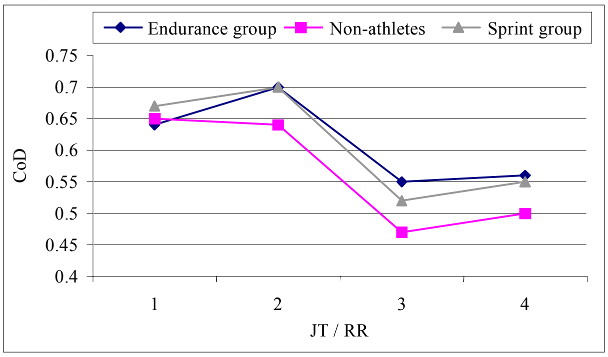

Fig. 2, F. **Correlation dimension (CoD) for heart parameter (JT / RR)**

Fig. 2. **Capacity, information and correlation dimensions for heart rate and heart parameter JT / RR. Number 1 on axis x reflects situation during bicycle ergometry, number 2 — the common, integrated evaluation during Roufier's test and 30 s jumps, number 3 — only Roufier's test and number 4 — only at 30 s jumps. The studied groups are: 1-st, endurance sportsmen, 2-nd, healthy non-athletes, 3-d, and sprint type sportsmen**

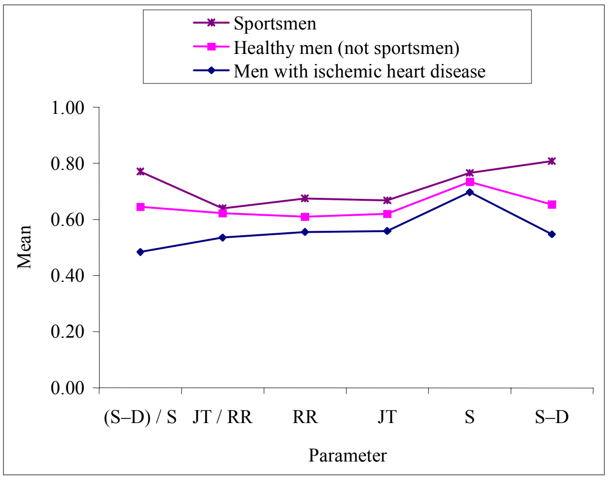

Fig. 3. **Mean of Information dimension for studied men groups**

groups of different age and gender but with the same physical fitness can point out conclusion, that the studied information dimension could be used as a measure of human functional state or healthiness. It integrates all features of reaction to load — the load and recovery as well.

DISCUSSION

The first investigation has shown that different fractal dimensions express different behavior in evaluation of human organism parameters. The question when and which dimension more effectively could be used is still open. In our study the best results we have from capacity and information dimensions. This fact can reveal that our dimensions being as an integral parameter are related to the form of a curve (function in time) of studied, normalized parameters (this is more typical feature for capacity dimension). It means, that those dimensions can reveal integrated in a curve form information and it could be very important and new information for a person's functionality evaluation. We think, our results from the first study support that opinion.

In the second study the information dimension was studied in details. The calculation for information dimension was made for the normalized parameters which were taken as the parameters of human organism's integral model. It means that they all must reflect the same level of complexity and Figure 3 can really support this statement. All parameters have about the same value of information dimension, only in the groups with different functional level it differs.

It is interesting that information dimension doesn't differ for different age groups, and the same gender. May be, it could be related to the statement that we can have the same good functional level at all ages if to take care about our health.

The obtained results support our previous opinion that fractal dimensions could be helpful integral parameters to reflect human body as a complex system.

CONCLUSIONS

1. The studied fractal dimensions can be used for the evaluation of a sportsman's functional state. The endurance trained sportsmen have the highest values of fractal dimensions.
2. Information dimension detects new unstudied information in sport and clinical medicine. It separates the investigated persons according to gender, disease and physical activity. But information dimension does not depend on age in the investigated groups of asymptomatic persons (men and women).

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