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ECG response to submaximal exercise from the perspective of Golden Ratio harmonic rhythm

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ABSTRACT

Background: The Golden Ratio (GR), derived from the Fibonacci sequences, has multiple representations in nature, as expressions of the repetition of specific geometric shapes called fractals.
Methods: The aim of the study focused on investigation of the cardiovascular homeostasis, at rest and during effort testing, with determination of the validity of the GR at the level of variables extracted from serial ECG. We used a group of 230 young subjects (average age 19.21 ± 1.87), each subject performing a 6 min submaximal exercise ergometer test (Astrand & Rhyming Protocol). We were interested in estimate the ratio between the electrical diastole and electrical systole (TQ/QT) and between the cardiac cycle and electrical diastole (RR/TQ), which has been much discussed as being related to GR value.
Results: We proposed using a new synthetic fractal indicator (SFI), with dynamic nonlinear evolution and we determined the intervals of acceptability for SFI. The mean values of the SFI of our subjects were significantly close to GR value, aspect that suggests the presence of harmonic rhythm, under different conditions of existence and adaptation of the human organism (rest and submaximal effort). The SFI and the heart rate values had very strong correlations, at rest ($R = 0.88$, $p < 0.001$, CI 95% 0.83–0.91) and postexercise ($R = 0.91$, $p < 0.001$, CI 95% 0.87–0.94).
Conclusions: Our results show a fractal dimension of the ECG interval dynamics for the study group. The proposed SFI imposes itself as a relatively simple parameter for assessing heart's electrical functionality during cardiac cycle that can be applied both at rest and exercise.

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1. Introduction

The Golden Ratio (GR), represented by the Greek letter Phi (φ), is known since ancient times also as the Golden Ratio, Golden Number, Golden Proportion, Golden Mean, Golden Section, Divine Proportion and Divine Section as a mathematic parameter with important symmetric and harmonic properties [1].

The Golden Ratio, as an irrational, continuous and non-repeating number [2], with the value of 1.61803398 . . .., can be considered as the first member of a family which can generate a set of generalized Fibonacci sequences [3].

The Fibonacci numbers is a series of terms $\{F_n\}^{\infty}{}_{n=1}$ wherein each term (except the first two) is the sum of the two previous terms, according to the following linear recurrence equation:

$$F_n = F_{n-1} + F_{n-2}$$

This results in a series of terms of the type 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144 .. . . . ., in which the ratio of two consecutive terms tends to the Golden Ratio value, as stated in the formula $\varphi = F_n/F_{n-1} = 1.61803398 \ldots\ldots$

The Fibonacci sequence is also defined by the quadratic equation $x^2 - x - 1 = 0$ which has two solutions: $x_1 = \varphi = 1.618\ldots$ and respectively $x_2 = -1/\varphi = -0.618\ldots$ [4].

The Golden Ratio, the Fibonacci sequence and also its q-deformed or "quantum" extension [4] are widely applied in modern sciences, particularly in theoretical physics, mathematics and computer science, but also in art, architecture, economics and natural sciences [5]. The multiple connections of these mathematical concepts with our life environment it led to their labelling with the term of "divine aesthetics" [6].

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It seems that the Golden Ratio has multiple representations in nature, as expressions of the repetition of specific geometric shapes called fractals, resulting at the biological level an interesting manifestation of the phenomenon of phyllotaxis.

In medicine, the applications of Golden Ratio are also very diverse, especially in Anatomy and Physiology, e.g. human body measurements (human face, human hand, other anthropometric parameters), lungs and bronchial divisions, hearing and vestibular functions, brain and cardiovascular rhythms, human genome DNA [7–9], biomechanical analysis on human gait [10,11].

Some researches focused on determining correlations between GR and the variations in systolic and diastolic blood pressure, induced by cardiac cycle, as a marker of health status [8,12,13].

Another special interest has been represented by the investigation of GR applicability to ECG testing. The results of several studies converge towards the idea of the existence of a ratio with φ value between the diastolic and systolic phases of the cardiac cycle, measured on the ECG [8,14–17]. According to some scholars, this harmonic rhythm of heart functioning is valid only during rest state and it represents a manifestation of phylogenesis, under the principle of physiological adaptation of the organism to an operating regime in conditions of maximum energy efficiency [18].

It is worth mentioning here the interesting studies by Svetskov on the symmetry and spatial organization of the heart cycle in mammals, in conditions of rest and physical exercise [19], used later as a reference by other authors [20].

These studies have highlighted the existence of certain biophysical parameters (temporal, volumetric, mechanical and coronary flow related), that have an invariant dynamics during cardiac cycle, which can be correlated with the Golden Ratio value.

Many recent studies documented that Golden Ratio and the Fibonacci sequence are strongly linked to hemodynamic variables [21,22], but we consider these data as being still controversial. In addition, most research especially focused on cardiovascular investigations at rest, mathematical modelling being less applied in exercise testing in human subjects.

2. Material and methods

2.1. Aim of the study

The practical objective of this research focused on the investigation of the cardiovascular homeostasis at rest and during effort testing, with determination by means of descriptive statistics (univariate and bivariate analysis) and inferential statistics of the validity of the GR harmonic rhythm at the level of a set of variables, which was extracted from serial ECG.

2.2. Participants

Basically, we used a group of 230 young subjects, with an average age of 19.21 ± 1.87 years, age range 18–22 years old and sex ratio 0.437 (70 men/160 women). The subjects are students in Physical Therapy at the University of Pitesti who are clinically healthy, without significant cardiovascular pathological history and who were declared apt for physical effort following a medical examination.

According to the most cited models in the specialty literature that can generate experimental variables in the cardiovascular field, which are possibly correlated with GR and Fibonacci sequence, we designed a double assessment of subjects, at rest (r) and after the effort (e).

2.3. Data acquisition

The assessments were carried out between 8 am and 12 am, with the same type of protocol, with the following sequence: at rest (after a 5 min rest) and during a 6 min exercise test. The exercise testing was performed according to the protocol of the Astrand & Rhyming Submaximal Bicycle Test, a classical, accurate and largely used standardized tool to estimate maximal oxygen consumption (VO_2 max) [23].

In practice, the ergometric bicycle test or the treadmill test are commonly used to assess the cardiovascular adaptability to effort, as there are various standard load protocols for ECG recording.

These protocols are based on a metered load of physical effort, with the recording of serial ECGs at rest and during effort, as well as during the recovery period after the effort. These tests are very useful for the diagnosis of ischemic heart disease, but especially for the exclusion of this type of pathology [24].

Considering that the physical effort represents a variant of the body's homeostasis, it becomes interesting to investigate the presence of the harmonic rhythm (or another type of derived rhythm) during physical exercise.

That's why we opted for the protocol of the Astrand & Rhyming Submaximal Bicycle Test. This test estimates the VO_2 max using a single-stage, six-minute submaximal cycling protocol, by recording the subject's heart rate at rest and at minute six, when usually subject is reaching a steady state. The test predicts the VO_2 max, based on the linear relationship between VO_2 max and heart rate, by reference to a nomogram [25].

Since the effort testing offers the possibility to dynamically investigate the electrophysiological systolo-diastolic activity of the heart, superimposable with myocardial mechanical activity, we proposed this model of experimental design of evaluation of the group of subjects.

Therefore, each subject performed a test of 6 min submaximal exercise ergometer test, cycling with a load of 150 W for males and 100 W for females, with a settled speed of 60 rotations per minute [26].

We recorded the ECG for all subjects in the mentioned circumstances by using a computerized protocol (Ergoline ergometer exercise bike – Ergoselect 200, with Cardimax FX-7402, Fukuda Denshi Co. Ltd., with 12 derivations).

Within the electrocardiogram, we were interested in conducting specific measurements on the duration of the heart systole and diastole in order to estimate the ratio between the two intervals, which has been much discussed as being related to a harmonic rhythm with φ value.

For the delimitation of the systolic component from the diastolic one of the cardiac cycle, we turned to the interpretation of consecrated authors, who define the electrical systole as the time between the start of the Q (by case R) wave and the end of the T wave (meaning the QT interval). On the other hand, the electrical diastole is described as the remaining period, from the end of the T wave to the beginning of the Q (by case R) wave of the next cardiac cycle (namely the RR − QT = TQ segment, where RR = QQ) [27–30].

The TQ on ECG represents a segment, because does not include waves. In the same time, for an easier understanding of the series of data, we will use further the appellative "interval" for the ST segment, taking into consideration his algebraic sense, as equivalent of the diastolic interval of the cardiac cycle [31–33].

As the heart rate increases, the dynamic of QT interval follows that of the ventricular systolic ejection (the mechanical systole), and the one of the TQ interval follows that of the ventricular filling (the mechanical diastole). As a result, the two mentioned intervals can be considered as electrical parameters of cardiac mechanical phenomena [28].

Table 1
Statistic indicators for heart rate, ECG intervals (QT, TQ and RR), at rest, for the experimental group.

Variable	HRr (beats/min)	QTr (ms)	TQr (ms)	QTrc (ms)	TQrc (ms)	RRr (ms)
Mean	74.59	363.17	451.95	403.32	596.68	815.12
SD	8.64	14.72	79.42	7.12	7.12	94.13
CV	11.59%	4.05%	17.57%	1.76%	1.19%	11.55%
Minimum	55	337	308.52	387.68	580.88	645.16
Maximum	93	410	684.73	419.12	612.32	1090.91
CI 95%	73.10–76.08	360.64–365.70	438.30–465.60	402.10–404.54	595.46–597.90	798.94–831.30

Note: HR: heart rate; r: rest; c: corrected; SD: standard deviation; CV: coefficient of variation; CI 95%: 95% confidence interval for the mean.

Based on these considerations, we extracted the average values of QT, TQ and RR intervals from data provided by the computerized ECG registration. For the data acquisition through the ECG system, we set the automatic recording mode for one rhythm lead (six channel to be displayed simultaneously + one rhythm lead), and we selected the lead II from the two options suggested by the software (lead II or V5, speed of 25 mm/s and 10-mm/mV amplitude).

We repeatedly recorded series of data for intervals of 15 s, at rest and then after each minute of exercise, till the sixth minute of the protocol. In fact, this protocol for ECG recording is the classical one indicated for exercise testing, in order to assess the cardiovascular reactivity at various levels of physical stress [25].

Every record, for a period of 15 s, contains about 13–41 RR intervals, depending on the subjects' heart rate, which varied between 55 and 162 beats/min for the entire group.

We preferred the lead II because the easiest and most efficient way to confirm the computer-derived QTc is to examine lead II and/or V5, these ECG channels usually providing the best delineation of the T wave [34]. Therefore, through this lead, we can determine if the manually measured QT interval matches the computer's QT measurement [35], by using the teach-the-tangent method [36].

2.4. Outcomes and statistical analysis

After completing the above-mentioned tests for our group of subjects we had obtained a number of data series, which were statistically analysed (descriptive statistics, univariate and bivariate analysis) by determining of average, standard deviation (SD), coefficient of variation (CV or relative standard deviation), 95% confidence interval for the mean (CI) and of maximum and minimum registered values. Then, we calculated average ratios between certain mean parameters, at rest (TQr/QTr, RRr/TQr) and respectively after the effort (TQe/QTe, RRe/TQe).

For the rest QT interval we also used the corrected QT value (QTc) according to the heart rate, as reproduced by the computer device and obtained by using the Bazett's formula.

Instead, for effort testing, numerous studies indicate that Bazett's formula is no longer applicable [37], the relationship between QT interval and heart rate having a dynamic character, and might be better illustrated by a linear equation of regression [38]. Thus, for the second assessment (after effort testing), we applied Rautaharju's formula, appropriate for effort testing [39].

$$QTc = QT \times (120 + HR)/180$$

In the context of using QTc form as a corresponding interval for ventricular electrical systole, both at rest and after effort (referring to a heart rate of 60 b/min and RR = 1000 ms), we can use for TQc interval, as the equivalent interval for ventricular electrical diastole, the following formula TQc = RRc − QTc = 1000 − QTc.

Results are presented as mean ± standard deviation. Then, for the same data series we applied inferential statistical methods, by determining specific correlation coefficients (linear regression) and their statistical significance, with 95% Confidence interval (CI).

Table 2
Statistic indicators for the rates between investigated parameters, at rest, for the experimental group.

Variable	TQr/QTr	RRr/TQr	TQrc/QTrc	RRrc/TQrc
Mean	1.238	1.823	1.480	1.676
SD	0.168	0.116	0.043	0.020
CV	13.53%	6.34%	2.93%	1.20%
Minimum	0.916	1.593	1.386	1.633
Maximum	1.686	2.091	1.579	1.722
CI 95%	1.206–1.270	1.803–1.843	1.470–1.490	1.672–1.680

Note: QT, TQ, RR: ECG intervals; r: rest; c: corrected; SD: standard deviation; CV: coefficient of variation; CI 95%: 95% confidence interval for the mean.

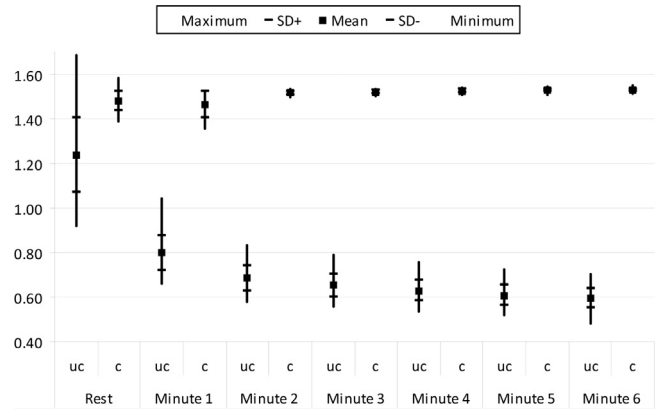

Fig. 1. The evolution of the TQ/QT ratio for the group of subjects during the exercise testing (uc: uncorrected; c: corrected; SD: standard deviation).

3. Results

The calculated statistical indicators for data series are shown in the tables below for the rest parameters (Tables 1 and 2) and after effort parameters (Tables 3 and 4).

Analysis of investigated cardiovascular parameters revealed mean values, both at rest and after effort testing, that confirm the status of normal health of studying subjects, data series having a medium-high homogeneity (coefficients of variation – CV below 20% for all parameters). This supports the idea of the validity of the study group in terms of a good health, factor that was taken into consideration in the selection of subjects.

In Figs. 1 and 2 we summarized the evolution of the investigated ratios for the group of subjects during the exercise testing:

4. Discussion

It should be noted that the intervals of heart rate variability of the group of subjects were 55–93 b/min at rest and respectively 116–162 b/min after effort. Meanwhile, the mean heart rates per group were 74.59 ± 8.64 b/min at rest and 134.83 ± 8.66 b/min after effort. From another perspective, Yetkin et al. [16], in their study on rest electrocardiograms, proposed to select only subjects who present values of heart rate between 60 and 80 b/min, in order

Table 3
Statistic indicators for heart rate, ECG intervals (QT, TQ and RR), after effort, for the experimental group.

Variable	HRe (beats/min)	QTe (ms)	TQe (ms)	QTec (ms)	TQec (ms)	RRe (ms)
Mean	134.83	279.72	167.07	395.52	604.48	446.79
SD	8.66	10.16	17.92	1.13	1.13	28.07
CV	6.42%	3.63%	10.72%	0.29%	0.19%	6.28%
Minimum	116	250	119.99	392.26	601.81	370.37
Maximum	162	304	213.54	398.19	607.74	517.24
CI 95%	133.34–136.32	277.97–281.47	163.99–170.15	395.33–395.71	604.29–604.67	441.96–451.62

Note: HR: heart rate; e: effort; c: corrected; SD: standard deviation; CV: coefficient of variation; CI 95%: 95% confidence interval for the mean.

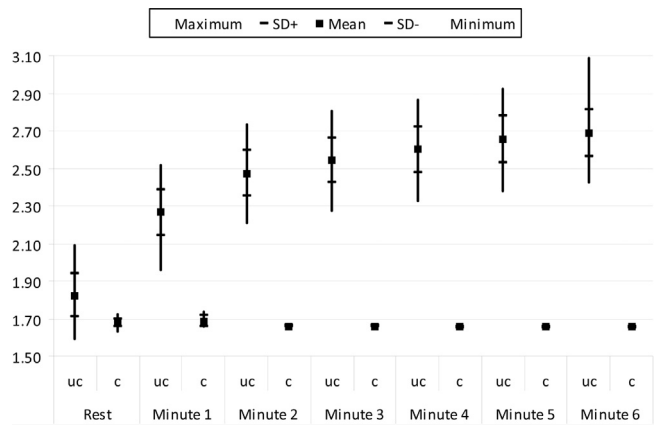

Fig. 2. The evolution of the RR/TQ ratio for the group of subjects during the exercise testing (uc: uncorrected; c: corrected; SD: standard deviation).

Table 4
Statistic indicators for the rates between investigated parameters, after effort, for the experimental group.

Variable	TQe/QTe	RRe/TQe	TQec/QTec	RRec/TQec
Mean	0.596	2.688	1.528	1.654
SD	0.043	0.124	0.007	0.003
CV	7.18%	4.63%	0.47%	0.19%
Minimum	0.479	2.422	1.511	1.645
Maximum	0.703	3.087	1.549	1.662
CI 95%	0.590–0.602	2.666–2.710	1.526–1.530	1.653–1.655

Note: QT, TQ, RR: ECG intervals; e: effort; c: corrected; SD: standard deviation; CV: coefficient of variation; CI 95%: 95% confidence interval for the mean.

to eliminate possible error factors related to higher variability of cardiac diastole.

Under these circumstances, in all studied subjects the mean QT interval at rest was 363.17 ± 14.72 ms, while the mean QT interval after effort was 279.72 ± 10.16 ms. Along with these values, we also calculated the mean RR at rest as 815.12 ± 94.13 ms, and the mean RR after effort as 446.79 ± 28.07 ms. Regarding the QT intervals at rest, none of the investigated subjects exceeded the maximum accepted value of 440 ms for men and 460 ms for women [40,41]. In addition, the QTc values in all subjects were similarly within the normal range, generally considered to be between 350 and 440 ms [42].

This analysis becomes more difficult when it comes to classifying the QT interval after exercise within normal limits, as in this case there are involved many more operational factors, such as neurohormonal ones and autonomic responses [43]. In our study, the heart rates after exercise were in the range of 116–162 b/min. In consequence, in order to specify the normal interval of variation of the QT interval in this case we used the diagram proposed by Goldenberg et al. [44], as well as one formula, which had been certified as accurate in case of high frequencies for determining the predictable value (QTp) of the same interval. According to this formula the QTp = 656/(1 + HR/100), and the minimum accepted value for the QT represents 88% of QTp [45–47].

Through these methods, we determined an equivalent normal range for QT after exercise of 220–304 ms. With reference to this range, we found also that the values of QT after effort in our group of subjects does not exceed the proposed limits.

The next step in our research focused on examining the reports values between the electrical diastole and electrical systole (TQ/QT) and between the cardiac cycle and electrical diastole (RR/TQ), according to the model proposed by Tsvetkov [7,14,19], at rest and after exercise, for the uncorrected and corrected values of the intervals.

According to Tsvetkov's studies, the ratios of systolic, diastolic and cardiac cycles in mammals at rest are closely related to the GR value. During physical exercise, the heart rate intervals suffer dynamic changes, starting from the mentioned reference pattern. This situation, characterized by a high degree of invariance, offers the possibility of providing an optimal blood flow for the body, for various states of hemodynamic solicitation [19].

The symmetric organization of the "golden" cardiac cycle is a result of a long evolution of mammals in the direction of optimization of their structure and functions [48]. The proposed model of the relationship between the phases of the cardiac cycle offers a systemic dimension for interpretation of the heart's activity, in terms of maximum efficiency, with minimum energy consumption [49,50].

Recently, this model, which denotes an optimal structure and an efficient physiological functioning of the heart, has been extensively investigated by other authors from the electrocardiographic and imagistic perspective [9,22,51,52].

Referring to this model, we have not confirmed the existence of a harmonic rhythm, very close to the Golden Ratio value (GR = 1.618). Although Tsvetkov [14] stated that, at least at rest, the two reports are simultaneously very close to GR in humans and mammals in general, our results contradict this hypothesis.

In our case, the values of the mean reports at rest are indeed closer to the GR value (TQr/QTr = 1.238 ± 0.168 and RRr/TQr = 1.823 ± 0.116) and more apart after effort (TQe/QTe = 0.596 ± 0.043 and RRe/TQe = 2.688 ± 0.124). Instead, the values of the reports that take into account the correction of the QT interval (for HR = 60 b/min and RR = 1000 ms) are approaching more to GR, in a similar way both at rest (TQrc/QTrc = 1.480 ± 0.043 şi RRrc/TQrc = 1.676 ± 0.020) and after exercise (TQec/QTec = 1.528 ± 0.007 şi RRec/TQec = 1.654 ± 0.003).

Obviously our results are different from those reported for rest testing by Tsvetkov [14]. Regarding the effort testing, for the analysed reports we found only indirect references published in the speciality literature.

We can mention here the results of other similar studies, which revealed an average value for the ratio diastolic time interval/systolic time interval of 1.611, while the medium ratio R–R interval/diastolic time interval was 1.618, meaning GR [16]. However, in that study, the authors defined systole as the time between the 'R wave' and the end of the 'T wave', and diastole as the difference between the RR interval and the systolic interval [16].

From a different methodological approach, we took into consideration the electrical phenomena (electrical systole and electrical diastole), anyway related to the mechanical ones. Moreover, it has been demonstrated that the QT interval (as the duration of electrical systole) is slightly shorter, but parallel with the total electromechanical systole (the period from the beginning of the QRS complex to the first aortic vibration of the second heart sound) in patients without heart disease [53].

Defining mechanical systole in conjunction with the electrical one has been a matter of concern since the 19th century. In this respect, A. D. Waller proposed the following formula: mechanical systole = $K \times RR^{1/2}$ where K has a value of 0.343 [54]. At the same time, during effort testing it has been demonstrated that the ratio of contraction time (systolic interval) to relaxation time (diastolic interval) increases as the heart rate increases. For example, at a normal heart rate of 75 b/min, the period of contraction constitutes 34% of the cardiac cycle, while at 200 b/min, it increases to 53% of the cardiac cycle [28].

There are still many controversies regarding the exact definition of electrical and mechanical cardiac intervals. For example, some authors consider that the T wave (from the electrical systole) would actually belong to myocardial diastole [55]. Other authors define systolic duration according to particular mixed criteria, as time from onset of the QRS complex to end of echografic isovolumic relaxation wave [56].

In the light of this information, we preferred to appeal to the safer alternative that of using the electrical intervals, which ensures better results reproducibility and reduces interpretation errors.

We note that data analysis was more focused on the comparison of the variables between rest and post-effort (6th minute of exercise). The explanation is based on the fact that, as can be seen from Figs. 1 and 2, practically between the two extreme moments, the uncorrected ECG interval ratios showed a progressive evolution between the resting and post-effort values, respectively. Instead, the corrected ECG interval ratios had a relatively linear trend, which is easy to interpret, given that the mathematical correction of the interval lengths refers to the standard heart rate of 60 beats/minute.

For all determinations, the same pattern of framing the ECG interval ratios between the normal ranges was constantly maintained. As a result of the progressive adaptation to effort, in the case of Astrand's submaximal test, the subject reaches a steady state after 5–6 min, when the heart rate and oxygen consumption, which are in a linear relationship, tend to stabilize.

To frame the obtained results in certain normal ranges, we proposed a new interpretation algorithm. Therefore, for a variation interval of the heart rate at rest of 50–100 b/min, RR values cover the interval between 600 and 1200 ms, and accepted QT values must be within the interval of 330–416 ms, according to a consecrated nomogram [57]. Appealing to an inequation system, we calculated that the TQr/QTr ratio must be within the interval of 0.818–1.884, and RRr/TQr ratio within 1.530–2.222.

From the same perspective, for an interval of variation of heart rate during effort of 100–170 b/min, RR values cover the interval from 353 up to 600 ms, and accepted QT values must be within the interval of 243–328 ms. According to the same reasoning, TQe/QTe ratio must be within 0.452–0.829, and RRe/TQe ratio within 2.205–3.209.

In Table 5 we centralized the obtained normal ranges for the ECG intervals ratios, both at rest and effort, uncorrected and corrected versions.

By analysing the intervals of accepted variation of the mentioned reports, we noticed that they do not include the GR value of 1.618 after exercise testing and for all corrected versions. On the other hand, our mean ratios, calculated on data series, are within the ranges defined as normal.

Table 5
Estimated normal ranges for the ECG intervals ratios, at rest and after effort, uncorrected and corrected versions.

Variable	Normal ranges
TQr/QTr	0.818–1.884
RRr/TQr	1.530–2.222
TQrc/QTrc	1.347–1.590
RRrc/TQrc	1.628–1.742
TQe/QTe	0.452–0.829
RRe/TQe	2.205–3.209
TQec/QTec	1.493–1.557
RRec/TQec	1.642–1.669

Note: QT, TQ, RR: ECG intervals; r: rest; e: effort; c: corrected.

Table 6
Statistic indicators for the synthetic fractal indicator, at rest and after effort, for the experimental group.

Variable	SFIr	SFIrc	SFIe	SFIec
Mean	1.531	1.578	1.642	1.591
SD	0.028	0.012	0.041	0.002
CV	1.86%	0.74%	2.49%	0.13%
Minimum	1.500	1.554	1.563	1.587
Maximum	1.639	1.606	1.783	1.597
CI 95%	1.522–1.540	1.576–1.580	1.630–1.654	1.590–1.592
Normal range	1.500–1.707	1.544–1.609	1.517–1.830	1.581–1.599

Note: SFI: synthetic fractal indicator; r: rest; e: effort; c: corrected; SD: standard deviation; CV: coefficient of variation; CI 95%: 95% confidence interval for the mean.

In elementary algebra, the GR value is one of the solutions of the following quadratic equation $x^2 - x - 1 = 0$ which has two solutions: $x_1 = \varphi = 1.618$ and $x_2 = -1/\varphi = -0.618$ respectively. If we note $x_1 = TQ/QT$ and $x_2 = RR/TQ = (QT + TQ)/QT = 1 + QT/TQ$, then the two reports may be simultaneously equal to φ value.

This particular situation can be theoretically found only at rest, only for low values of heart rate, in accordance with the above demonstration.

For an easier and realistic interpretation of electrocardiographic data in relation to the harmonic ideal theoretical rhythm of GR, we propose using a new synthetic fractal indicator (SFI), with dynamic nonlinear evolution, defined as the arithmetic mean of the two reports TQ/QT and RR/TQ, with variants at rest and during exercise. Consequently, applying the principles of the polynomial functions of the second degree, we determined an interval of acceptability for SFI of 1.500–1.707 at rest, and respectively of 1.517–1.830 after effort.

The mean values of SFI for our study group, corresponding to uncorrected and corrected QT intervals, at rest and after exercise, are presented in Table 6.

It can be observed that the mean values of the SFI of our subjects, at rest and after effort, are within the estimated normal ranges.

Regarding the SFI evolution for the group of subjects during the 6 min exercise test (Fig. 3), our results suggest the presence of harmonic rhythm, under different conditions of existence and adaptation of the human organism (rest and submaximal effort). Thus, the uncorrected values had a progressive dynamics between the rest and the post-effort values, passing very close to the GR value in the 4th minute. The corrected forms of the indicator showed a more linear evolution, with values close to the GR value.

A plausible explanation for the existence of harmonic asymptotic rhythm at the level of the reports between the analysed electrocardiographic intervals could be given by the existence of certain patterns of distribution and function of the excitoconductor tissue of the heart. Thus, recent studies indicate that the branches of the conducting system of the heart perform a scaling process of the electrical signals depending on the considered section, this processing being carried out according to the Golden Ratio and the law of Fibonacci [58].

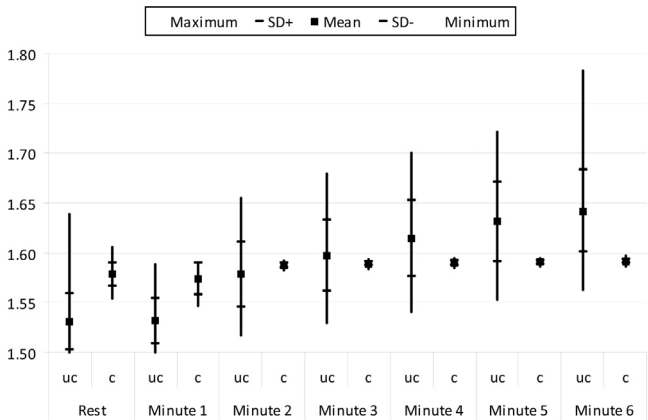

Fig. 3. The evolution of the SFI for the group of subjects during the exercise testing (uc: uncorrected; c: corrected; SD: standard deviation).

An ECG fractal regular pattern, of nonlinear type, but as a variant of interpretation of heart rate variability, was also highlighted by some authors, especially in healthy subjects, from the perspective of the neuroautonomic control mechanisms [59–62].

Finally, the correlation coefficients between HR and SFI, for each patient, at rest and postexercise were calculated. Both correlation coefficients (R) were statistically significant, showing very strong correlations between parameters at rest ($R = 0.88$, $p < 0.001$, CI 95% 0.83–0.91) and postexercise ($R = 0.91$, $p < 0.001$, CI 95% 0.87–0.94). Also, other authors have confirmed the existence of an increased correlation between the ratio of the systolic to diastolic duration (echographically assessed) and HR in normal subjects [63], however, less for postexercise version [56]. In our case, the novelty consists in obtaining significant very strong correlations, both at rest and postexercise, in the conditions of using the SFI as an indicator of the dynamics of the heart's electrical systole and diastole.

We believe that the research offers a new perspective regarding the possibility of applying of mathematical models in human heart electrophysiology. The practical applications of the results refer to the optimizing of the diagnostic accuracy with the rest and exercise ECG, by using mathematical modelling.

The fact that the newly proposed parameter has a very narrow and similar variation in both resting and exercise states allows us to use it under very diverse conditions of hemodynamic loads. Thus, the new parameter can be used to diagnose the normal adaptability of the heart to exercise, for various stages of body stress.

In conclusion, based on the proposed mathematical modelling of the data, we can integrate the interferences of contextual adaptation factors in the interpretation of the electrophysiological normality of the heart.

5. Limitations of the study

The research did not focus on assessing the parameters variability during data series recording, as variant for the implication of random factors, according to the models of fractal geometry. Otherwise, in case of the ECG intervals ratios, some variability has been reported in healthy subjects [64].

6. Conclusion

Systolic and diastolic ECG interval dynamics, with reference to the SFI, has a nonlinear fractal behaviour, regardless of the type of the body solicitation (rest or effort), showing a higher regularity pattern. From the perspective of the theory of large deviations and of the idea of convergence of probability measures, the demonstrated SFI pattern is manifested through an asymptotic behaviour, tending to concentrate around GR value in different instances (rest and after submaximal effort).

The proposed SFI imposes itself as a relatively simple parameter for assessing heart's electrical functionality during cardiac cycle that can be applied both at rest and exercise. Consequently, it can be use in order to cover a niche for the investigation of the electrical adaptability of the heart to the demands of exercise, with multiple other possibilities of expanding applicability in medical practice (human performance, cardiovascular diseases, aging process etc.).

Our results show a fractal dimension of the systolic and diastolic ECG interval dynamics for the study group. However, further investigations of larger groups are required in order to confirm more practical applications of these findings.

Disclosure of interest

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