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Allometry of ECG waves in mammals

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The present allometric study deals with the duration of three electrocardiographic intervals (PQ, QRS, QT) and their relationships with the corresponding cardiac cycle length (R-R interval) in mammals across a wide body mass range. The numerical values of the different ECG intervals were obtained from Grauwiler's (1965) monograph on the subject. Because the corresponding body masses were not given by this author, Heusner's (1991) data on basal metabolic rate as function of body mass were used to establish the most likely body mass figure for each case, based on the taxonomic identity between the corresponding specimens. On the other hand, in a recent study we established the "duality" of physiological times (Günther & Morgado, 1996) and, therefore, we adopted this novel approach to investigate the ECG intervals and their relationships with the R-R interval (heart rate reciprocal). Considering that the anatomy and physiology of auricles and ventricles are different (spheroids versus quasi-cylinders), and that excitation (sino-atrial node and His-Purkinje's system) and contraction processes can be described either by Euclidean or fractal geometries, only a quantitative analysis of the different ECG waves could resolve the dilemma. From the present preliminary study we can conclude that fractal geometry is prevalent with regard to ECG intervals.

***Key words**: allometric equations, body mass, comparative physiology, electrocardiogram.*

INTRODUCTION

From the analysis of 27 allometric equations ($Y = a \cdot W^b$) pertaining to all time functions of mammals and birds, Calder (1984) obtained a mean value of 0.247 ± 0.049 for Huxley's (1932) allometric exponent (b). However, the mean value for this chronobiological exponent ($b \cong 0.25$) did not agree with the expected time exponent for biological similarities ($b = 0.30$), which was based on the statistical analysis of 203 empirical allometric equations (Günther *et al*, 1992). Recently this discrepancy could be settled by establishing the "duality" for physiological times, with one time exponent for the Euclidean time scales ($b = 0.33$) and another one ($b = 0.25$) for those processes which follow a fractal geometry (Günther & Morgado, 1996).

Does the electrocardiogram (ECG) of mammals, as a paradigm of a chronological event of vital importance, provide quantitative information to decide between Euclidean and fractal alternatives? To our

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knowledge, this specific problem, namely the duration of the different ECG waves as function of body mass (M), has not been investigated. By accident, and as another example of serendipity, we had access to Grauwiler's (1965) monograph concerning the comparative physiology of heart and circulation in mammals of different sizes, which included a systematic analysis of the ECG of numerous mammals, besides several hemodynamic variables (heart rate, systemic arterial pressure, plasma volume and cardiac output). The aim of the present study was to test whether different ECG intervals are correlated with R-R interval or its reciprocal (heart rate), when all these variables are expressed as functions of body mass (M).

METHODS

The present study on the ECG intervals was entirely based on mammalian specimens provided by the Basel Zoological Garden, Switzerland, as reported in Grauwiler's (1965) monograph. Since body mass values (M in kg) were not specified in Grauwiler's monograph, the corresponding body masses were obtained from Heusner's (1991) thorough investigation on metabolic rate as a function of body mass in 391 mammalian species. We estimated the approximate body mass (M) of each specimen by using Linnean taxonomic identity in each instance.

The present study must take into account that: *i*- in 50% of the cases, the ECG was measured in only one or two specimens; *ii*- anesthesia was necessary in 50% of the ECG recordings; *iii*- about 20 % of the animals were juveniles; *iv*- the number of specimens varied from 1 (whale) to 535 (dogs) and, consequently, the ECG values reported were not equally representative. Thus, only arithmetic means from Grauwiler's data could be used in the present statistical analysis.

Nevertheless, the duration of ECG intervals was correlated with the most probable body mass (M, in kg) in 39 cases. Finally, the above facts justify that only elementary statistical procedures were applied in the present study.

RESULTS

Table I summarizes the values for allometric parameter **a** and exponent **b** of ECG intervals, together with some statistical parameters: standard error (b_s), determination coefficient (r^2), as well as 95% confidence limits for the allometric exponent **b**. The mean value of this exponent for different ECG intervals (Table I, items 2, 3, 4) is b = 0.202, which is very close to the value of the exponent of the R-R interval (b = 0.212 ± 0.018).

Our results obtained from the R-R intervals (Table I, item 1) may be also compared with the reciprocals of R-R intervals, namely the heart rate of different mammalian species, as summarized in Table II. The allometric exponents (b) for the heart rate of mammals vary from b = -0.25 to b = -0.27, which are slightly different from b = 0.212, estimate of the R-R interval (Table I, item 1), whose upper 95 % confidence limit is b = 0.248.

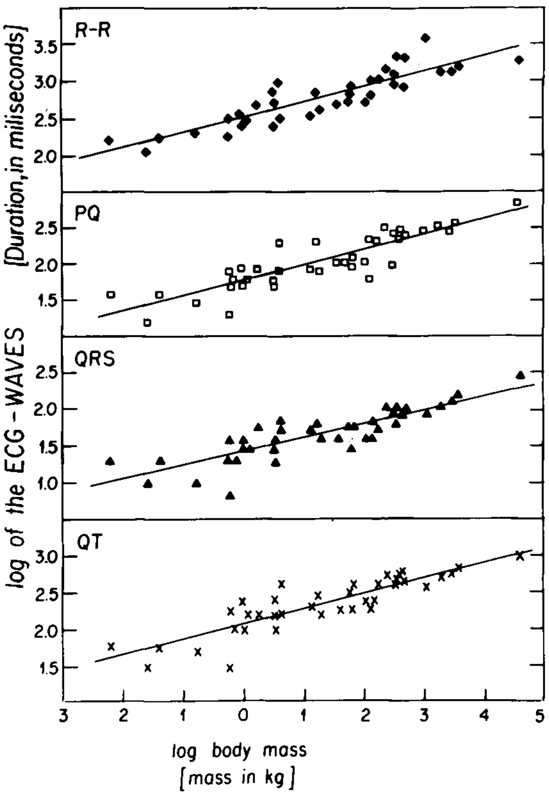

Fig 1. Log-log plot of the durations of ECG waves (ms) as functions of body mass (kg). The corresponding numerical parameters (**a** & **b**) of the four allometric equations are given in Table I.

Table I

Allometry of the different waves of the ECG in milliseconds (ms), as functions of body mass (kg), in 39 mammalian species.

Item	Function	Parameter (a)	Exponent (b)	b_S *	r^2 #	95% Confidence Limits Of Exponent
1	Interval R-R	300.1	0.212	0.018	0.790	0.175-0.248
2	Interval P-Q	58.04	0.211	0.019	0.760	0.172-0.250
3	Interval QRS	27.04	0.188	0.019	0.719	0.150-0.227
4	Interval QT	117.14	0.207	0.019	0.755	0.168-0.246

* b_S = standard error of exponent (b)
# r^2 = determination coefficient

Table II

Allometric parameters of heart rate (s^{-1}) in mammals, as function of body mass (kg).

Item	Mass-coefficient (a)	Allometric exponent (b)	References
1	**3.62**	-0.27	Brody, 1945
2	**3.61**	-0.27	Adolph, 1949
3	**3.60**	-0.27	Günther & León de la Barra, 1966
4	**3.93**	-0.25	Günther, 1975
5	**4.03**	-0.25 ± 0.01 *# (O.230-0.270) **	Stahl, 1981, quoted by Peters, 1983, p 257

* M ± SE = mean ± standard error
\# n = 447
** 95% confidence limits of exponent

DISCUSSION

The cardiac anatomy is an example of the ubiquitous nature of fractal geometry (West & Goldberger, 1987) because the His-Purkinje´s conduction path is an irregular, but self-similar dichotomous branching system giving rise to the QT complex of the ECG. On the other hand, the PQ interval is the result of the progressive depolarization of the myocardial syncytium of both auricles, whose spheroidal form leads to the monophasic and positive P deflection of the ECG, preceding the QRS complex representing the right and left ventricles depolarization (Bassingthwaighte *et al*, 1994). One should expect that the time course of the auricular PQ interval could be different from the QT interval of the His-Purkinje´s conduction system. The contraction of both ventricles, with quasi-cylindrical cavities and different wall thickness, might be correlated differently with the size of the entire heart, when all variables are expressed in allometric form. Therefore, we were interested in the analysis of the durations of each of the components of the normal ECG and their relationships with the duration of the entire cardiac cycle (R-R interval) in mammals of different size.

From the comparison of Tables I and II, we may conclude that the 95% confidence limits (0.175-0.248) of the allometric exponent for the R-R interval (Table I, item 1) is in the range of Stahl's (1981; quoted by Peters, 1983) data for the heart rate of mammals (0.230-0.270), as shown in Table II, item 5. Furthermore, the 95% confidence limits for the allometric exponent of the R-R interval are almost the same than those for the allometric exponents of other ECG intervals (Table I, items 2-4). In particular, the estimated exponent of the P-Q interval seems to indicate that auricular depolarizations do not follow the expected Euclidean geometry but a fractal one, probably due to the dichotomous or trichotomous spreading of excitation waves.

A new mathematical model (West *et al*, 1997) for living organisms, comprising 21 orders of magnitude, from microbes to whales, could predict **b** values for scaling of structural and functional variables. These values were in close agreement with measured values reported in the literature. The fractal approach of this novel theory gives us a 0.25 power scaling rule for all biological periods, and also the 0.75 power of body mass (M) which predicts the enigmatic 0.75 exponent for metabolic rate when expressed as a function of body mass (M). This quantitative model is based on only three unifying principles or assumptions: *i*- a space-filling fractal-like branching is assumed to supply the entire volume of organs and organisms; *ii*- the final branch of this network is a size-invariant unit, such as the capillary in the circulatory system; *iii*- the energy required to distribute resources is minimized. This model provides a theoretical, mechanistic basis for further understanding the central role of body size in all aspects of biology, including the 0.25 power for all biological cycles, as for instance the cardiac cycle length and its components (ECG intervals).

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