Nonstationary time series analysis of heart rate variability

P.B. Siegel[1], J. Sperber[2], W. Kindermann[2], and A. Urhausen[2]

July 14, 2004

[1]Physics Department, California State Polytechnic University Pomona, Pomona, CA 91768
[2]Institute of Sport and Preventative Medicine, University of Saarland, 66041 Saarbruecken, Germany

Abstract

An analysis of the RR-interval time series, t_i, is presented for the case in which the average time, $\bar{t}$, changes slowly. In particular, $\bar{t}$ and a short-time scale variability parameter, V, are simultaneously measured while $\bar{t}$ decreases for subjects in the reclined position. The initial decrease in $\bar{t}$ is usually linear with V yielding parameters that can be related to physiological quantities.

PACS: 87.19.Hh, 87.80.Tq, 87.80.Vt, 05.45.Tp

1 Introduction

Heart rate variability is used to examine the autonomous nervous system's control of heart rate, with the goal of assessing health and fitness in humans[1]. The main measurement is the time between successive heartbeats, which is referred to as the RR-interval. Measurements are taken over time periods that can be as short as minutes or as long as days, and the resulting data are a series of times, t_i, measured to an accuracy of milliseconds. Data analysis includes methods from spectral analysis[2, 3, 4, 5], statistical physics [6, 7], and nonlinear dynamics[8, 9, 10, 11]. These methods are applied to situations for which the time series is stationary, that is, the average value of the t_i does not change significantly in time. These approaches have been useful in

determining certain aspects of heart rate control. However, there may be ambiguities in relating the analysis parameters, which are often scaling exponents, to physiological quantities.

In this report, we consider the feasibility of using a nonstationary time series of the RR-interval times to assess heart rate control. If the average value of the t_i, $\bar{t}$, changes sufficiently slowly, then it is possible to also measure a short-time scale variability parameter, V. If $\bar{t}$ and V depend upon physiological quantities in different ways, then a plot in the $\bar{t} - V$ plane for a controlled process may yield information about the influences causing the change.

2 Description of Measurements and Data Analysis

The average heart period ($\bar{t}$) and the variability (V) of the RR-interval times depend primarily on the autonomous nervous system, which has two main influences: sympathetic (m) and parasympathetic (n) nerve activity. One would like to learn about m and n from the non-invasive measurements of $\bar{t}$ and V. A model used by physiologists to describe the relationship of the average heart rate B to the sympathetic and parasympathetic influences is given by the equation [12, 13, 14] $B = B_0 mn$ where B_0 is the intrinsic heart rate, m is the sympathetic factor and n the parasympathetic factor. The sympathetic factor m is greater than one, increasing the heart rate, and the parasympathetic factor n is less than one, decreasing the heart rate. The factors m and n which multiply the intrinsic heart rate depend, among other influences, upon a person's activity level, posture, recent diet, degree of fitness, age, and health. We label all these parameters, which affect the sympathetic (m) and parasympathetic (n) factors, by the symbol β: m(β) and n(β). One can also write $n = 1/(1 + P(\beta))$, where the parasympathetic control parameter P is unitless and varies from zero to its maximum value P_{max}. In terms of the average heart period, the equation can be written as $\bar{t} = T_0(1 + P(\beta))/m(\beta)$, where $T_0 = 1/B_0$ is the intrinsic heart period.

While in general variability is influenced by both sympathetic and parasympathetic effects, short-time scale variability depends primarily on parasympathetic activity. Short-time scales are variations with frequencies greater than 0.15 Hz. Since average heart rates are around one beat per second, this corresponds to variations in heart rate taking place in less than roughly 6 heartbeats. There is good evidence that high frequency (> 0.15Hz) spectral power depends only on P, and is not influenced by sympathetic nerve activity. Thus, if V is a measure of short-time scale variation, it can be expressed as a function of parameters other than m, namely $V(P, \beta)$. Expressing P in terms of V and the "β" factors, the relationship between the average heart

period and its variability can be written as $\bar{t} = T_0(1 + P(V, \beta))/m(\beta)$. Measurements of $\bar{t}$ and V during slow changes of these values can yield information about changes in m, T_0, and the function $P(V, \beta)$.

For this study, we chose as the variability parameter V the respiratory sinus arrhythmia (RSA) amplitude, which is the amplitude of the fluctuations of the RR-interval times due to breathing, for a breathing rate of 12 breaths/min. We have chosen this parameter for V since it has been shown in unconscious dogs[12] and humans[13] that $(\bar{t} - T_0/m)$ is proportional to the RSA amplitude. The experiments carried out in Refs. [12] and [13] used pharmacological methods (parasympathetic blockade) to decrease $\bar{t}$ while keeping m constant. If this linear relationship holds in general, then $V(P, \beta)$ takes on the simple form $V = k(\beta)P$, where k has the same units as V. Letting V represent the RSA amplitude for a 12 breath/min breathing rate, we have

$$\bar{t} = \frac{T_0}{m}(1 + \frac{V}{k}) \tag{1}$$

where m and k might depend on posture, tidal volume, environmental factors, diet before measurement, etc. The hope is that $\bar{t}$ and V can be varied keeping k constant.

We measured both the average heart period in msec, and the amplitude of the RSA in msec for various subjects while they underwent slow warm up in the lying position. Since the amounts of sympathetic and parasympathetic influences are posture dependent, it is important to maintain the same posture while the heart rate changes. The lying position was chosen because the parasympathetic activity is maximized in this position. The subject slowly increased his/her pulse by pedaling a stationary bicycle in the lying position while breathing at 12 breaths/min the whole time. He/she started by lying still for 2 minutes, and then began pedaling slowly with a load of 25 watts for the duration of one minute. The subject then pedaled faster until the heart rate increased to around 20 bpm above its resting value. The load was increased by increments of 25 watts each two minutes thereafter, until a pulse of around 110 beats/min was reached.

Breathing was controlled by having the subjects breathe in concert with increasing and decreasing tones, which they listened to from a CD player. RR interval times were recorded using a heart rate monitor from Polar, Model S810. The average heart period and RSA amplitude were computed from a sequence of 100 consecutive RR-interval times, with the start of the interval shifted 50 beats after each calculation. For example, the first sequence is beat numbers 1 to 100, the second from 50 to 150, etc. Since breathing was controlled at 12 breaths/min, the peak in the Fourier spectrum was distinct at 0.2 Hz. From each sequence of 100 times, the RSA amplitude

was set equal to this peak Fourier amplitude at or near the breathing frequency of 12 cycles/min (i.e. 0.2 Hz).

3 Discussion

We carried out the test for 20 subjects, and plot some typical cases in figures 1 to 3. In each figure, the initial part of the warm up is linear, labelled $1 \rightarrow 2$, in which both the heart period and the variability decrease. This is followed by a decrease in heart period with little change in variability, labelled as $2 \rightarrow 3$ in the figures. About 75% of the subjects we measured had similar plots.

The data can be interpreted using the model of Eq. 1. During the initial linear stage of the warm-up, $1 \rightarrow 2$, parasympathetic influences are reduced since the RSA amplitude decreases. If the RSA amplitude is proportional to P, the data are consistent with T_0/m and k being constant during this first stage. After the initial parasympathetic decrease, the plot moves to the left, $2 \rightarrow 3$. Since the variability does not change during this stage, the data indicate that m is increasing. For the initial linear stage, three parameters can be determined: T_0/m, k, and P_{max}. The parameter P_{max} is unitless, and is the fraction that the parasympathetic activity increases the heart period from T_0 to the maximum value of $\bar{t}$: $P_{max} = (t_{max} - T_0/m)/(T_0/m)$, where t_{max} is the maximun value of the average heart period. These parameters can always be determined for a linear stage of the graph. If the model of Eq. 1 is valid and k remains constant, then the parameters have physiological significance. In the figures we state P_{max}, k, and T_0/m for the slow warm-up phase.

Some subjects show interesting results, which we graph in figures 2 and 3. In figure 2, the plot shows four stages which can be interpreted using Eq. 1. Initially $(1 \rightarrow 2)$ the RSA amplitude decreases significantly suggesting P decreases with m constant. Then $(2 \rightarrow 2a)$ the heart period decreases but the RSA amplitude remains constant, meaning that m increases with P constant. The next change from $2a \rightarrow 2b$ is similar to the change from $1 \rightarrow 2$, and the final stage from $2b \rightarrow 3$ has m increasing with P constant as from $2 \rightarrow 2a$. For this subject it appears that the heart rate increases via alternating parasympathetic and sympathetic influences.

In figure 3 we compare two different subjects. Both subjects have the same resting heart rate of 50 bpm. One subject (circles) has a resting RSA amplitude of 70 msec, while the other (triangles) only 25 msec. One might be lead to believe that the first subject has a stronger parasympathetic activity, since the RSA amplitude is larger. However, during warm-up the RSA amplitude for the first subject (circles) was reduced to its minimum value of 10 msec for only a 350 msec decrease in heart

period. For the other subject (triangles), the heart period decreased by 600 msec before the RSA amplitude was reduced to its minimum value. Thus the second subject has a larger change in heart period due to the reduction in parasympathetic activity, and consequently a larger value of P_{max}. The plots in the $\bar{t} - V$ plane are quite different for these subjects even though they have the same resting heart rate.

We also used the absolute value of the difference between successive RR-intervals without controled breathing as a variability parameter. If the subject is breathing at a consistent rate throughout the exercise, the results are similar to those obtained using the RSA amplitude with a different value of k. Other possible candidates for a variability parameter are the standard deviation of the RR-interval times, the square-root of the high-frequency power, or the RSA from Ref. [15]. Heart rate $(1/\bar{t})$ versus variability are plotted in Refs. [15] and [16]. However, in neither case are the data modeled using the parameters of Eq. 1. In figure 4 of Ref. [16], the loci of points are similar to the figures presented here: a large decrease in RSA for a small increase in heart rate (parasympathetic reduction), and a small decrease in RSA for a large increase in heart rate (sympathetic increase). Perhaps if the time ordering of the points and posture are taken into account, T_0/m, P_{max}, and k could be measured for different types of daily activity.

In conclusion, we propose that a simultaneous measurement of the average heart period $\bar{t}$ and a parameter related to short time-scale variability V can yield insight into the autonomous nervous system. For slow changes in the heart rate, a graph in the $\bar{t} - V$ plane can assist in understanding the influences causing the change. For situations in which the change in heart rate is caused only by the parasympathetic nerve activity, one can extract three parameters, T_0/m, P_{max}, and k. These new parameters could have a simple relationship to physiological quantities.

References

[1] D. Eckberg, Ann. Med. **32**, 341-349 (2000).

[2] M.D. Prokhrov, V.I. Ponomarenko, V.I. Gridnev, M.B. Bodrov, and A.B. Bespyatov, Phys. Rev. E **68**, 041913 (2003).

[3] D. Eckberg, Circulation **96**, 3224-3232 (1997).

[4] M. Malik, Circulation **93**, 1043-1065 (1996).

[5] M. Pagani et. al., Circulation Research **59**, 178-193 (1986).

[6] M. Costa, A.L. Goldberger, and C.-K. Peng, Phys. Rev. Lett. **89** 068102 (2002).

[7] R. Yulmetyev, P. Hanggi, and F. Gafarov, Phys. Rev. E **65**, 022901 (2002).

[8] C.-K. Peng, J. Mietus, J¿M¿ Hausdorff, S. Havlin, H.E. Stanley, and A.L. Goldberger, Phys. Rev. Lett. **70**, 1343-1346 (1993).

[9] S. Thurner, M.C. Feurstein, and M.C. Teich, Phys. Rev. Lett. **80**, 1544-1547 (1998).

[10] M. Wessel, A. Schirdewan, and J. Kurths, Phys. Rev. Lett. **91**, 119801 (2003).

[11] E. Ching, D.C. Lin, and C. Zhang, Phys. Rev. E **69**, 051919 (2004).

[12] P. Katona and F. Jih, J. Appl. Physiol. **39**, 801-805 (1975).

[13] F. Fouad, R. Tarazi, C. Ferrario, C Fighaly and C. Alicandri, Am. J. Physiol. **246**: H838-H842 (1984).

[14] W. Kenney, Med. Sci. Sports. Exer. **17**, 451-455 (1985).

[15] B. Hatfield, T. Spalding, D. Santa Maria, S. Porges, J. Potts, E. Byrne, E. Brody, and A. Mahon, Med. Sci. Sports Exerc. **206**, 14 (1998).

[16] P. Grossman, F. Wilhelm, and M. Spoerle, Am. J. Physiol.Heart Circ. Physiol. PMID: 14751862 (2004).

Figure Captions

Figure 1. Graph of RSA (respiratory sinus arrhythmia) versus heart period as a subject's heart period slowly deceases while in the lying position. From the straight-line section $1 \to 2$ the parameters T_0/m, P_{max}, and k are determined using equation 1.

Figure 2. Same graph as in Figure 1, but for a different subject. The decrease in heart period can be interpreted as alternating between the influences of parasympathetic decrease $(1 \to 2)$ and $(2a \to 2b)$ and sympathetic increase $(2 \to 2a)$ and $(2b \to 3)$.

Figure 3. Same graph as in Figure 1, comparing two different subjects. Both subjects have the same resting rate. Eventhough one subject (circles) has a higher RSA, the parasympathetic control parameter P_{max} is less.

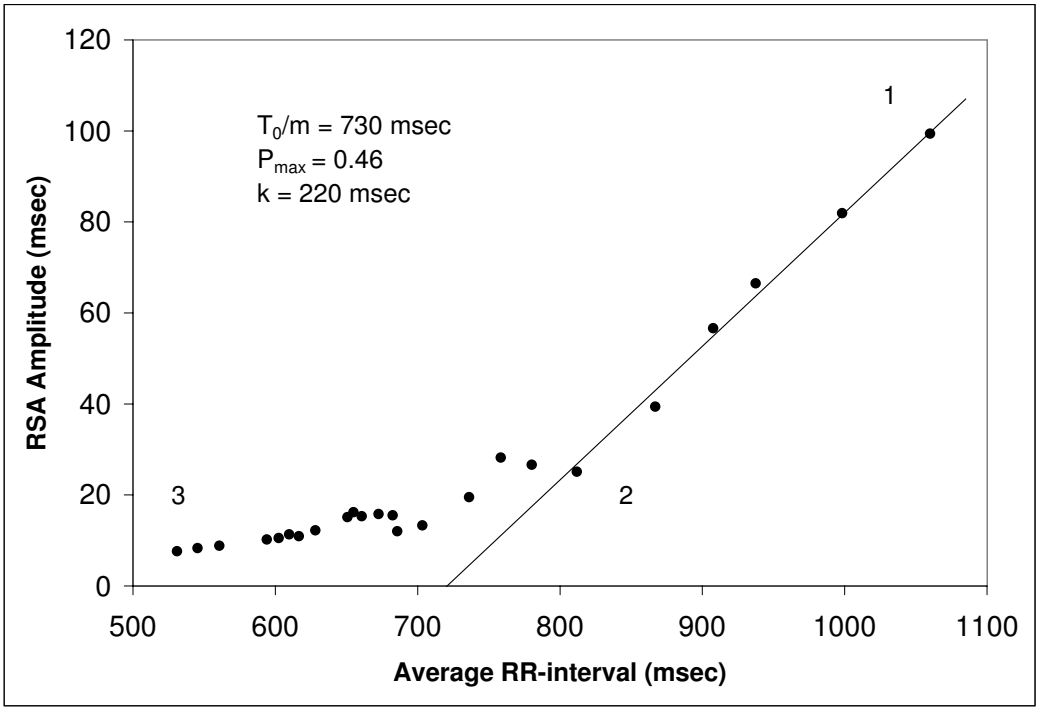

Figure 1. Graph of RSA (respiratory sinus arrhythmia) versus heart period as a subject's heart period slowly decreases while in the lying position. From the straight-line section $1 \rightarrow 2$ the parameters T_0/m, P_{max}, and k are determined using equation 1.

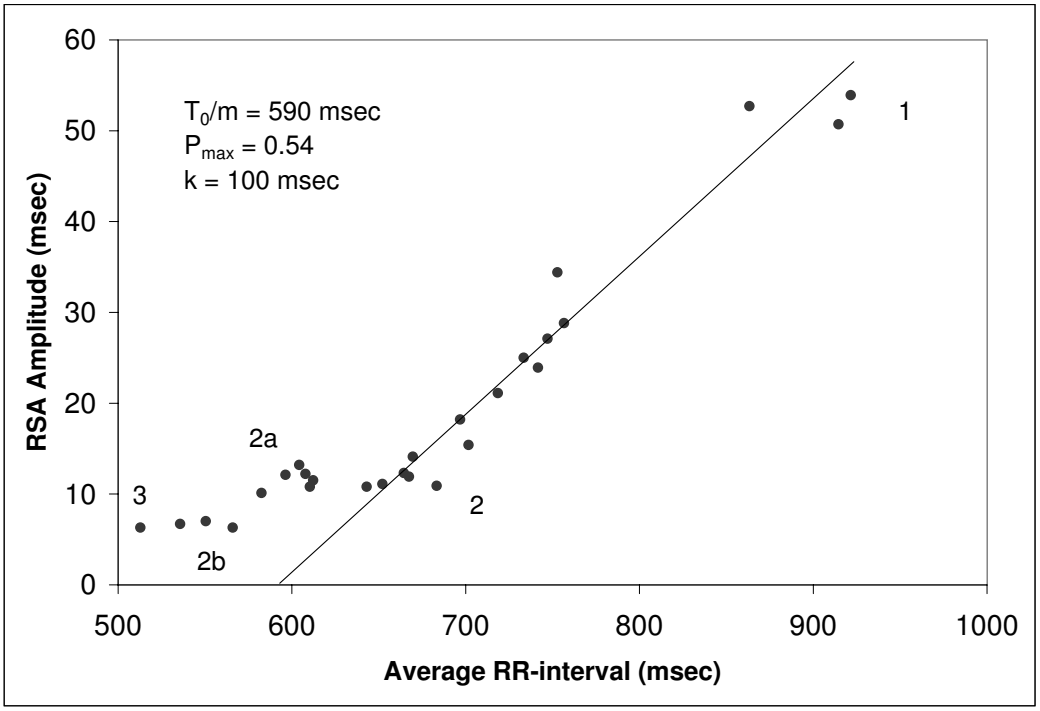

Figure 2. Same graph as in Figure 1, but for a different subject. The decrease in heart period can be interpreted as alternating between the influences of parasympathetic decrease ($1 \rightarrow 2$) and ($2a \rightarrow 2b$) and sympathetic increase ($2 \rightarrow 2a$) and ($2b \rightarrow 3$).

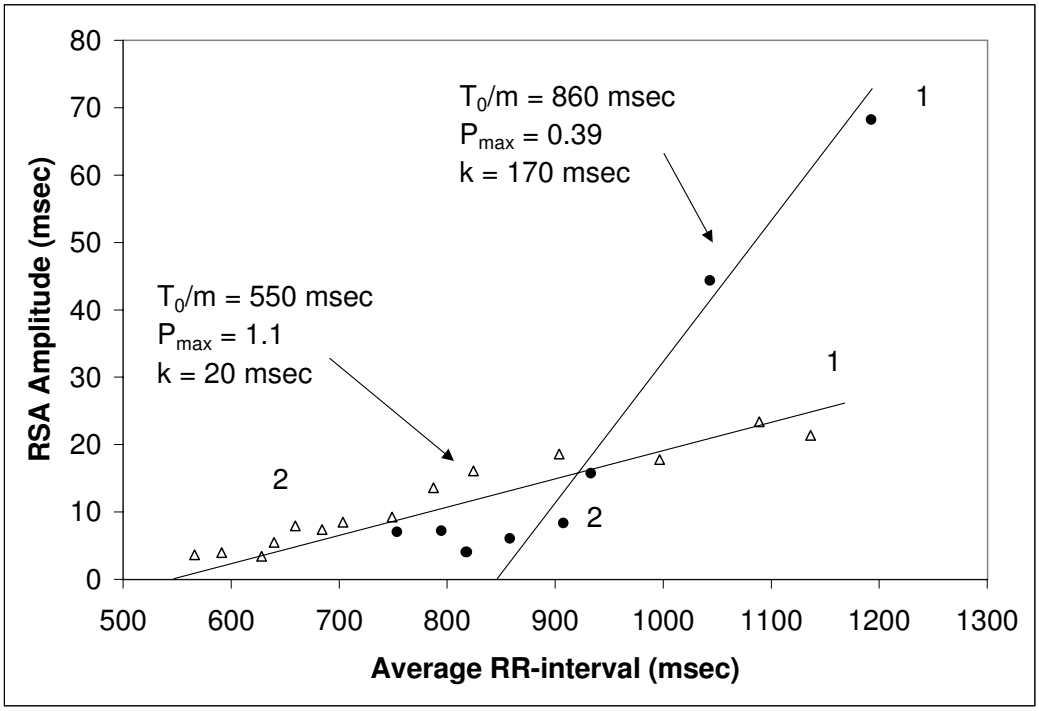

Figure 3. Same graph as in Figure 1, comparing two different subjects. Both subjects have the same resting rate. Eventhough one subject (circles) has a higher RSA, the parasympathetic control parameter P_{max} is less.