Correlations between the Poincaré Plot and Conventional Heart Rate Variability Parameters Assessed during Paced Breathing

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Abstract: Aim: To analyze the correlation of the Poincaré plot descriptors of RR intervals with standard measures of heart rate variability (HRV) and spontaneous baroreflex sensitivity (BRS). A physiological model of changing respiratory rates from 6 to 15 breaths/min provided a wide range of RR intervals for analysis. Material and methods: Beat-to-beat finger blood pressure, ECG, and respiratory curves were recorded noninvasively in 15 young healthy volunteers (19–25 years old; 7 females) breathing for 5 min at 4 different respiratory rates of 6, 9, 12, and 15 breaths/min. Four descriptors of the Poincaré plot (SD1, SD2, S, and SD2/SD1), time and frequency domain HRV, and spontaneous BRS (cross-correlation method) were calculated for each 5-min recording. Results: The values of SD1 characterizing short-term HRV, SD2 describing long-term HRV, and S measuring total HRV were significantly correlated with BRS and time and frequency domain measures of short, long, and total HRV. The LF/HF significantly correlated with SD2 and SD2/SD1 representing the balance between long- and short-term HRV. None of the Poincaré plot descriptors was correlated with the mean RR interval. The increased respiratory rate caused a significant reduction of BRS, measures of total and long-term HRV, and an increase of HF that peaked at 12 breaths/min. Conclusions: The descriptors of the Poincaré plot of RR intervals are significantly correlated with measures of BRS and time and frequency domain HRV, but not with heart rate. A faster respiratory rate reduces long-term HRV measures and temporarily increases HF.

Key words: Poincaré plot, heart rate variability, baroreflex sensitivity, respiratory sinus arrhythmia, paced breathing.

The measurement of heart rate variability (HRV) is a valuable tool in both clinical practice and physiological research [1, 2]. The assumption is that variability is inherent in heart rate, reflecting the ability of the cardiovascular system to adapt to external and internal changes. Multiple studies show that HRV is reduced in various diseases and old age. Indeed, reduced HRV has proven valuable in predicting mortality in the survivors of myocardial infarction [2, 3]. In spite of its usefulness, there is no single accepted measure of HRV [1, 3].

The Poincaré plot of RR intervals is one of the recent methods of HRV analysis. It has also been used to measure the autonomic modulation and randomness of the heart rate [1, 4–12]. The Poincaré plot is a graphical representation of temporal correlations within the RR intervals derived from ECG [4, 5]. In this plot (Fig. 1), each RR interval is a function of the preceding RR interval, i.e., the duration of the current cardiac beat (RRn) is represented on the x axis, and the duration of the following beat (RRn+1) on the y axis, so each point (RRn, RRn+1) in the plot corresponds to two successive heart beats. Various descriptors are associated with this plot, some of which have a convincing physiological interpretation [5, 6].

In the present study we aimed to evaluate four distinct descriptors of the Poincaré plot of RR intervals, compare and contrast them with conventional parameters of HRV and with a measure of spontaneous baroreflex sensitivity (BRS) in a physiological model of changing respiratory rate from 6 to 15 breaths/min. To this end we have correlated the Poincaré plot descriptors with standard HRV parameters derived from time-domain and frequency-domain analyses and BRS [1–3, 13]. We have used the changing respiratory rate because it provides a wide range of RR intervals for HRV analysis. The change in RR intervals caused by breathing is known as respiratory sinus arrhythmia, which is regulated by breathing phase, depth, and rate [14–16]. The variation of RR intervals with respiration was suggested as a measure of the autonomic nervous system function in the 1970s, and it has been evaluated by different methods with particular focus on the spectral approach to HRV, but never with an analysis of Poincaré plots [14, 17–19].
beats of equal duration (RR) duration of the following beat (RR)
prolongations (RR

Fig. 1. A typical Poincaré Plot of RR intervals. The duration of the current cardiac beat (RR
 is shown on the x axis and the duration of the following beat (RR
) on the y axis. In this way each point in the Poincaré plot is described in the (RR
, RR
) space. All points described by consecutive cardiac beats of equal duration (RR
 = RR
) are located on the identity line. The points above the identity line correspond to all prolongations (RR
 < RR
), and the points below this line represent all shortenings of the interval between 2 consecutive beats (RR
 > RR
) [4].

MATERIAL AND METHODS

Subjects. Fifteen healthy volunteers (19–25 years old; 7 females) participated in this study. All subjects refrained from tobacco, alcohol, and coffee for 24 h prior to the study. No participant was addicted to drugs, taking any medications or hormones, or involved in endurance training. Four participants were occasional smokers, and the rest (n = 11) were nonsmokers. All volunteers gave informed consent to participate in the study. This project was approved by the University Bioethics Committee.

Protocol. The study was performed at rest in the supine position. First, the subjects were allowed to breathe spontaneously for 20 min for cardiovascular adaptation. They were then asked to breathe at a paced respiratory rate of 6, 9, 12, or 15 breaths/min (0.1, 0.15, 0.2, and 0.25 Hz, respectively) for 5 min each. During paced breathing, inspiration and expiration were both of equal duration. The pattern of paced breathing was directed by hand movement, as well as by verbal instruction by one of the examiners. The beginning of the inspiration and expiration phases was explicitly indicated. The 5-min segments of controlled breathing were separated by 2-min breaks of spontaneous breathing. Our preliminary results had shown that breathing for 5 min at rates in the range of 6 to 15 breaths/min is well tolerated, and the subjects are easily able to maintain the pattern. At slower- (3 breaths/min) or faster- (18 breaths/min or more) paced breathing, the pattern is often lost. The order of the 4 paced respiratory rates was random and changed from subject to subject.

Methods. Three channels of a bipolar chest lead ECG with respiratory curve and finger blood pressure wave were simultaneously recorded with a sampling frequency of 1,600 Hz by an A/D converter (Porti 5, TMSI, The Netherlands). These data were then transferred to a PC for on-screen monitoring and data storage. Respiratory curves were measured by using an elastic piezoelectric belt (Porti 5, TMSI, The Netherlands) secured around the subject’s trunk at the level of the xyphoid. The respiratory curves and ECG were recorded directly by the A/D converter. For BRS measurement, a noninvasive beat-to-beat finger arterial blood pressure was recorded continuously with the use of a volume-clamp photoplethysmographic method (Portapres 2, FMS, The Netherlands) and transferred to the A/D converter [20]. The preliminary automatic evaluation of the recordings was performed with the use of the libRASCH/RASCHLab software from the libRASCH project (v. 0.6.1; http://www.librasch.org, Germany). This was then followed by a visual inspection of all signals and necessary corrections of the obtained values [21]. The values of the RR intervals and systolic blood pressure were retrieved from the stored recordings and used in further analysis.

Heart rate and heart rate variability. Heart rate, shown as the mean RR interval, and its variability were measured in all 5-min segments of paced breathing. Three methods of HRV quantification were used, namely, the time domain analysis, the frequency domain analysis, and the Poincaré plot analysis.

The time domain HRV analysis was evaluated by calculating the following, widely accepted [1] parameters: SDNN (the standard deviation of normal-to-normal RR intervals), HRVI (heart rate variability triangular index), and RMSSD (the square root of the mean squared successive differences between normal-to-normal RR intervals) [1]. SDNN and HRVI are measures of total heart rate variability; RMSSD corresponds to short-term variability.

The frequency domain HRV analysis was assessed by calculating the following parameters: total power (TP), low-frequency power (LF) (from 0.04 to 0.15 Hz), high-frequency power (HF) (from 0.15 to 0.4 Hz), and the ratio LF/HF [1]. TP is believed to characterize the total HRV [1, 2]. HF is usually interpreted as reflecting high-frequency oscillations caused mainly by changes in vagal tone, which are responsible for short-term HRV [22]. LF describes low-frequency oscillations that depend on both sympathetic and parasympathetic activities and are responsible for long-term HRV [1, 2, 22]. The ratio of LF to HF (LF/HF) reflects the balance between low- and high-frequency oscillations, i.e., long- and short-term HRV [1, 2, 22, 23].
The calculation of HRV in the time and frequency domains was performed with the implementations available from the libRASCH project [1, 21]. The parameters of spectral HRV analysis were calculated with an equidistant tachogram of normal-to-normal RR intervals (at least 300 ms and no more than 2,000), its linear interpolation, smoothing with a boxcar filter with a width of 2 samples, and the application of Hanning’s window. Finally, the Fast Fourier Transformation was performed with the calculation of power in the frequency bands as recommended [1].

The analysis of the Poincaré plot of RR intervals was performed with the use of the Matlab package (the MathWorks Inc., USA), according to published references [5, 6]. The following 4 descriptors of the Poincaré plot were used in the study (compare Fig. 2):

(1) SD1—the standard deviation measuring the dispersion of points in the plot across the identity line. All points of the Poincaré plot are projected on a line perpendicular to the line of identity, and the standard deviation of the resulting distribution is calculated. This parameter is usually interpreted as a measure of short-term HRV – for a convincing discussion see [6].

(2) SD2—the standard deviation measuring the dispersion of points along the identity line. All points are projected on the identity line, and the standard deviation is calculated. This variable is interpreted as a measure of both short- and long-term HRV [6].

Additionally, two other nonstandard descriptors of the Poincaré plot are used:

(1) S—corresponds to the area of an imaginary ellipse ($S = \pi \times SD1 \times SD2$) with the axes of lengths: SD2 (parallel to the identity line) and SD1 (perpendicular to the line of identity). In the present paper this descriptor is interpreted as a measure of total HRV because it has the qualities required for such a descriptor—e.g., it grows with the growth of either SD1 or SD2, or with both, and it remains constant if SD1 grows at the rate at which SD2 decreases.

(2) SD2/SD1—is the ratio of SD2 to SD1 [8, 9]. Our hypothesis is that SD2/SD1 measures the balance between long- and short-term HRV, by analogy to LF/HF from spectral HRV analysis [1, 8].

As already noted, our goal was to investigate the interpretation of the above parameters and their relation to the established HRV parameters. The Matlab scripts for all the Poincaré plot descriptors used in the present paper may be found in our previous report [24].

**Baroreflex sensitivity.** The BRS was measured in all 5-min segments of paced breathing with the use of the cross-correlation method, which computes a time-domain sequential BRS on spontaneous blood pressure and RR interval variability for fixed windows 10-s in long [25]. The geometric mean of the obtained series of BRS estimates from each 5-min segment was taken into further analysis.

**Statistical analysis.** All continuous data are presented as mean ± standard error of the mean (SEM). To explore the relationship between the increasing respiratory rate, we used the values of HRV, BRS, and the RR interval, the nonparametric repeated measures ANOVA (Friedman’s test). If the overall ANOVA $p$-value was statistically significant ($p < 0.05$), the Dunn’s multiple comparison post-test was performed to determine the differences in data between respiratory rates of 6 vs. 9, 12, and 15 breaths/min. The relationship between the Poincaré plot descriptors and the mean RR interval, values of the other HRV measures and BRS, was calculated with the use of the nonparametric Spearman correlation coefficient. This correlation was calculated for pooled data containing values from all respiratory rates yielding a total of 60 pairs for each correlation. Only values with $p < 0.05$ were considered statistically significant.

**RESULTS**

**The influence of paced respiratory rate on heart rate, HRV, and BRS**

Increasing respiratory rate caused a significant prolongation of RR intervals from 829.4 ± 30.2 ms (6 breaths/min), 859.3 ± 28.4 ms (9 breaths/min), to 878.4 ± 25.1 ms (12 breaths/min), up to a maximum of 879.2 ± 28.4 ms (15 breaths/min) (ANOVA $p = 0.0117$). The posttest revealed that only RR intervals for 12 ($p < 0.05$) and 15 ($p < 0.05$) breaths/minute were significantly longer than the RR intervals for 6 breaths/min. The results of HRV and BRS analyses are shown in Fig. 3.

An increasing respiratory rate caused a significant reduction in SDNN ($p = 0.0136$). The posttest multiple com-
comparison for SDNN showed that the only significant ($p < 0.05$) difference was between the SDNN values for 6 and 15 breaths/min.

Increasing respiratory rate was associated with significant changes of all frequency domain parameters studied. More specifically, TP ($p < 0.05$), LF ($p < 0.0001$), and LF/HF ($p < 0.0001$) were reduced, and HF ($p < 0.0001$) was increased. The posttests revealed that in comparison with 6 breaths/min, TP was significantly reduced for 15 paced breaths/min, LF was significantly decreased for 12 ($p < 0.001$) and 15 ($p < 0.001$) breaths/minute, and LF/HF was significantly lower for 9 ($p < 0.01$), 12 ($p < 0.001$), and 15 ($p < 0.001$) breaths/min. The HF power for 9 ($p < 0.001$) and 12 ($p < 0.001$) breaths/min was significantly higher than for 6 breaths/min.

An increasing respiratory rate decreased the values of S ($p = 0.0272$), SD2 ($p = 0.0078$), and SD2/SD1 ($p < 0.0001$) significantly. The posttest showed that in comparison with 6 breaths/min, the S value was significantly reduced for 15 breaths/min ($p < 0.05$), SD2 was significant-
ly decreased for 12 (p < 0.05) and 15 (p < 0.05) breaths/ 
min, and the SD2/SD1 ratio was significantly lower for 12 
(p < 0.01) and 15 (p < 0.001) breaths/minute. The samples 
of 4 Poincaré plots of RR intervals representing 4 different 
respiratory rates in the same subject are shown in Fig. 4.

BRS (p = 0.0177) significantly decreased as the paced 
respiratory rate increased. In the posttests, the BRS value 
for 6 breaths/min was significantly higher than for 9 (p < 
0.05) and 15 (p < 0.05), but not for 12 breaths/min.

**Correlations between descriptors of the Poincaré plot and established HRV and BRS**

The correlations between the descriptors of the 
Poincaré plot of RR intervals and the mean RR interval as 
well as the time and frequency domain measures of HRV 
and BRS are presented in Table 1 and Fig. 5.

There were significant correlations, all with p < 
0.0001, between the area of the Poincaré plots and BRS 
and all measures of HRV with the exception of LF/HF. An 
extremely high correlation was found between S and

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**Table 1.** Results of Spearman correlation analysis of the relationship between descriptors of Poincaré plot and time and spectral 
HRV parameters as well as BRS for pooled data collected at various paced respiratory rates. For abbreviations see text.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S</th>
<th>SD1</th>
<th>SD2</th>
<th>SD2/SD1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p value</td>
<td>r</td>
<td>p value</td>
</tr>
<tr>
<td>RR intervals</td>
<td>0.12</td>
<td>n.s.</td>
<td>0.12</td>
<td>n.s.</td>
</tr>
<tr>
<td>SDNN</td>
<td>0.98</td>
<td>&lt;0.0001</td>
<td>0.86</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>HRVI</td>
<td>0.71</td>
<td>&lt;0.0001</td>
<td>0.60</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>RMSSD</td>
<td>0.93</td>
<td>&lt;0.0001</td>
<td>1.00</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TP</td>
<td>0.86</td>
<td>&lt;0.0001</td>
<td>0.75</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LF</td>
<td>0.64</td>
<td>&lt;0.0001</td>
<td>0.48</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>HF</td>
<td>0.58</td>
<td>&lt;0.0001</td>
<td>0.71</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LF/HF</td>
<td>0.08</td>
<td>n.s.</td>
<td>-0.10</td>
<td>n.s.</td>
</tr>
<tr>
<td>BRS</td>
<td>0.80</td>
<td>&lt;0.0001</td>
<td>0.75</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
SDNN \((r = 0.98)\). RMSSD and TP also correlated well with S \((r > 0.85)\). SD1 correlated significantly \((p < 0.0001)\) with all measures of HRV and BRS studied, with the exception of LF/HF. However, the \(r\) values were considerably smaller than for S, except for HF, which had a higher correlation with SD1 than with S. Another exception was for RMSSD with \(r = 1\), which is a natural consequence of a known relationship between these two variables, which is RMSSD = \(\sqrt{2} \times SD1\) [6]. There were significant correlations between SD2 and BRS and all HRV measures, including LF/HF, most with \(p < 0.0001\). The highest correlation \((r = 1)\) was observed between SD2 and SDNN. The correlations between SD2/SD1 and other analyzed variables were statistically significant for most HRV measures studied, with the exception of RMSSD, but with larger \(p\) values and smaller \(r\) values than for S, SD1, and SD2. The highest correlations, although of moderate strength, were observed between SD2/SD1 and LF/HF \((r = 0.63)\) and LF \((r = 0.54)\). SD2/SD1 was significantly and negatively correlated with HF. There were no significant correlations between SD2/SD1 and the mean RR interval and BRS.

**DISCUSSION**

We found that increasing respiratory rate decreased heart rate, BRS, and HRV parameters that reflect total variability, long-term variability, and sympathovagal balance. HF power increased with respiratory rate, peaking at 12 breaths/min, but RMSSD and SD1, which are also HRV parameters that describe short-term HRV, showed no change with respiratory rate.

The Poincaré plot descriptor characterizing the total HRV is S, which is best correlated with other established measures of total HRV like SDNN, TP, and HRV1. The association of S with other indices of autonomic modulation of heart rate suggests that S is related to parasympathetic tone (HF, RMSSD), reflex vagal activity (BRS), and sympathetic activity (LF). A parameter similar to S has already been used by Toichi *et al.* [9]. However, there are substantial differences in the mathematical definitions and physiological interpretation between the S used in the present paper and the variable used by Toichi *et al.* Additionally, unlike the present paper, in the study by Toichi *et al.* the product SD1 \(\times SD2\) is interpreted as reflecting only parasympathetic tone.

The perfect correlation of SD1 is with RMSSD because mathematically the two parameters are equivalent, although their origin is different [6]. Thus SD1 has the same interpretation as RMSSD, which is an accepted measure of short-term HRV [1, 2, 22]. Other significant correlations with HF and BRS confirm that SD1 is a good marker of parasympathetic control of heart rate. SD1 is also significantly correlated with LF, which might suggest some dependence on sympathetic activity. Another explanation may be that in the case of short 5-min recordings, LF is strongly affected by vagal activity, particularly in the supine position [1], as in our study. However, the connection of SD1 to sympathetic activity cannot be ruled out.

SD2 was best correlated with measures of total HRV, which seems to be a consequence of the relation of total HRV to long-term HRV in short recordings [1, 11]. The correlation between SD2 and LF is twice as large as with HF, which supports the hypothesis that SD2 is related more strongly to sympathetic than to parasympathetic tone [11]. This conclusion is further supported by a significant correlation between SD2 and LF/HF.

We interpret the ratio of SD2/SD1 as a measure of the balance between long- and short-term HRV by its analogy and similar properties to LF/HF [8, 9]. In both ratios the numerators correspond to a parameter depending on both long-term (low frequency) and short-term (high frequency) variability, and the denominators depend solely on short-term variability. Thus, as expected, SD2/SD1 correlates most strongly with LF/HF. Of note, SD2/SD1 is positively correlated with LF, negatively with HF, and not significantly with RMSSD or BRS. These figures suggest that higher values of SD2/SD1 may express an increased sympathetic drive and/or decreased parasympathetic activity. Although strongly criticized, the ratio of LF/HF is believed to be an indirect index of (or at least to be related to) the sympathovagal balance [1, 9, 11, 23]. The correlations found in the present study suggest that SD2/SD1 might be considered to some extent as an alternative for LF/HF. Moreover, the SD2/SD1 parameter is mathematically equivalent to the cardiac sympathetic index defined by Toichi *et al.* with a similar physiological interpretation [9]. Some other authors use the reciprocal of this parameter as an index of heart rate randomness rather than autonomic balance [7, 12].

The technique of the Poincaré plot allows us to visualize all points described by consecutive RR intervals and to easily identify the points corresponding to outliers in the heart rhythm fluctuations like premature beats, compensatory pauses, or even technical artifacts. The outliers do not influence the Poincaré plot as strongly as the traditional time and frequency domain measures of HRV. Further, the Poincaré plot can be used to remove the identified outliers [5, 6, 24]. For obvious reasons this visualization is not possible with spectral analysis and most time domain methods.

The descriptive time domain measures, such as the mean RR, SDNN, and pNNx, are extremely sensitive to artifacts and are impossible to interpret if the analyzed signal is nonstationary [3]. The frequency distributions underlying the above measures, which can be produced for visual inspection, lack widespread clinical application, and their preparation involves some arbitrary decisions, for example, the selection of the number of bins [3]. We might also add that the traditional time domain methods
completely ignore the time series structure of the set of RR intervals derived from an ECG. Besides, compared with the time domain HRV, the Poincaré plot analysis may give some additional information about the balance between short- and long-term variability. The traditional frequency methods (spectral power evaluation) also require stationarity of the analyzed signal and are sensitive to artifacts. Moreover, they are very difficult to calculate and various methods may give different results [3].

The Poincaré plot of RR intervals is a technique that is somewhere between the above methods. Its descriptors are time-based, so their calculation is straightforward, but it is possible to single out parameters responsible for short-term (SD1) and long-term (SD2) changes of HRV as well as the balance between them—in this the Poincaré plot technique is similar to the frequency-domain methods.

The autocorrelation structure, which is reflected in the shape of the Poincaré plot and, indirectly, in the $r$ coefficient between $RR_n$ and $RR_{n+1}$ intervals as well as the SD2/SD1 ratio, summarizes some aspects of the time series structure of the RR intervals set, so it is not lost as in the traditional time-domain methods [5, 6, 24]. Another advantage of the Poincaré plot method is that nonstationary data can be included in the Poincaré plot analysis.

There seems to be a renewed interest in the Poincaré plot of RR intervals method [3, 5, 6, 8, 11, 12, 26–29]. It has been applied in various physiological studies evaluating the influence of catecholamines or autonomic blockade on HRV, changes of autonomic control of heart rate during sleep and exercise (5, 9, 26, 30–32). This method has also been used in other clinical settings, such as stroke, diabetes, chronic renal failure, in patients after coronary artery bypass grafting or with sleep apnea syndrome (27–29, 33, 34). The Poincaré plot method also provides prognostic information about mortality in post myocardial infarction, chronic heart failure, and sudden infant death syndrome and about the risk of life threatening ventricular arrhythmias in patients subjected to cardiac surgery (4, 7, 12, 35–37).

And as we have recently shown with the use of the Poincaré plot analysis, it is possible both to visualize and quantify the heart rate asymmetry, i.e., the different contributions of decelerations and accelerations of RR intervals to short-term HRV [38]. It seems that no other currently known HRV method identified this phenomenon, though the phase-rectified signal averaging of RR intervals from Holter recordings of survivors of myocardial infarction provides prognostic information based on decelerations and accelerations of heart rate about future mortality [39].

Thus it is worthwhile to find out as much as possible about the possible interpretations of the various parameters and their applications. The present paper, by comparing the Poincaré plot descriptors with the established HRV and BRS parameters, tries to accomplish this goal. By testing the correlations of these parameters over a wide range of RR intervals, we are trying to learn more about the interpretation and applicability of the technique.

In this study, we did not focus on the physiological meaning of the findings. However, a few remarks on this would be in order here. Except for short-term and high-frequency measures of HRV, all other analyzed parameters of RR intervals variability together with the used measure of BRS had the highest values at the slowest respiratory rate of 6 breaths/min. In other words, these values decreased significantly with increasing respiratory rates. It is known that slow breathing has the effect of entraining all heart rate fluctuations. These fluctuations are forced to merge at the rate of respiration and to increase greatly in amplitude-enhancing measures of HRV and BRS [14, 40–44]. Breathing rate as slow as the 6 breaths/minute used in this study can be obtained by a paced respiration, a rhythmic speech, recitation of some poetry, rosary prayer, or yoga mantras [40–44]. As reported by Cysarz et al. [43], the guided recitation of hexa meter verse poetry exerts a strong influence on respiratory sinus arrhythmia by a prominent low-frequency component in the breathing pattern, generating a strong cardiorespiratory synchronization. Bernardi et al. [44] demonstrated that recitation of the rosary and yoga mantras slowed respiration to approximately 6 breaths/min and increased both HRV and BRS. Further, the respiratory rate of 6 breaths/minute corresponds to the rhythm of 10-s duration with a frequency of 0.1 Hz, which is the resonance frequency of the baroreflex loop and Mayer waves of arterial pressure and is probably responsible for the increase of the respiratory sinus arrhythmia [14, 41, 42, 45]. This resonance might also be responsible for the observed significant changes of HRV and BRS for the slowest respiratory rate and its loss at higher rates.

**Limitations of the study**

The aim of this study was not to explain the mechanisms responsible for changes in heart rate, HRV, and BRS caused by increasing respiratory rate. We used the model of increasing respiratory rate only to obtain a wide range of RR intervals for the evaluation of the Poincaré plot analysis of HRV. Among the limitations of this study is the lack of control of tidal volume and carbon dioxide level. We are aware that these factors may have a relevant contribution to cardiovascular variability [15, 40–42]. Some other limitations might be associated with the calculation of BRS using only the cross-correlation method and not the phenylephrine method [13, 25]. However, the cross-correlation method was shown to be reliable in persons with a wide range of BRS values and needs no interventions producing non physiological increases of blood pressure over a short time [25]. We were interested in spontaneous changes of autonomic modulation, which ap-
pear to be well expressed by BRS, and the applied methods of short 5-min recordings, and thus its results should not be extrapolated to other studies using longer recordings.

SUMMARY

In the present paper, we have evaluated the interpretation of 4 descriptors of the Poincaré plot, two of which are widely used (SD1, SD2), but the remaining two are used only occasionally, and whose interpretation has not been agreed on (S, SD2/SD1) [5–12]. As a result of theoretical considerations and the correlations established in the present study, we conclude that it is reasonable to consider SD1 as a measure of short-term variability, SD2 as a measure of combined long- and short-term variability, S as a measure of total variability, and SD2/SD1 as a measure of the long-to-short-term balance of HRV [5, 6, 8, 9, 24]. The parameters may be considered as alternatives or complementary to other standard HRV measures. Their main advantage is that they overcome the major problems of other methods, such as data stationarity, and are characterized by mathematical simplicity (especially as compared with spectral analysis).

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