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Defining asymmetry in heart rate variability signals using a Poincaré plot

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Abstract

The asymmetry in heart rate variability is a visibly obvious phenomenon in the Poincaré plot of normal sinus rhythm. It shows the unevenness in the distribution of points above and below the line of identity, which indicates instantaneous changes in the beat to beat heart rate. The major limitation of the existing asymmetry definition is that it considers only the instantaneous changes in the beat to beat heart rate rather than the pattern (increase/decrease). In this paper, a novel definition of asymmetry is proposed considering the geometry of a 2D Poincaré plot. Based on the proposed definition, traditional asymmetry indices—Guzik’s index ($GI$), Porta’s index ($PI$) and Ehlers’ index ($EI$)—have been redefined. In order to compare the effectiveness of the new definition, all indices have been calculated for RR interval series of 54 subjects with normal sinus rhythm of 5 min and 30 min duration. The new definition resulted in a higher prevalence of normal subjects showing asymmetry in heart rate variability.

Keywords: Poincaré plot, asymmetry, heart rate variability

1. Introduction

Physiological systems are inherently complex and subject to energy, entropy and information fluxes across their boundaries. These systems function in disequilibrium under healthy conditions. Their self-organizing capability is related to asymmetricity of the underlying processes (Costa et al 2005). In pathological perturbations, a loss of self-organizing capability associated with aging or disease is a function of loss of asymmetricity (Costa et al 2005). Intuitively, asymmetry refers to the lack of symmetry, i.e. the distribution of signals is imbalanced. This imbalance or dissimilarity can easily be observed in the geometry of the phase space plots. Asymmetry is expected to be present in physiological systems (Chialvo and
as it is the fundamental property of a non-equilibrium system (Prigogine and Antoniou 2007). Moreover, asymmetry is linked with the time irreversibility, which is reported as highest in systems with healthy physiology (Costa et al 2005, 2002). Thus, asymmetry represents the presence of complex nonlinear dynamics in physiological signals. So far, very little work has been published in defining and measuring asymmetry in physiological signals (Piskorski and Guzik 2007).

Heart rate variability (HRV), the variation of the time period between consecutive heartbeats, is thought to reflect the heart’s adaptability to the changing physiological conditions. HRV is a net effect of extrinsic regulation and intrinsic heart rhythm. It is however predominantly dependent on the extrinsic regulation of the heart rate (Acharya et al 2006). The autonomic nervous system (sympathetic (SNS) and parasympathetic (PNS)) plays a major role in regulating the heart rate. The SNS is responsible for increasing the heart rate while the parasympathetic tone lowers the heart rate. Both of them work concurrently to control the heart rate in a given range. In practice there is always some variability in the heart rate, due to imbalances in the activity levels of the SNS and PNS. Hence, any heart rate cannot increase or decrease indefinitely but instead will be followed by an opposite trend. However, it is unlikely that any increase or decrease in the RR interval has a reversing effect on the very next RR interval. The speed at which the heart rate increases or decreases is variable, which implies that the periods of increasing or decreasing RR interval are also not equal. As a result, heart rate asymmetry (HRA) should be a common phenomenon present in the healthy heart, which is also reported by Piskorski and Guzik (2007) and Porta et al (2008), and is the main focus of the present study.

Poincaré plot analysis is a visual technique to recognize the hidden patterns in a time series signal. It is also a quantitative technique in the sense that it has various parameters (called standard descriptors) to quantify the visual information in the plot. In various studies, it has been shown to reveal patterns of heart rate dynamics resulting from nonlinear processes (Tulppo et al 1996, Brennan et al 2001). In general, the Poincaré plot of the HRV signal is constructed as a two-dimensional plot by plotting consecutive points of the RR interval time series (i.e. lag-1 plot). It is a representation of the HRV signal on phase space or cartesian plane (Liebovitch and Scheurle 2000), which is commonly used to assess the dynamics of the HRV signal (Tulppo et al 1996, 1998, Toichi et al 1997, Hayano et al 1999). The Poincaré plot is also used to study patients with heart failure, norepinephrine infusion and post-myocardial infarction (Woo et al 1992, Huikuri et al 1996, Makikallio et al 1997, Stein et al 2005). Tulppo et al (1996) fitted an ellipse to the shape of the Poincaré plot and defined two standard descriptors of the plot $SD_1$ and $SD_2$ for quantification of the Poincaré plot geometry. These standard descriptors represent the minor axis and the major axis of the ellipse, respectively, as shown in figure 1. The definitions of $SD_1$ and $SD_2$ in terms of linear statistics, given by Brennan et al (2001), show that the existing standard descriptors guide the visual inspection of the distribution. In the case of HRV, it reveals a useful visual pattern of the RR interval data by representing both short- and long-term variations of the signal (Tulppo et al 1996, Brennan et al 2001).

One of the visible phenomena present in a typical Poincaré plot is asymmetry with respect to the line of identity (line with 45° slope which passes through the origin). In one study (Porta et al 2008), the authors have examined the asymmetry of a Poincaré plot and shown the inter-relationship between time reversibility, pattern asymmetry and nonlinear dynamics. While doing so, the authors have used three different indices, namely Guzik’s index ($GI$), Porta’s index ($PI$) and Ehlers’ index ($EI$) (Porta et al 2006, Guzik et al 2006, Ehlers et al 1998). In Guzik et al (2006), the authors analyzed the asymmetry of short-segment HRV signals (5 min) and extended for long segment (30 min) (Piskorski and Guzik 2007). It was reported that about
Asymmetry in a Poincaré plot

80% of subjects were showing heart rate asymmetry. Since, asymmetry is a phenomenon of healthy physiologic systems (Costa et al. 2005, 2002), it is expected that in resting situation, the healthy heart should always exhibit the asymmetry. One important fact behind the absence of asymmetry could be the definition of asymmetry used by the authors. Since, short-term variability is always present in the heart rate, the points in the Poincaré plot may always flip on both sides of the line of identity without representing any specific pattern in heart rate variability. This local variability induces an apparent ‘asymmetry or symmetry’ as visibly detected in the Poincaré plot with respect to the line of identity. Initially Guzik et al. (2006) defined asymmetry as a unidirectional phenomenon. But later, Porta et al. (2008) defined asymmetry as a bidirectional phenomenon. This implies that asymmetry should be considered as an imbalance between points above and below the line of identity which could be termed as either positive or negative asymmetry.

In this study, a novel definition of asymmetry in the Poincaré plot is presented which is based on the physiological phenomena of heart rate asymmetry. The new definition considers at least two points of the plot to define any pattern in the plot. Similar to the existing definition, each point of the Poincaré plot is labelled as either increasing (I), decreasing (D) or neutral (N) compared to the neighboring point (3 RR intervals are used) rather than the two RR interval values of the present point. Thereafter, asymmetry is measured using the points belonging to cloud I or D.

We have also analyzed the asymmetry of the HRV signal with the existing definition of asymmetry. Systematic evidence to support the claim that asymmetry is better extracted using the proposed definition in the HRV signal, both in short and long segment is presented.

2. New definition of asymmetry in RR interval time series

As mentioned earlier, the line of identity in the Poincaré plot is defined as the line that passes through the origin at an angle of 45° with x-axis. Therefore, any point \( P(x, y) \) on the line of identity can be expressed as \( x = y \). The line of identity was defined by Brennan.
et al (2001), where the authors have shown that SD1 is the standard deviation perpendicular to the line of identity and SD2 is the standard deviation of plotted points along the line of identity. But, the mathematical formulation given for SD1 and SD2 in Brennan et al (2001) does not comply with the concept of line of identity which is shown by Piskorski and Guzik (2007). Piskorski and Guzik (2007) have also shown that the line of identity defined by Brennan et al (2001) is a line, which actually passes through the moment of inertia or centroid of the plotted data points with slope of 45\degree. The authors have named that line as l1 and showed the difference in calculation of SD1 and SD2 with respect to the line of identity and l1 (figure 1). The standard descriptors calculated with respect to the line of identity and l1 show a negligible difference. As the line of identity has a special criterion \( x = y \), Piskorski and Guzik (2007) suggested that the line of identity will be the best option for measuring SD1 and SD2. This line is critical in understanding the concept of asymmetry. In our work, we have followed Piskorski and Guzik (2007) in defining the line of identity.

2.1. New definition of asymmetry

The asymmetry indices GI and PI are defined based on the asymmetry definition by Piskorski and Guzik (2007). On the other hand, EI does not depend on any specific definition of asymmetry. It is directly calculated from the time series information by computing skewness of the first derivative of the signal i.e. the points of the Poincaré plot are not necessarily divided into two groups (increasing and decreasing). The details of calculating all indices are given in section 3. In Piskorski and Guzik (2007), asymmetry is defined with respect to the line of identity. All points on the line of identity (\( x = y \)) have equal consecutive RR intervals. Hence, any point above the line of identity corresponds to increasing RR interval (i.e. decreasing heart rate) and any point below corresponds to decreasing RR interval (i.e increasing heart rate). Based on this, asymmetry is defined and quantified using different indices. Moreover, this heart rate asymmetry can visually be observed as the clouds of points above and below the line of identity. Under healthy conditions, the heart shows continuous short-term variability owing to SNS and PNS activities, which impacts on the formation of cloud around the line of identity. However, this definition of asymmetry does not represent true increasing or decreasing pattern in the heart rate. To overcome this problem, we have defined the asymmetry of the heart rate in a Poincaré plot independent of the line of identity i.e. decision about a point whether it is increasing or decreasing is not made based on its position with respect to the line of identity. All points on the line of identity (\( x = y \)) have equal consecutive RR intervals. Therefore, the analysis corresponds to at least three consecutive RR intervals of the RR interval time series for the lag-1 Poincaré plot. Let the vector RR be defined as \( \text{RR} \equiv \{ RR_1, RR_2, RR_3, \cdots, RR_N \} \) where \( RR_i \) is the \( i \)th RR interval and \( N \) is the total number of RR intervals. Furthermore, let \( P \), the set of all points in a lag-1 Poincaré plot, be defined as \( P \equiv \bigcup_{i=1}^{N-2} P_i(RR_i, RR_{i+1}). \)

For any two points \( P_i(RR_i, RR_{i+1}) \) and \( P_{i+1}(RR_{i+1}, RR_{i+2}) \) of the Poincaré plot, which involves three RR intervals \( \{ RR_i, RR_{i+1}, RR_{i+2} \} \), the status of the point \( P_i \) with respect to
clouds of points is defined as follows:

\[ P_i \in I : \begin{cases} \text{RR}_i < \text{RR}_{i+1} \land \text{RR}_{i+1} < \text{RR}_{i+2} \lor \text{RR}_i \geq \text{RR}_{i+1} \land \text{RR}_{i+1} < \text{RR}_{i+2} \lor \text{RR}_i > \text{RR}_{i+1} \land \text{RR}_{i+1} \leq \text{RR}_{i+2} \end{cases} \]

\[ \begin{cases} \text{RR}_i > \text{RR}_{i+1} \land \text{RR}_{i+1} > \text{RR}_{i+2} \lor \text{RR}_i \leq \text{RR}_{i+1} \land \text{RR}_{i+1} > \text{RR}_{i+2} \lor \text{RR}_i < \text{RR}_{i+1} \land \text{RR}_{i+1} \geq \text{RR}_{i+2} \end{cases} \]  

\[ P_i \in D : \begin{cases} \end{cases} \]

\[ P_i \in N : \text{RR}_i = \text{RR}_{i+1} = \text{RR}_{i+2} \]  

After defining the clouds, the asymmetry is defined between the points of I and D i.e. the asymmetry is defined as the lack of symmetry among the distribution of points in I and D. Hence, any point that belongs to cloud N is not considered for calculating asymmetry. According to this definition, it is possible to find points I or D on both sides of the line of identity as shown in figure 2. An example of the proposed definition with the RR interval series shown in figure 2 is given in figure 3.

3. Redefining traditional asymmetry indices

In this section, the asymmetry indices are redefined in accordance with the proposed definition of asymmetry. The traditional asymmetry indices used in the previous studies are GI, PI and EI (Guzik et al 2006, Porta et al 2006, 2008, Ehlers et al 1998). For redefining all the indices, let us assume that the increasing cloud I and the decreasing cloud D are a set of points
Figure 3. RR interval time series of length $N (=13)$. The cloud type (I, D or N) corresponds to the point $\{P_i(\text{RR}_i, \text{RR}_{i+1})\}$ for Guzik’s definition and point $\{P_i(\text{RR}_{i+1}, \text{RR}_{i+2})\}$ for the new definition.

as shown below, respectively:

$I \equiv \bigcup_{i=1}^{M} P_i(\text{RR}_i, \text{RR}_{i+1})$

and

$D \equiv \bigcup_{i=1}^{K} P_i(\text{RR}_i, \text{RR}_{i+1})$

where $M$ and $K$ represent the number of points in increasing and decreasing clouds.

3.1. Guzik’s index ($GI$)

Guzik et al (2006) have defined the index for measuring the asymmetry of the Poincaré plot. For defining $GI$, the distance of the plotted points from the line of identity is used. For $i$th point $P_i(\text{RR}_i, \text{RR}_{i+1})$ of the plot, the distance can be calculated as

$D_i = \frac{|\text{RR}_i - \text{RR}_{i+1}|}{\sqrt{2}}.$

$P^+_i$ represents the point above the line of identity ($\text{RR}_i < \text{RR}_{i+1}$) and the distance $D_i$ is denoted as $D^+_i$. Whereas $P^-_i$ is the point below the line of identity, i.e. $\text{RR}_i < \text{RR}_{i+1}$, and the distance is denoted by $D^-_i$. Guzik index $GI$ is defined as follows:

$GI = \frac{\sum_{i=1}^{C(P^+)} (D^+_i)^2}{\sum_{i=1}^{N-1} (D^-_i)^2} \times 100\%$ (2)

where $C(P^+)$ gives the number of points above the line of identity. In the new definition of asymmetry, the line of identity is not used for grouping the plotted points into two different clouds. As a result, it is not possible to calculate the new $GI$ using equation (2). The set of points $\{P^+_i\}$ used in equation (2) is equivalent to the increasing cloud defined in the new definition of asymmetry. Hence, using the increasing cloud $I$, equation (2) can be redefined using the proposed definition:

$GI_p = \frac{\sum_{i=1}^{M} (D^+_i)^2}{\sum_{i=1}^{N-1} (D^-_i)^2} \times 100\%$ (3)
where the numerator corresponds to the increasing cloud, the denominator corresponds to the total number of points and $GIp$ is the redefined Guzik’s Index.

### 3.2. Porta’s index ($PI$)

Porta et al (2006) have defined asymmetry with respect to the line of identity. Rather than considering the relative distance of the points with respect to the line of identity, the authors have assessed asymmetry by evaluating the number of points below the line of identity with respect to the overall number of points not on the line of identity. Hence, $PI$ is defined as follows:

$$PI = \frac{C(P^-)}{C(P^+)} \times 100\%.$$  \hspace{1cm} (4)

According to the proposed definition, the set of points $P^-$ is equivalent to the set of points belonging to the decreasing cloud $D$. Hence, equation (4) can be redefined as follows:

$$PI_p = \frac{K}{M + K} \times 100\%$$ \hspace{1cm} (5)

where $K$ and $M$ are the number of points in clouds $D$ and $I$, respectively.

### 3.3. Ehlers’ index ($EI$)

Ehlers et al (1998) have used the first derivative of the RR interval series for assessing asymmetry of the given distribution. Skewness is measured over the first derivative signal to estimate the asymmetry of the distribution. Hence, for RR interval time series it can be defined as follows:

$$EI = \frac{\sum_{i=1}^{N-1} (RR_i - RR_{i+1})^3}{\left(\sum_{i=1}^{N-1} (RR_i - RR_{i+1})^2\right)^{3/2}}.$$ \hspace{1cm} (6)

Ehlers’ index $EI$ can be redefined with the proposed definition splitting into positive and negative cloud as follows:

$$EI_p = \frac{\sum_{i=1}^{M} (\Delta I_i)^3 + \sum_{i=1}^{K} (\Delta D_i)^3}{\left(\sum_{i=1}^{N-1} (RR_i - RR_{i+1})^2\right)^{3/2}}$$ \hspace{1cm} (7)

where

$$\Delta I_i = RR_{i+1} - RR_i, \quad P_i(RR_i, RR_{i+1}) \in I$$

and

$$\Delta D_i = RR_i - RR_{i+1}, \quad P_i(RR_i, RR_{i+1}) \in D.$$  

**Normalization of indices.** For the sake of comparison, the normalization of the indices to a convenient scale is recommended. Both $GI$ and $PI$ values range between 0 and 100, with the index value of symmetry $S = 50$. Asymmetry of the signal is ranked based on the difference of the index value from $S$. An index value >50 represents that the distribution is positively skewed, either by the magnitude or by the number of points. Whereas, an index value <50 corresponds to the reverse distribution. The symmetry in $EI$ ($EI \in [-1, 1]$) is characterized as $S = 0$ and values >0 or <0 ranks the asymmetry of the signal. Therefore, to compare $EI$ with $GI$ and $PI$, it is necessary to use a normalized scale for the index value calculated. In this study, we have defined a range, $R$, for the index values to define asymmetry. The range is defined as 1% of the difference between minimum and maximum index values; where, index is either $GI$, $PI$ or $EI$. Now, if index $\in (S \pm R)$ then the signal is symmetric, otherwise asymmetric. The redefined indices ($GI_p$, $PI_p$ and $EI_p$) are also normalized in the same manner.
4. Data and results

In order to validate the new definition of asymmetry, $G_I$, $P_I$ and $E_I$ using Guzik’s definition and $G_{ip}$, $P_{ip}$ and $E_{ip}$ using the proposed definition of asymmetry are calculated for RR interval data of short segment (5 min) and long segment (30 min) which belongs to short-term HRV analysis (Electrophysiology 1996). The data from MIT-BIH Physionet database (Goldberger et al 2000) are used in this study. 54 RR interval series of subjects with normal sinus rhythm (30 men, aged 28.5–76, and 24 women, aged 58–73) from Physionet Normal Sinus Rhythm database (Goldberger et al 2000) have been used for evaluating the proposed definition. Hence, we had 54 sets of 30 min recordings (long segment), of which the first 5 min were used for short-segment analysis. The original long-term ECG recordings were digitized at 128 Hz, and the beat annotations were obtained by automated analysis with manual review and correction (Goldberger et al 2000). The short- and long-segment RR interval series were taken from beginning of each subject’s RR interval but the time of the day or night cannot be mentioned as it was not clearly stated in Physionet database. More details about the RR interval time series can be found in Bigger et al (1995).

Figure 4 shows the $G_I$ values for short-segment (panels A and B) and long-segment (panels C and D) RR interval time series. Top panels (A and C) of figure 4 represent the $G_I$ values. For short segment, 61.11% of the subjects are found asymmetric, $G_I \in (49, 51)$, with $G_I$ values $52.37 \pm 5.72$ (mean $\pm$ sd). Furthermore, 53.74% of the subjects are found...
asymmetric, \( GI \in (49, 51) \), with \( GI \) values 52.18 ± 4.13 for long-segment study. The presence of asymmetry using Guzik’s definition is not consistent and the reason for this is reported as unknown.

The \( GI_p \) values for both short- and long-segment RR interval signals are shown in the bottom panels (B and D) of figure 4. In the case of short segment, the \( GI_p \) values range within 44.72 ± 11.12 and 79.63% of the subjects are found to be asymmetric. In addition, 81.48% of subjects showed asymmetry for long-segment signals with \( GI_p \) values 45.81 ± 6.56. This shows significant improvement in consistency of \( GI_p \) for defining asymmetry using the proposed definition in contrast to Guzik’s asymmetry definition.

In figure 5, \( PI \) and \( PI_p \) values for short-segment (panels A and B) and long-segment (panels C and D) RR interval time series are shown. Top panels (A and C) represent the \( PI \) values whereas the bottom panels (B and D) show \( PI_p \) values. For short-segment signals 61.11% subjects showed asymmetry, \( PI \notin (49, 51) \), with \( PI \) values 50.11 ± 2.63, whereas 53.70% of subjects showed asymmetry, \( PI_p \notin (49, 51) \), with \( PI_p \) values 49.94 ± 2.12 in accordance to the proposed definition. In the case of long-segment variability, 40.74% of subjects showed asymmetry with \( PI \) values 50.65 ± 1.94. On the other hand, 31.48% of subjects showed asymmetry with \( PI_p \) values 50.27 ± 1.47.
Figure 6. Ehlers’ index ($EI$) of asymmetry for short-segment (5 min, panels A and B) and long segment (30 min, panels C and D) RR interval signals of normal sinus rhythm subjects ($n = 54$). Top panels (A and C) show the $EI$ (see equation (6)) values using Guzik’s asymmetry definition and bottom panels (B and D) show $EIP$ (see equation (7)) values using new asymmetry definition.

Figure 6 shows the values of asymmetry index $EI$. 50% of the subjects with $EI$ values $0.0290 \pm 0.0711$ are found asymmetric in the case of short-segment signals with Guzik’s definition of asymmetry. On the other hand, 94.44% of the subjects are screened asymmetric using the proposed definition with $EIP$ values $-0.1979 \pm 0.2344$. Similarly, for long-segment signal, 20.37% subjects are found asymmetric with $EI$ values $0.0145 \pm 0.0331$ using Guzik’s definition. However, 85.19% subjects are screened asymmetric with $EIP$ values $-0.1909 \pm 0.2053$. Table 1 shows the mean and standard deviations of values of all indices, and asymmetry subjects (%) for both short- and long-segment signals.

5. Discussion

Asymmetry is related to nonlinear dynamics and time irreversibility, which exhibit the most complex inter-relationships (Costa et al 2005, 2002). It is reported to be highest for healthy physiological systems under resting conditions (Costa et al 2005) and decrease with pathology, thus providing a marker for any loss of normal functionality. Guzik et al (2006) have reported that the asymmetry in heart rate variability might be related to the response of the baroreflex to increase or decrease the blood pressure (Eckberg 1980). However, the exact reason for such asymmetry is largely unknown.
Table 1. Mean and standard deviation (SD) of Guzik’s index ($G_I$), Porta’s index ($P_I$) and Ehlers’ index ($E_I$) for 5 min and 30 min signals of subjects, $n = 54$, with normal sinus rhythm. Subjects (%) found to be asymmetric using both definitions for all indices are also given.

<table>
<thead>
<tr>
<th>Index</th>
<th>Length (min)</th>
<th>Guzik’s definition</th>
<th>New definition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Asymmetry (Mean ± SD)</td>
<td>Asymmetry (%)</td>
</tr>
<tr>
<td>Guzik’s index</td>
<td>5</td>
<td>47.63 ± 5.72</td>
<td>61.11</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>47.82 ± 4.13</td>
<td>53.74</td>
</tr>
<tr>
<td>Porta’s index</td>
<td>5</td>
<td>50.11 ± 2.63</td>
<td>61.11</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>50.65 ± 1.94</td>
<td>40.74</td>
</tr>
<tr>
<td>Ehlers’ index</td>
<td>5</td>
<td>0.0290 ± 0.0711</td>
<td>50.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.0145 ± 0.0331</td>
<td>20.37</td>
</tr>
</tbody>
</table>

In this study, a novel way for defining asymmetry of RR interval time series in the Poincaré plot has been presented. Two merits of the proposed definition are (1) It is correctly defined from the geometrical point of view because it considers the pattern rather than a single point of the Poincaré plot to categorize a point either as increasing, decreasing or stable. (2) It captures HRA of healthy subjects using existing asymmetry indices at a higher prevalence than that defined by Guzik et al (2006). Though Guzik’s definition of asymmetry is very simple and intuitive, using such a definition may not be physiologically correct. For instance, it is known that the HRV signal of normal resting subjects should be asymmetric (Piskorski and Guzik 2007, Costa et al 2005). In our study, using Guzik’s definition only 62% of such subjects showed asymmetry, whereas the new definition showed asymmetry in more than 94% of the subjects. Also, the regulation of the heart rate in resting subjects is not instantaneous but takes a couple of seconds (Eckberg 1980). In such a case, it is important to measure the pattern of changes in the heart rate rather than instantaneous effect. Therefore, the consideration of instantaneous changes could be a major limitation of the existing definition. As a result, use of patterns in the proposed definition, rather than instantaneous changes, reveals much higher incidence of asymmetry in healthy subjects.

The present study exploits the physiological phenomena of the system to define the asymmetry in the signal. Important findings of this study are (a) existing asymmetry indices are better equipped to capture asymmetricity with the proposed definition of asymmetry than the existing definition (figures 4, 5, 6, table 1). (b) $G_I$ and $E_I$ capture the asymmetricity better than $P_I$; i.e. for both definitions, use of location of points in the 2D map with respect to the line of identity for calculating the indices performs better than using only the information about the number of points in the distribution (figures 4, 5, 6, table 1). Furthermore, the asymmetricity has been calculated for subjects with normal sinus rhythm using both definitions. The results are in accordance with the reported asymmetry in heart rate variability (Costa et al 2005, Porta et al 2006, 2008, Guzik et al 2006). In the present study, we have found that 79.63% and 81.48% of subjects are shown to be asymmetric using the proposed definition. Whereas, only 61.11% and 53.74% of subjects were found to be asymmetric with Guzik’s definition for short-segment and long-segment signals, respectively (figure 4).

However, other than the definition of HRA, the index calculation by Piskorski and Guzik (2007) and Porta et al (2008) was also different than the way we have calculated in this study. We have used the bidirectional and normalization criteria (as discussed in section 3.3) to compare between different indices popularly used for asymmetry measurement. Moreover, if
we used the same asymmetry measure as used by Piskorski and Guzik (2007), then it would be 48.15% and 40.74% for short segment and long segment, respectively, in our results. Hence, use of bidirectional criteria for defining asymmetry has increased the prevalence of having asymmetry. However, the intention of using bidirectional criterion has been supported by the time reversibility or asymmetry theory. In reference to the result published in Piskorski and Guzik (2007), the 81% or 82% subjects showing asymmetry cannot be comparable to this study as the data set used in their study was different. In this study, only 61.11% and 53.74% of subjects were showing asymmetry using Guzik’s definition with bidirectional and normalization criteria for short segment and long segment, respectively.

Using Guzik’s definition and Porta’s index $PI$, 61.11% of the subjects are classified as having asymmetry in the case of short-segment signals and 40.74% in the case of long-segment signals, in contrast to the findings reported in (Porta et al. 2006). However, using the new definition, $P_{Ip}$ was reduced to 53.70% and 31.48% for short-segment and long-segment signals, respectively. The reason behind the reduced performance of $P_{Ip}$ against $PI$ is the difference in the number of points used for calculating the index. If we observe the two definitions closely, there is hardly any difference in the number of points in the increasing and decreasing clouds. Hence, similar numbers were expected. The use of the number of points has been shown by the authors to work well under certain conditions like foetal heart rate monitoring (Porta et al. 2006). In this study, we did not find any specific advantage with Porta’s index.

This justification is strongly supported by the result obtained using $EI_{Ip}$, which showed 94.44% and 85.19% of subjects having asymmetry for both short-segment and long-segment signals, using the new definition. In contrast, 50.00% and 20.37% of subjects are found to be asymmetric using Guzik’s definition for the short-segment and long-segment signals, respectively. Therefore, we confirm that our definition performs better in quantifying asymmetry using existing indices than the previous ones.

Piskorski and Guzik (2007) performed surrogate analysis to show that HRA is related to some unknown underlying dynamics rather than a random behavior. In that study, they showed that the presence of asymmetry or the time irreversibility is abolished in the randomized HRV signal. Piskorski and Guzik (2007) used the random shuffling surrogate method, in which the signals were randomly shuffled so that the probability of distribution remained same but the temporal correlations were destroyed (Theiler et al. 1992, Nkamura and Small 2006). However, nonlinear measurement is not necessarily affected by such surrogation (Nurujjaman et al. 2009). The discrimination (by any measure either linear or nonlinear) of the original time series from this type of surrogation only suggests the presence of hidden correlation in the original time series. Therefore, we conclude that surrogation does not have a specific impact on the nonlinear properties like asymmetry or time irreversibility. However, it has an impact on asymmetricity measured with respect to the line of identity, because the correlation of the signal changes with surrogation and it affects the distribution of points in the Poincaré plot around the line of identity. Therefore, results of surrogate analysis have no significance in the proposed definition of our study.

6. Conclusion

A novel definition of asymmetry in the Poincaré plot is proposed. The proposed definition provides an improvement in analyzing asymmetricity of physiological time series signals. The three earlier indices (Guzik’s index, Porta’s index and Ehlers’ index) which were used to represent asymmetry have been redefined according to the new definition. The indices $GI_{Ip}$ and $EI_{Ip}$ have been shown to perform better in detecting asymmetry in heart rate series of normal
healthy subjects with a slight reduction in performance using $P_{IP}$ with the new definition. The experiment described here has resulted in a relatively higher performance compared to the existing definition. In future, it would be interesting to look at new indices based on the proposed new definition.

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