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Asymmetry of lagged Poincare plot in heart rate signals during meditation

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A B S T R A C T

Background and aim: Heart rate variability (HRV) quantifies the variability in the heart's beat-to-beat intervals. This signal is a potential marker of cardiac function in normal, pathological, and psychological states. Signal asymmetry refers to an unequal distribution in the signal, which can be found by a two-dimensional Poincare plot. Earlier, heart rate asymmetry (HRA) was assessed using a conventional Poincare plot (lag of 1). In this study, we have investigated the effect of delay on the phase space asymmetry using lagged Poincare's plot.
Experimental procedure: This study compared the presence/lack of asymmetries in the HRV data of 12 meditators (four Kundalini yoga (Yoga) at an advanced level of meditation, eight Chinese Chi meditators (Chi) ~1–3 months) to 25 non-meditators (11 spontaneous nocturnal breathing (Normal) and 14 metronomic breathing (Metron)). Poincare's plots were constructed with six different lags, and HRA was calculated. The analysis was conducted using HRV data provided in the Physionet database.
Results: The results showed that using conventional Poincare's plot (lag of 1), the lowest HRA was observed in the Metron group. In addition, the HRA index was different between meditators and non-meditator groups. Moreover, as the most significant difference between groups was observed in a delay of 6, the role of the delay selection on the signal asymmetry was revealed.
Conclusion: The difference between lagged HRA responses on Yoga in comparison with other groups can be an emphasis on the importance of choosing the type of meditation technique and its effects on the cardiovascular system.

1. Introduction

Meditation refers to a family of mystical and religious traditions. Today, these techniques are mainly used to reduce anxiety and stress, increase concentration, to provide physical and mental relaxation, and generally to promote health. The advantages of these practices have attracted many scientists' attention to examining the mechanisms in which human health benefits are derived. Among them, analysis of biological signals is of particular importance in the evaluation of physiological systems.

Heart rate variability (HRV) has been considered as a potential marker of cardiac function. It is a quantification of the variability in the heart's beat-to-beat intervals, which demonstrates the status and relations between the autonomic nervous arms, i.e. the sympathetic and the parasympathetic nerves. This signal has emerged as an indispensable tool for studying pathological, physiological, and psychological conditions. A wide range of literature has been conducted to detect and categorize arrhythmias,[1,2] sudden cardiac death,[3] emotions,[4,5] mental stress,[6] and authentication[7,8] by using heart-based parameters, particularly HRV. In addition, examining the changes in HRV signal during meditation is a topic of interest to some researchers, especially in the last decade.[9–23]

Preliminary studies sought to link the effect of meditation on autonomic activation using spectral analysis.[10,11] Although spectral approaches are typically accepted for HRV analysis, the main limitation of them is their conditionalization with vast sources of noise. To restrict the interacting sources and to catch a stationary signal,

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List of abbreviations:

HRA	Heart rate asymmetry
HRV	Heart rate variability
Metron	metronomic breathing
Normal	Spontaneous nocturnal breathing
On Chi	during Chinese Chi meditation
On Yoga	during Kundalini yoga meditation
Pre Chi	pre Chinese Chi meditation
Pre Yoga	pre Kundalini yoga meditation

controlled experimental settings are needed. To overcome the problem of non-stationary, different nonlinear approaches have been proposed. Some of these techniques were based on the analysis of the shape of the signal's phase space, like the Poincare and recurrence plots.[16,18,20,23] The others examined some global and local indicators of dynamic and chaotic signal behavior, like complexity,[12,16] fractal and multi-fractal analysis,[13,15] similarity measures[17]; higher-order spectra,[19] Hilbert transforms,[9] Lyapunov exponents,[16,21,22] and some entropy measures.[14,16,21]

In this study, we intend to investigate the asymmetry of the signal. Signal asymmetry refers to an unequal or the unbalanced distribution in the signal,[24] which emerges as a characteristic of a physiological system.[25] Asymmetry is associated with a lack of time reversibility, which is often perceived in healthy bio-systems.[24] This parameter can be obtained by visual evaluation of the two-dimensional Poincare plot. In the conventional form of the plot, each point represents a pair of successive intervals (RR_i, RR_{i+1}), which portrays the increase and decrease of the heart rate. To quantify this plot, an ellipse is generally fitted to it. Then, the width of the ellipse along and perpendicular to the line of identity are considered as two indicators of cardiac dynamics. Heart rate asymmetry (HRA) has occurred as long as a distribution of the superior portion of the plot (which links to decelerations of the heart rate) is not equal to its lower portion (indicating accelerations of heart rate). Several indices have been presented to quantify the asymmetry of the signal.[26–33] These measures have been studied in healthy individuals as well as in different diseases. In this study, we used the index proposed by Karmakar et al.[29] to evaluate the effect of meditation on the HRA. In several previous articles,[16,18,23] we have shown the advantage of analyzing lagged Poincare's plots in meditation study. However, for the first time, in this experiment, we have investigated the effect of delay on the phase space asymmetry. Most studies have focused on one or two psychological practices (meditation styles), while we have examined six modes, including metronomic breathing (Metron) and spontaneous nocturnal breathing (Normal) as non-meditator groups and pre Chinese Chi meditation (pre Chi), during Chinese Chi meditation (on Chi), pre Kundalini yoga meditation (pre Yoga), and during Kundalini yoga meditation (on Yoga) as meditator groups. This study assumes that distinctive meditation techniques have different effects on physiological measures. Therefore, it is expected that the influence of Chi meditation is distinctive from the effect of yoga meditation on cardiac parameters. It is also hypothesized that continuous meditation practice will affect baseline values of physiological indices. Consequently, it was supposed that the cardiac factors of normal individuals are different from those of the participants who did meditation over a period of time (pre Chi and pre Yoga). These hypotheses were examined by comparing non-meditators and meditators HRA measures, as well as pre and on the performance of two types of meditation.

2. Material and methods

2.1. Data selection

In this study, we examined the HRV of the healthy groups of meditators and non-meditators available at Physionet database.[9] The meditators practiced Kundalini yoga (as trained by Yogi Bhajan) and Chinese Chi meditation techniques. For the former, the ECG signals of four expertly trained meditators were recorded for about 1 and ½ hours while wearing a Holter. First, a 15-min signal was recorded before beginning the meditation practice (pre Yoga). Then, for about 1 h, a concatenation of breathing and chanting exercises was performed (on Yoga) in a cross-legged posture. For the latter, the ECG signals of eight meditators were recorded, which were healthy graduated or post-doctoral students. Often they started the training for about one to three months before the test. While wearing a Holter, they performed their ordinary activities for approximately 10 h. At about 5 h in the ECG recording, each of them carried out an hour of Chinese Chi meditation in a sitting cross-legged position. Listening to the taped guidance of the master, they were taught to breathe freely while visualizing the opening/closing of a perfect lotus in their stomach.

In addition, the HRV of two groups of non-meditating participants available in Physionet database[9] was studied (Metron and Normal). One group performed metronomic breathing and the other spontaneous nocturnal breathing. The former involved 14 healthy participants during supine metronomic breathing at a steady rate of 0.25 Hz. The latter included 11 healthy volunteers. They breathe spontaneously during sleep hours for about 6 h, except for one subject (4.6 h).

The general health of the groups was comparable.[9] In addition, all participants provided informed consent in agreement with an approved protocol of the Beth Israel Deaconess Medical Center Institutional Review Board.[9] The signals were sampled at 128 Hz. Table 1 presents demographic information about the groups.

2.2. Heart rate asymmetry index

In this study, the HRA index proposed by Karmakar et al.[29] was assessed. However, this index was previously evaluated for conventional Poincare plot (lag-1). In this experiment, we generalized it to the lagged Poincare's plot. In the following, we briefly describe the generalized form of the HRV index.

Consider two points of the Poincare plot: one point of the plot P_i, and the next point P_{i+m}, where m is the time lag. The position of each point can be determined as above, below, or on the line of identity. Considering P_i as a pole of the polar coordinate system, the situation of the consecutive point of the plot (P_{i+m}) relative to the Pi can be described as follows.

$$P_i \in I, \quad 0^\circ \leq \theta < 180^\circ \\ \in D, \quad 180^\circ \leq \theta < 360^\circ \\ \in N, \quad r = 0 \tag{1}$$

where (r,θ) is the polar axis of the next point; i.e. the polar distance and angle of P_{i+m}. In addition, I, D, and N represent increasing, decreasing, and neutral cloud, respectively.

First, consider the ith point P_i (RR_i, RR_{i+m}) of the plot. The distance of it from the line of identity (D_i) can be computed as (2).

$$D_i = \frac{|RR_i - RR_{i+m}|}{\sqrt{2}} \tag{2}$$

P_i^+ shows that the point locates above the line of identity, and the distance is symbolized as D_i^+. Considering the increasing cloud I

Table 1
Demographic information of the groups of meditators and non-meditators.

	Meditators		Non-meditators	
	Kundalini yoga • pKYM • dKYM	Chinese Chi meditation • pCCM • dCCM	Spontaneous nocturnal breathing	Metronomic breathing
Age	20–52	26–35	20–35	20–35
Mean age	33	29	29	25
Gender	2 women, 2 men	5 women, 3 men	8 women, 3 men	9 women, 5 men

(Eq. (1)), the HRA can be defined as follows.

$$GI_p = \frac{\sum_{i=1}^{M} (D_i^+)^2}{\sum_{i=1}^{N-1} (D_i)^2} \times 100 \quad (3)$$

where N and M are the number of RR intervals and the number of points in the cloud I, respectively. The GI_p values are in the range of 0–100. When it is equal to 50, it shows symmetry. To diminish the noise effect on HRA index, 1% of the difference between the minimum and maximum values; i.e. 49–51 were considered as a symmetric range.

For the ith participant, the distance between the symmetric range and the GI_p ($Dist_{sym}$) is calculated as follows:

$$Dist_{sym} = |GI_p(i) - GI_p(sym)| \quad (4)$$

where $GI_p(sym)$ is an index for symmetric range and determined as follows:

$$\begin{cases} GI_p(sym) = 49, & if \quad GI_p(i) < 49 \\ GI_p(sym) = 51, & if \quad GI_p(i) > 51 \\ GI_p(sym) = GI_p(i), & O.W \end{cases} \quad (5)$$

If $Dist_{sym} = 0$, then the absence of HRA is revealed, otherwise ($Dist_{sym} > 0$), the presence of HRA is confirmed.[29]

In this study, we set m (time lag) equal to 6 as suggested in our previous study.[23]

3. Results

Fig. 1 and Fig. 2 show the GI_p and the corresponding $Dist_{sym}$ values of all participants for all modes in different lags. In GI_p plots, the dotted lines represent the symmetric range ($49 \le GI_p \le 51$).

Considering the lag of 1 (Figs. 1(a) and Fig. 2(a)), the highest symmetry in HRV was observed in the metronomic breathing state, where the most $Dist_{sym}$ values were close to zero. The mean $Dist_{sym}$ of Metron group was 8.29 ± 8.34, and 42.86% of them were under 3.8. This pointed out that the HRA reduces in the metronomic group. In addition, it can be perceived that the GI_p index for meditation groups was below the symmetry line, except for one subject on Yoga. Precisely, the mean GI_p of pre Chi, on Chi, pre Yoga, and on Yoga was 40.25 ± 6.35, 46.2 ± 3.36, 34.68 ± 10.27, 50.99 ± 11.15 and, respectively. In contrast, for the other non-meditator groups, it was distributed both above and below the symmetric range.

By increasing one delay unit ($m = 2$; Figs. 1(b) and Fig. 2(b)), the significant change was seen in the asymmetry indices of the pre Yoga group. In this case, the GI_p of most participants was extremely close to the symmetric interval (46.5 ± 2.97) and the $Dist_{sym}$ values were close to zero (2.65 ± 2.75).

As the delay increases (Fig. 1(c)–(f) and Fig. 2(c)-(f)), the distance between symmetric range and the GI_p ($Dist_{sym}$) decreased for all different states, except for on Yoga. Therefore, with the increase in the lag, the symmetry of the signal augmented in five modes, including pre Chi, on Chi, pre Yoga, Metron, and Normal. In contrast, the HRA was increased for the meditators that were doing Yoga.

More precisely, the most values of the $Dist_{sym}$ in lag-1 were in the range of 5–20/4–6 for the pre Chi/on Chi. In contrast, the corresponding values for the lag of 6 were in the range of 2–6/1–8. For pre Yoga, the $Dist_{sym}$ values were usually near 20 in the lag of 1, which shifted to zero in the lag of 6. In contrast, for on Yoga, the $Dist_{sym}$ values were below 15 in lag-1 and increased to above 20 in lag-6. For the other two groups (Metron and Normal), the increase in delay has caused a decrease in the $Dist_{sym}$ index value.

Statistical analysis was also performed using the Wilcoxon rank sum test (Mann-Whitney U test) to evaluate significant differences between GI_p values of different groups (Table 2).

As Table 2 shows the most significant difference between groups was observed in delay of 6. This emphasizes the importance of the delay effect on signal asymmetry.

4. Discussions

In this experiment, to explore HRV dynamics in distinctive modes, the HRA was evaluated. To this effect, we applied the HRV signals of the Physionet database.[9] Various modes of meditation (pre and on Chi, pre and on Yoga) and non-meditation (Metron and Normal) HRV signals were incorporated in the database, which all applied in this paper. In an attempt to explore the HRA during these states, for the first time, lagged Poincare's plot was used. The results revealed the difference between HRA in different states. In addition, with increasing delay, variations in the pattern of signal symmetry varied in different modes.

Previously, using the conventional indicators of the Poincare plots (like SD1, SD2, and SD1/SD2), we showed the chaotic pattern of HRV fluctuates in these modes.[16] Moreover, increasing the lag provokes to an alteration in the Poincare plot's profile.[16,18,23] Our previous results showed that the most differences in the lagged Poincare measures were perceived for pre and on Yoga and the minimum differences were detected for Metron.[16] These studies have emphasized the change in plot pattern from the perspective of the minor and the major axis of the fitted ellipse on the Poincare plot in different states. However, it was not investigated whether these exercises also affect the signal's asymmetry. Precisely, they have not probed whether the distribution of the upper portion of the plot is equal to its lower portion. Furthermore, in these studies, it was shown that the delay adjustment causes a change in the geometry of the phase space. However, it was not explored whether this delay alteration affects the signal asymmetry.

The results of this study showed that using conventional Poincare's plot (lag of 1), the lowest HRA was observed in Metron group. Besides, the GI_p index was restricted to the beneath the symmetry line for meditation groups, which was distributed both above and below the symmetrical range for the other non-meditator groups. In addition, increasing the delay leads to a decrease in the distance between symmetrical range and the GIp ($Dist_{sym}$) in four states, including pre Chi, Pre Yoga, Metron, and Normal. Whereas during

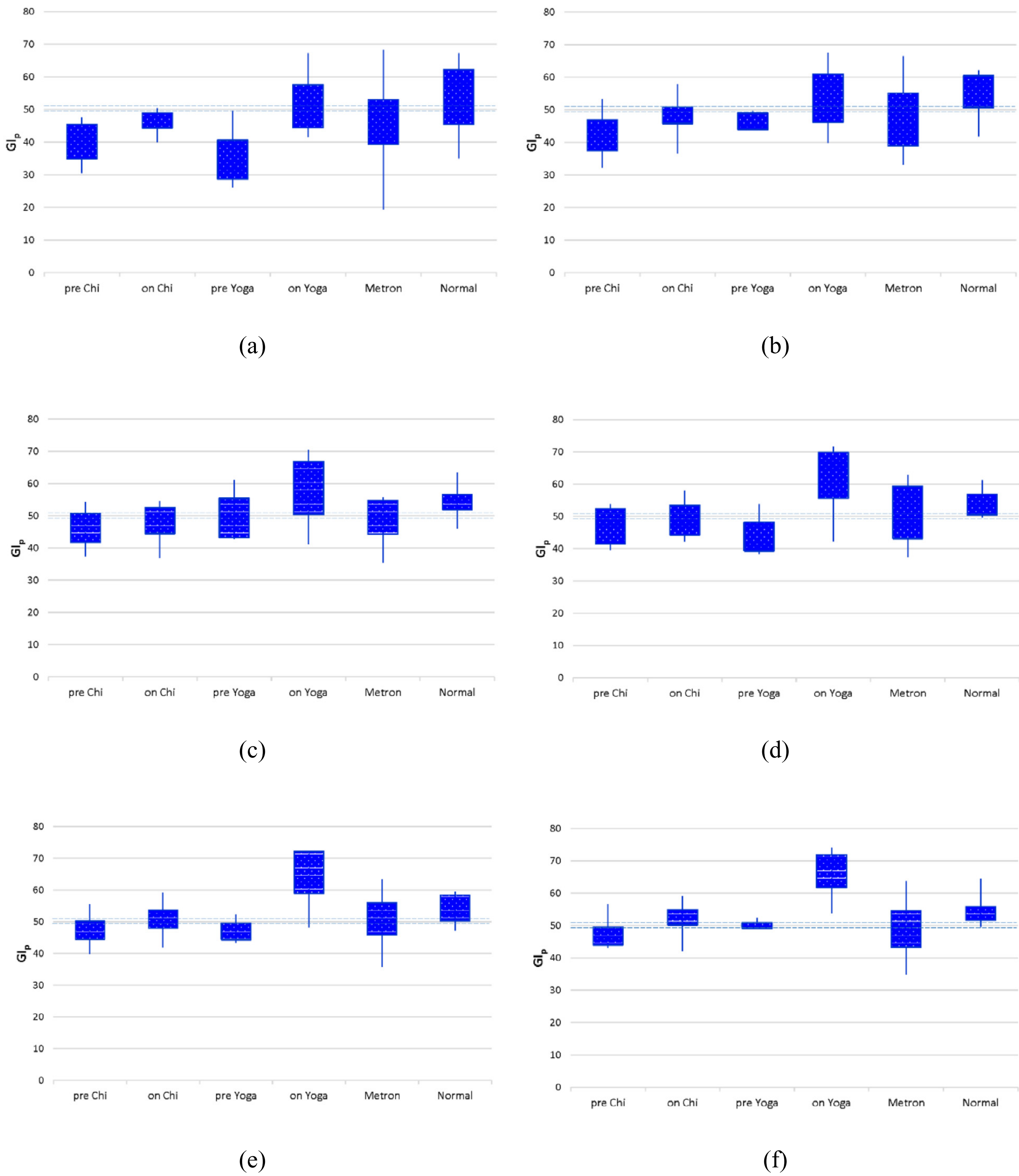

Fig. 1. GI_p values for all six modes, i.e. pre Chi, on Chi, pre Yoga, on Yoga, Metron, and Normal in different lags; (a) lag 1, (b) lag 2, (c) lag 3, (d) lag 4, (e) lag 5, and (f) lag 6. The symmetric range is shown by dotted lines.

the meditation exercise, especially on Yoga, the $Dist_{sym}$ index tends to higher values.

This article had some shortcomings and limitations. We used an available free database collected by Peng et al.,[9] where a small number of HRV is provided. Furthermore, the number of HRVs in different groups is imbalanced. Reliable confirmation of the results is achieved by assessing the HRA on big and balanced data in the future. On the other hand, HRA is an interesting but a poorly assumed phenomenon. There are many established algorithms for examining HRA and in this study, we tested only one of them. More practical, empirical, and descriptive studies are needed to better appreciate HRA, especially in different psychological states.

5. Conclusions

This study explored the presence/lack of asymmetries in the dynamics of HRV signals. The lagged Poincare's plot was applied to indicate that asymmetry is contained in the heart rhythms of

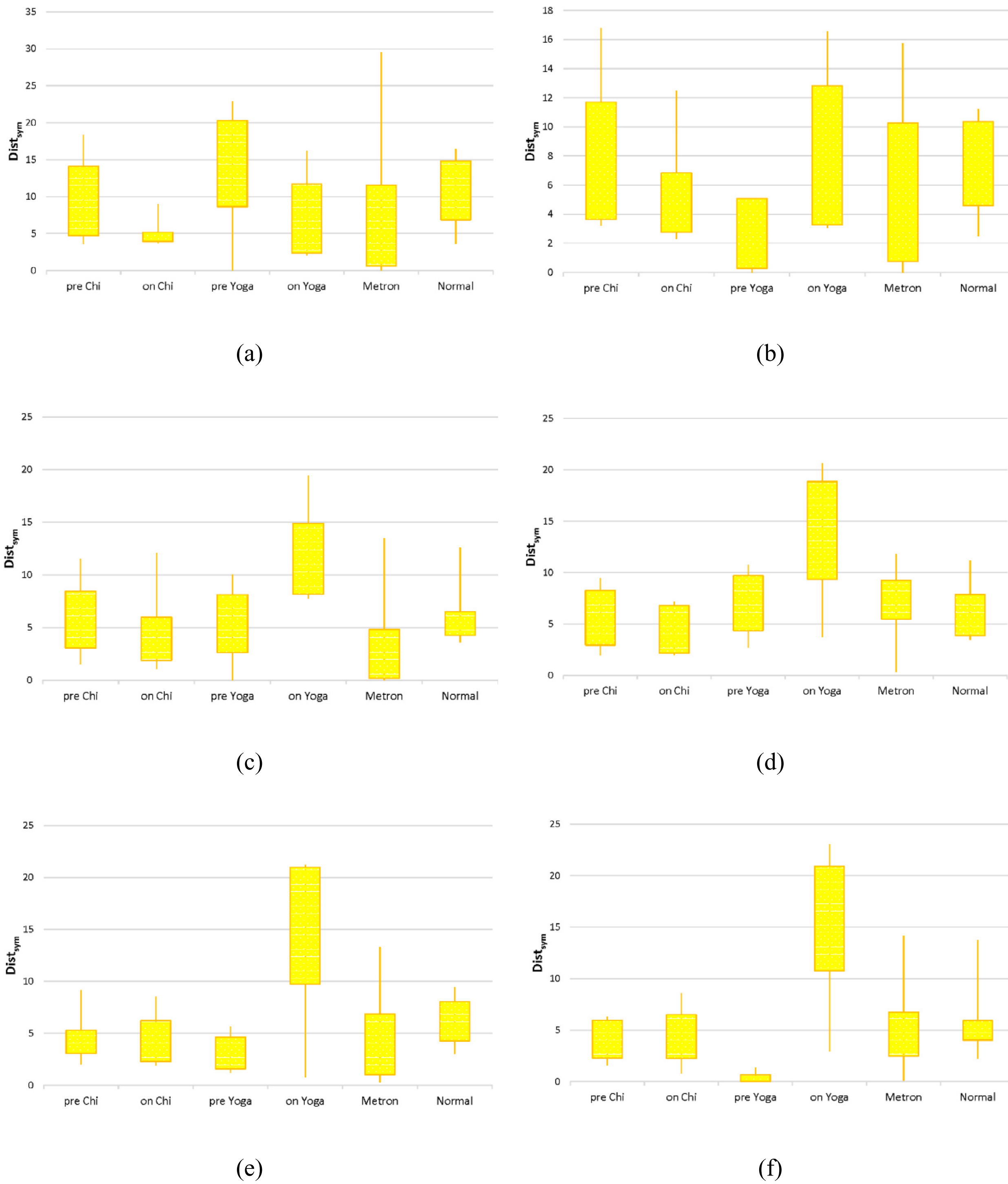

Fig. 2. *$Dist_{sym}$* values for all six modes, i.e. pre Chi, on Chi, pre Yoga, on Yoga, Metron, and Normal in different lags; (a) lag 1, (b) lag 2, (c) lag 3, (d) lag 4, (e) lag 5, and (f) lag 6.

Table 2
Statistical test results between GI_p values of different states.

	On Chi	Pre Yoga	On Yoga	Metron	Normal
Pre Chi	Lag 1	–	Lag 5 & Lag 6	–	All lags except for lag 4
On Chi		–	Lag 6	–	Lag 3
Pre Yoga			Lag 4, Lag 5 & Lag 6	–	Lag 1, Lag 5 & Lag 6
On Yoga				Lag 4, Lag 5 & Lag 6	Lag 6
Metron					Lag 3

meditators and no-meditators. Generally, using a conventional Poincare's plot the HRA reduces in the metronomic group. As the delay increases, the symmetry of the HRV increased in pre Chi, on Chi, pre Yoga, Metron, and Normal. The effect is inverted for the meditators during the performance of the Yoga whose HRA exhibits an increase. An index of HRV asymmetry was able to discriminate between the dynamics of meditators and non-meditators statistically. The comparative HRA measures of the lagged Poincare's plot in groups of meditators and non-meditators give more insight into the HRV in a particular psychophysiological state. In addition, the difference between lagged HRA responses during Yoga in comparison with other groups can be an emphasis on the importance of choosing the type of meditation technique and its effects on the cardiovascular system.

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Ethical approval

"This article examined the HRV signals of Physionet dataset,[9] which is freely available in the public domain. This article does not contain any studies with human participants performed by any of the authors."

Informed consent

Informed consent was obtained from all individual participants included in the study.[9]

Declaration of competing interest

The authors declare that they have no conflict of interest.

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