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# Detection of Circaseptan Rhythm and the "Monday Effect" from Long-term Pulse Rate Dynamics

Ying Chen, *Student Member*, *IEEE*, and Wenxi Chen, *Member*, *IEEE*

***Abstract*—This study proposes a methodology to detect circaseptan (CS) rhythm in pulse rate (PR) data and to investigate the "Monday effect" in CS rhythm. Daily PR was collected from a middle-aged healthy working woman over one year. PR, SDNN index and sample entropy (SampEn) were chosen as the indexes of PR dynamics. In order to avoid interference from other biorhythms, ensemble empirical mode decomposition (EEMD) method was used to decompose the original PR series into multiple components. And the single cosinor method was applied to fit the detrended component signal. An optimal 7-day period was found in all indexes ($P$ = 0.0103, $P$ = 0.0133, $P$ = 0.0122 for PR, SDNN index and SampEn, separately) that demonstrated an underlying CS rhythm. In the following study, a statistical Monday decrease in PR dynamics was observed especially significant in the detrended signal. The results suggested a direct relationship between the "Monday effect" and the CS variation, and also indicated a cardiac susceptibility to the social activities. The findings in CS periodicity and the "Monday effect" may help understand the human's biorhythm, provide evidence for preventive and optimized timing treatment, and also serve to daily health management.**

## I. Introduction

The human "biological week", a nearly 7-day cycle, has been known as the circaseptan (CS) rhythm. Within the human body, this about-weekly feature has been found in fluctuations of blood pressure, urine chemical excretion, rise and fall of certain hormones, the immune system, mood and the performance of reaction time [1]–[6]. A prominence of the CS component is also demonstrated for heart rate (HR) and heart rate variability (HRV) indices [7].

Circaseptans have been found in morbidity or mortality statistics of human sudden death, myocardial infarctions, life-threatening ventricular arrhythmias and strokes [8]–[11]. A meta-analysis study shows that the incidence of myocardial infarction increases sharply on Mondays with a secondary peak on Thursdays and Fridays [9]. Another meta-analysis shows that the incidence of sudden cardiac death markedly increases on Monday, similar for men and women [8].

CS variations in HR and HRV may serve to preventive treatment of these cardiac mortalities that appear to be time-dependent. Indeed, CS rhythm and its performance have been so far not completely explored. One of the reasons might be the paucity of high quality data. Most of the reports on CS rhythm are based on population statistics but not from continuous observation. Even if CS component is detected from continuous collected data, the interactions of multiple biorhythms are not considered. Since CS component can be merged in the overall trends synchronized with biweekly, monthly, seasonal, or circannual rhythms. It is better to separate it from others before analysis.

In this study, we aimed to detect CS rhythm from daily PR signals recorded throughout one year during sleep. A healthy working woman in her 30's was involved in this study. Ensemble empirical mode decomposition (EEMD) was utilized to detrend and eliminate the interference of low frequency components. Then, a single cosinor analysis method was used to fit the detrended signal to find out the optimal period length ($P < 0.05$). A Monday decrease was studied before and after signal detrending from indexes including pulse rate (PR), SDNN index and sample entropy (SampEn).

## II. Materials and Methods

### A. Subject

A female subject in her thirties was involved in this study. She is an office worker who strictly sticks to a regular nine to five routine and works five days a week, from Monday to Friday. She is free of cardiac pathology or arrhythmia and does not have smoking or drinking habits. Informed consent was obtained from the subject.

### B. Data Collection and Signal Processing

Pulse rate recording was conducted at volunteer's home during her daily sleep time. Pulse signal is acquired by an Internet-based unconstrained sleep monitoring system. There are three main units in the system: a sensor unit, an amplifier and a network module. The sensor unit is placed beneath a pillow. Two air-free water-filled vinyl tubes and two micro tactile switches are sandwiched between two acrylic boards. The pressure signal will be detected by sensor heads, amplified by pressure amplifiers and digitized as well as transmitted to a remote database server via a network module. The schematic image is shown in Fig. 1 and details of the system can be found in [12].

Data collection was initiated from March 31, 2004 and ended on March 31, 2005. The first five hours of the

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Y. Chen is with the University of Aizu, Aizu-wakamatsu, Fukushima 965-8580, Japan (e-mail: d8112101@u-aizu.ac.jp).

*W. Chen is with the University of Aizu, Aizu-wakamatsu, Fukushima 965-8580, Japan (phone: 81-242-37-2606; fax: 37-2728; e-mail: wenxi@u-aizu.ac.jp).

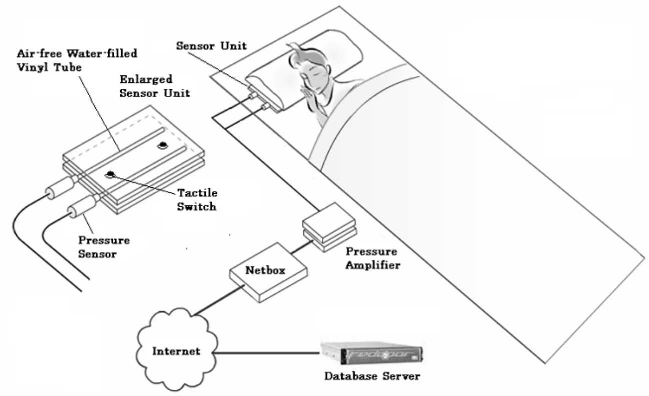


Fig. 1. Schematic illustration of an Internet-based system for vital signs monitoring during sleep.

recorded data during one night's sleep were used in analysis. In total, 324 nights' data were actually available for the study because some days have too short data and some have no data recorded at all. All the signal processing procedures were implemented using MATLAB. Digital signal processing for pulse-wave peak detection was implemented on the server using the algorithms described in [13].

### C. Pulse Rate Variability Indexes

PR is calculated and averaged on a nightly basis. SDNN index is defined as the mean of the 5-min standard deviation of the pulse interval calculated over one night. It reflects trends and inconstancies in the average PRs. SampEn is computed every 10 minutes and averaged over night. It provides a generalized measure of complexity in a time series [14]. Before indexes computing, Box-and-Whisker plot is used to graphically depict profiles of daily PR, SDNN index and SampEn over one year through five-number summaries: the lower limit of 95% confidence interval, lower quartile, median, upper quartile, and upper limit of 95% confidence interval (Fig. 2). Outliers indicated as small circles or stars are removed from the data set before further analysis because they might be caused by measurement error or systematic error which can mislead the interpretations of the data.

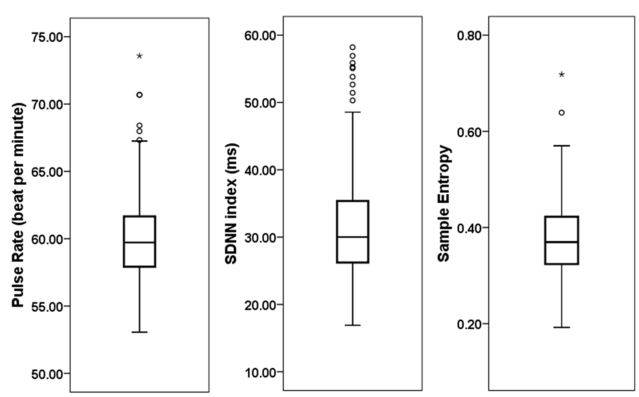


Fig. 2. Box-and-Whisker plots of daily PR (left), SDNN index (middle) and SampEn (right) over one year.

### D. Ensemble Empirical Mode Decomposition (EEMD)

Empirical Mode Decomposition (EMD) was first introduced by Huang *et al* and had successful applications in biomedical applications [15]. It is an empirical, intuitive, direct and self-adaptive data processing method which is proposed especially for nonlinear and non-stationary data. It assumes that the data, depending on its complexity, may have many different coexisting modes of oscillations at the same time. EMD can extract these intrinsic modes from the original time series, based on the local characteristic scale of data itself. The core of EMD is to decompose data into a small number of independent and nearly periodic intrinsic mode function (IMF). The process of finding IMF components is a sifting procedure which stops finally when the residue becomes a monotonic function from which no more IMF can be extracted. A detailed process can be found in [15].

Since mode mixing is one of the major drawbacks of EMD, EEMD method has been proposed recently by Wu and Huang [16] to be a noise-assisted data analysis method and represent a significant improvement over the original EMD. The principle of EEMD is to add white noise, which populates the whole time–frequency space uniformly with the constituent components of different scales separated by a filter bank. The added white noise series cancel each other in the final mean of the corresponding IMFs; the mean IMFs stay within the natural dyadic filter windows and thus significantly reduce the chance of mode mixing and preserve the dyadic property.

We applied EEMD to daily PRV index. And in order to avoid signal intermittency, a linear interpolation method was applied to each time series before signal decomposing.

### E. Single Cosinor Analysis Method

Cosinor analysis uses the least squares method to fit a sine wave to a time series that demonstrate predictable rhythms [17]. For a time series $f(t_i)$, a cosinor function can be presented as:

$$f(t_i) = M + A\cos(\omega t_i + \varphi)$$

where $M$ represents the mean level (Midline Estimating Statistic Of Rhythm (MESOR)) of the cosine curve, $A$ is the amplitude of the function, $\omega$ is the angular frequency (reciprocal of the cycle length) of the curve, and $\varphi$ is the acrophase (horizontal shift) of the curve. Here, a single cosinor is used to fit the detrended signal in order to find out the optimal cycle length. The optimal $\omega$, which has the minimum value of the residual sum of squared (*RSS*) error ($P$< 0.05), can best reflect its periodicity. In order to find out the optimal $\omega$, we assign the $\omega$ from $2\pi/2$ to $2\pi/365$ and calculate corresponding $P$ value. The cycle length with the minimal $P$ value is chosen as the optimal period length of the time series.

### F. Statistical Analysis

Mean values of PR, SDNN index and SampEn were calculated and the statistical comparisons between Sundays and the other days of the week were conducted by ANOVA. Significant difference level was set to $P$ <0.05.

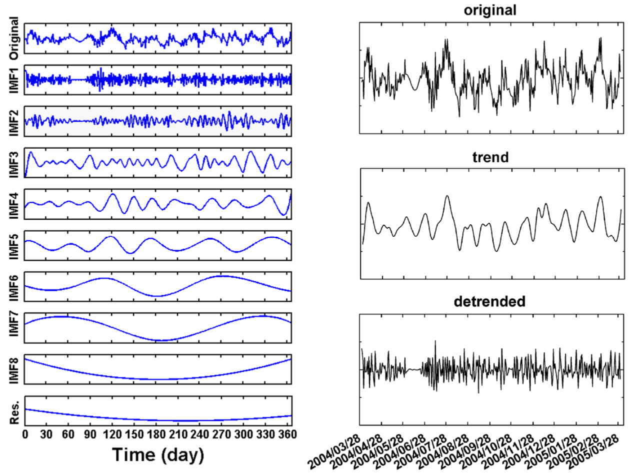


Fig. 3. Results of EEMD (left) and signal detrending (right) in daily pulse rate.

## III. Results

Decomposition results were similar in all three indexes, and here we only presented the decomposed and detrended results of PR data (Fig. 3). The original PR data was decomposed into eight IMFs and a residual (Fig. 3 (left)). The residual indicated the overall trend and each IMF suggested a variation with different frequency. Cosinor analysis was then applied to each IMF component. In order to avoid interference from lower frequencies as much as possible, we made a partial reconstruction with IMF1 and IMF2 since an about 20-day optimal cycle was detected in IMF3 component. The detrended signal was presented in Fig. 3 (lower right).

Cosinor analysis was applied to the detrended signal. Fig. 4 showed the results of computed *P* values in PR, SDNN index and SampEn. We found accordance in all indexes that

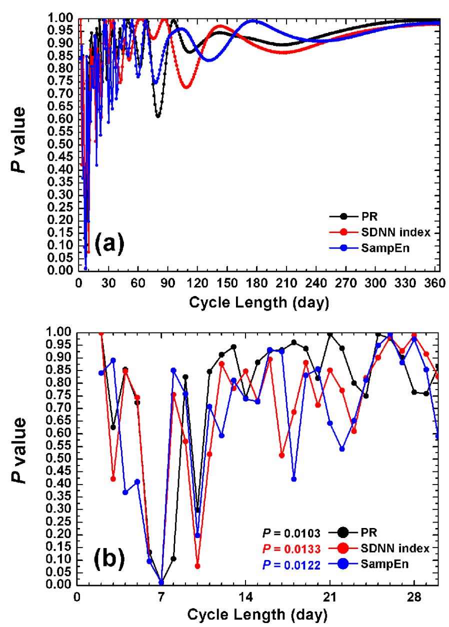


Fig. 4. *P* values of cosinor analysis method in (a) pulse rate, SDNN index, sample entropy and (b) the partial enlargement.

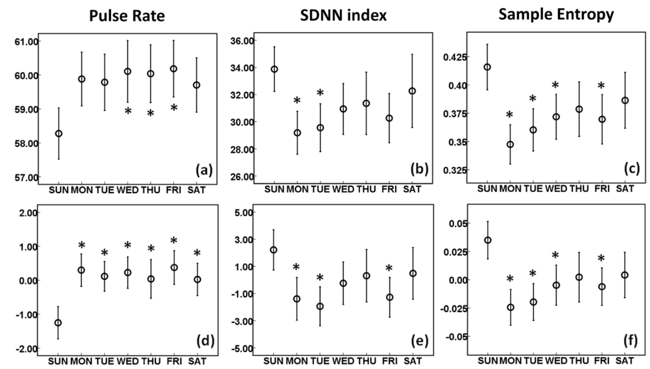


Fig. 5. Mean values of pulse rate, SDNN index and sample entropy on each Day-of-Week before (a)-(c) and after (d)-(f) signal detrending.

the minimal *P* values appeared at the very beginning. To figure out the minimal *P* value, we made a partial enlargement (Fig. 4 (b)). The only *P* value that smaller than 0.05 was observed in the cycle length of 7 days in all three indexes. This indicated an optimal periodicity as CS rhythm.

PR, SDNN index and SampEn on each Day-of-Week were averaged and presented in Fig. 5. The upper three figures showed the results based on original data, while the lower three were based on detrended data. The asterisks in the figure indicated significant different compared to Sundays. On the average, PR reached its minimum while SDNN index and SampEn reached their maximal levels on Sundays. A sudden change happened subsequently, indicating a sharp decrease in cardiac dynamics on Mondays ("Monday effect"). The CS patterns remained similar before and after signal detrending, while the statistical differences between Monday and Sunday became more remarkable after detrending ($P$ <0.01). A secondary, less significant decrease in PR dynamics was observed in SampEn series and detrended SDNN index on Friday. However, we failed to detect a circasemiseptan (CSS) (about half week) rhythm by cosinor method. In that case, a determined CSS cycle could not be confirmed.

## IV. Discussion

Human bodies are carefully designed for self-protection and self-regulation even in matters of time. A central feature of biological time structure is the harmonic relationship that exists among the various component frequencies. The components themselves appear to be harmonics or sub harmonics, multiples or submultiples. In this study, we found out a CS pattern in PR indexes, this independent seven-day cycle might also synchronize one or several natural endogenous rhythms, with periods close to 7 days, regulated by external factors, constituting a putative "biological week".

Some of the previous studies on CS rhythm were mostly based on population. By statistical averages, they found peak and valley in one-week cycle. Other longitudinal researches on long-term heart rate CS rhythm rarely took the impact of other biorhythms into consideration. This weekly pattern might be submerged by other low-frequency variations such as biweekly, monthly, seasonal or yearly and became invisible. In this study, we were not able to detect such CS component from the original signals. But after detrending, a single cosinor analysis method was able to discover this underlying 7-day cycle. This might suggest the coexistence of multiple biorhythms that intervene among each other. On the other side, “Monday effect” could be observed before and after detrending and became even remarkable after signal detrending. This phenomenon indicated a direct relationship between the “Monday effect” and the CS rhythm while accompanied with minor influences from other biorhythms.

The possible factors that contribute to the CS rhythm are proposed to include three main aspects: a built-in periodicity which is demonstrated by genetic basis [18]; the response to influences from the solar system and geomagnetic activity [19]; and impact of the social 7-day routine on the physiological rhythm, such as the weekly alternation of work and rest, stress and depression [20]. In this study, the working woman leads a regular five-day week life; the social activities may have brief influences on her physiological dynamics. Our recording was conducted under a relatively comfort and stable state during night time sleep which can better reflect the impact of daily activities or mental changes on the physical conditions. After a whole weekend rest, one can gain energy or recover from fatigue and get oneself ready for the new workday. It results in high PR dynamics on Sunday nights. A followed Monday drop might reflect a body’s response to the stress and the tense working atmosphere brought by the shift from rest to working state. An association between mood, stress and cardiac events has been shown in previous studies [21]. This mental stress might be also related to reduced parasympathetic activity and HRV and be associated with onset of certain cardio diseases on Monday.

However whether this “Monday effect” suggests an overload on the cardiovascular system and is potentially dangerous for people with health problems is as yet to be examined. To answer the questions, subjects with different ages, genders, occupations (housewives, retired elders and time-shift workers), and health conditions should be included in further studies on CS performances and the “Monday effect”.

## V. Conclusion

This longitudinal study unveiled CS features in long-term PR and PRV from a middle-aged healthy working woman by using EEMD and cosinor analysis method. Salient Monday decrease in PR dynamics was observed which might reveal a social impact on autonomic and cardiac activities. Our findings provide an approach for studying CS rhythms in cardiovascular systems. Since CS variations in cardiac mortality appear to be time-dependent, transient risk states for catastrophic cardiac events, we hope our results can help understand the human’s biorhythm, pave way for preventive and optimized timing treatment and also serve to daily health management.


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## References


[1] M. S. Lee, *et al.*, "About 7-day (circaseptan) and circadian changes in cold pressor test (CPT)," *Biomed Pharmacother,* vol. 57 Suppl 1, pp. 39s-44s, Oct 2003.

[2] G. Y. Nicolau, E. Haus, M. Popescu, L. Sackett-Lundeen and E. Petrescu, "Circadian, weekly, and seasonal variations in cardiac mortality, blood pressure, and catecholamine excretion," *Chronobiol Int,* vol. 8, pp. 149-59, 1991.

[3] F. Halberg, *et al.*, "Chronobiology, growth hormone and healthy and malignant growth," *J Endocrinol Invest,* vol. 12, pp. 41-7, 1989.

[4] E. Haus and M. H. Smolensky, "Biologic rhythms in the immune system," *Chronobiol Int,* vol. 16, pp. 581-622, Sep 1999.

[5] G. Cornelissen, *et al.*, "Mapping of Circaseptan and Circadian Changes in Mood," *Scr Med (Brno),* vol. 78, pp. 89-98, 2005.

[6] J. Beau, M. Carlier, M. Duyme, C. Capron and F. Perez-Diaz, "Procedure to extract a weekly pattern of performance of human reaction time," *Percept Mot Skills,* vol. 88, pp. 469-83, Apr 1999.

[7] A. Delyukov, Y. Gorgo, G. Cornelissen, K. Otsuka and F. Halberg, "Infradian, notably circaseptan testable feedsidewards among chronomes of the ECG and air temperature and pressure," *Biomed Pharmacother,* vol. 55 Suppl 1, pp. 84s-92s, 2001.

[8] D. R. Witte, D. E. Grobbee, M. L. Bots and A. W. Hoes, "A meta-analysis of excess cardiac mortality on Monday," *Eur J Epidemiol,* vol. 20, pp. 401-6, 2005.

[9] G. Cornélissen, *et al.*, "Non-photic solar associations of heart rate variability and myocardial infarction," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 64, pp. 707-720, 2002.

[10] R. W. Peters, S. McQuillan, S. K. Resnick and M. R. Gold, "Increased Monday incidence of life-threatening ventricular arrhythmias. Experience with a third-generation implantable defibrillator," *Circulation,* vol. 94, pp. 1346-9, Sep 15 1996.

[11] R. Manfredini, F. Manfredini, B. Boari, R. Salmi and M. Gallerani, "The Monday peak in the onset of ischemic stroke is independent of major risk factors," *Am J Emerg Med,* vol. 27, pp. 244-6, Feb 2009.

[12] W. Chen, *et al.*, "Unconstrained detection of respiration rhythm and pulse rate with one under-pillow sensor during sleep," *Med Biol Eng Comput,* vol. 43, pp. 306-312, 2005.

[13] X. Zhu, *et al.*, "Real-time monitoring of respiration rhythm and pulse rate during sleep," *IEEE Trans Biomed Eng,* vol. 53, pp. 2553-63, Dec 2006.

[14] J. S. Richman and J. R. Moorman, "Physiological time-series analysis using approximate entropy and sample entropy," *Am J Physiol Heart Circ Physiol,* vol. 278, pp. H2039-49, Jun 2000.

[15] N. E. Huang, *et al.*, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," *Proc. R. Soc. Lond.* A, *vol.* 454, pp. 903-995, March 8, 1998.

[16] Z. Wu and N. E. Huang, "Ensemble Empirical Mode Decomposition: a Noise-Assisted Data Analysis Method," *Advances in Adaptive Data Analysis,* vol. 1, pp. 1-41, 2009.

[17] W. Nelson, Y. L. Tong, J. K. Lee and F. Halberg, "Methods for cosinor-rhythmometry," *Chronobiologia,* vol. 6, pp. 305-23, Oct-Dec 1979.

[18] F. Halberg, "The week in phylogeny and ontogeny: opportunities for oncology," *In Vivo,* vol. 9, pp. 269-78, Jul-Aug 1995.

[19] T. K. Breus, *et al.*, "The biological effects of solar activity," *Biomed Pharmacother,* vol. 56 Suppl 2, pp. 273s-283s, 2002.

[20] M. Shinagawa, *et al.*, "Seven-day (24-h) ambulatory blood pressure monitoring, self-reported depression and quality of life scores," *Blood Press Monit,* vol. 7, pp. 69-76, Feb 2002.

[21] E. Clays, *et al.*, "The perception of work stressors is related to reduced parasympathetic activity," *Int Arch Occup Environ Health,* vol. 84, pp. 185-91, Feb 2011.