Effect of Window Length on the Analysis of Cardiorespiratory Synchronization

Lin-Sen Pon[1], Chih-Hsiang Tsou[2,3], Jong-Chih Chien[4], Jun-Jih Liang[5], Tsair Kao[6]

[1]Chinese Culture University, Taipei, Taiwan, [2]University of National Yang-Ming University, Taipei, Taiwan, [3]Taipei City Hospital, [4]Kainan University, Taoyuan, Taiwan, [5]Fu Jen University, New Taipei City, Taiwan, [6]Hungkuang University, Taichung, Taiwan

Abstract

The cardiac and respiratory rhythms interact with each other and may exhibit a synchronous behaviour in the human body. The mutually coupled relationship is investigated by analyzing the biological electro-cardiogram (ECG) and respiration signals. In general, these two types of signals are non-stationary, irregular and somewhat chaotic. Consequently, it is hard to use the widely applied Fourier transform or any other stationary processes to analyze the data. Respiratory and cardiac rhythms alike are periodical in themselves. Signals of these two physiological systems exhibit similar patterns and the change in individual rhythm may affect on one another. Comparing the phase variations of the selected signatures between the two signals periods of cardiorespiratory synchronization can be identified. The continuous 'R' peaks of heartbeat are picked out and the phase difference of two adjacent peaks is set to 2π. The starting points of respiratory signal are used as the zero-phase points and the phases within two continuous signals are linearly interpolated in the range of 2π. This derived phase information is related to the instantaneous radian frequency for each one. By inspecting the existence of R peaks and different respiratory cycles, the cardio-respiratory synchrogram is presented. Gamma evaluation method (γ evaluation) is used to quantify the strength of cardiorespiratory synchronization. This method processes a selected window length of data and calculates the degree of interaction. The analysis of the synchronization between cardiac and respiratory rhythms is presented and the effects of using different window lengths on γ, n, m are discussed.

1. Introduction

Cardiorespiratory synchronization is to describe the phase rhythms between the appearing time of R peaks and the times of the inspiratory onsets in two coupled systems [1-3]. Also the appearing of both data is one kind of temporal incidences, but the periodical signature of these biological activities can be interpreted in the spectral domain. It describes the phases of heart rhythm and respiratory rhythm are consistent with integer ratio (n:m), called as phase locking ratio [4,5]. The integer ratio of cardiorespiratory synchronization has been found in healthy adults, athletes, infants [6-8]. The temporal coherence of cardiac and respiratory rhythms is also detected in healthy subjects [9]. The mechanisms and physiological interactions between respiration and heart rhythm are not yet fully explored to explain their coupling action, but cardiorespiratory synchronization can be observed by using mathematical and physiological models.

This study is to compare the phase relationships between ECG and respiratory data with respect to varied window length. Different respiratory epochs were selected as a filtering window and the corresponding gamma evaluations were derived. The averages of gamma strength corresponding to varied window length, m, over the whole time period are derived. After processing all data sets, the means of gamma evaluations for different window length are aligned together. The shape of this alignment looks like a parabolic equation. It found that the longer the window length it is, the weaker gamma indication it will be. The results imply that the smaller window length produces higher degree of synchronization for cardiorespiratory system. Furthermore, the contiguous repeated patterns with same n:m ratio are investigated. The appearances of these patterns are considered as a stronger sign of synchronization. The occurrence numbers of possible ratios are extracted and the highest value is the most dominant phase locking interaction.

The first section is the introduction of this study and the second one explains the data collection and the background of mathematical models. The third section shows the experiment results. At the end, a discussion is presented.

2. Methods

The cardiac and respiratory systems are considered as two independent oscillators coupling with each other. The cardiorespiratory coupling activities are investigated by

analysing of the phase of R peaks corresponding to the phase of inspiratory onsets.

2.1. Subject population

The cardiac and respiratory signals are collected from twenty healthy male/female (18/2) college students whose ages are between 18 and 22 years old without any known diseases. One hour long cardiorespiratory data was recorded for each subject, who was laid down on bed as comfortable as possible. At the middle of experiment, subjects will be noticed that the half of data was being recorded and the experiment continued. The mean (std) of heart interval is 0.81 (0.08) seconds and their ranges are between 0.7–1.0 seconds. The mean (std) of respiration interval is 4.4 (1.26) and the ranges of these intervals are from 2.9 to 6.4 seconds.

2.2. ECG and respiratory data

The sampling rate of electrocardiogram (ECG) and respiratory is recorded at 500 Hz. Low frequency baseline is filtered out by using a butterworth low-pass filter at 0.01 Hz. A MATLAB (The Mathworks, USA) code is written to automatically identify sharp pulse-like R peaks for off-line analysis and manually inspected by human is edited to eliminate artifacts. The time differences between two contiguous R peaks indicate the period of heart beating. Since each cycle of heart beat is a complete activity of heart beat. The full cycle of R-R period is defined as 2π. Even the phase of each cycle is the same, but the time durations of each period are different for real word data.

The respiration data is recorded by using "End-Tidal Carbon Dioxide" device which records the variation of the concentration of carbon dioxide (CO_2) in the arterial blood. Inspiratory onsets were defined as the turning points from local maximum to the local minimum in the respiratory trace due to the fast variation of CO_2 density. The times of peak R_i ($I = 1,\ldots,n_R$) and the times of the inspiratory onset I_j ($j = 1,\ldots,n_I$) were marked and saved for further analysis. On Figure 1, top one is ECG signal and bottom is end-tidal respiratory signal. The marks, 'x', are corresponding to the R_i peaks and inspiratory onsets, I_j.

2.3. Cardiorespiratory analysis

The relationship between phase and frequency of a periodic signal is given by $d\phi / dt = \omega$, where ϕ and ω are the phase and radian frequency. The phase of each respiratory cycle is 2π long and for the rest points, which are aligned between two onsets, their phases are derived by using a linear phase increment model:

$$\phi_r(t) = 2\pi(t - t_j)/(t_{j+1} - t_j) + 2\pi j, t_j \le t \le t_{j+1},$$

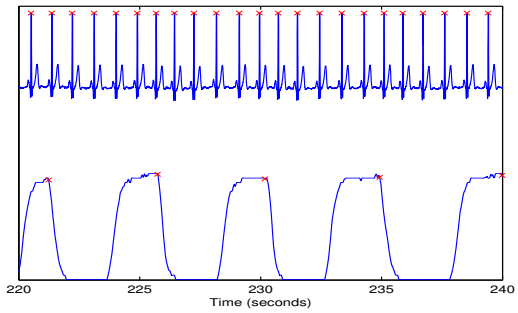

Figure 1. The alignment of ECG and respiratory data

where t_j is the j-th inspiratory onset, I_j. If two oscillated systems, such as cardiorespiratory responses, are synchronously interactive with each other, then the rhythms of two signals are correlated with the radian frequencies. Such coupling interactions will lead to a locking of the phases between two systems. At this situation, the synchronization is defined by $n\omega_I \approx m\omega_r$. The ω_r and ω_I are the radian frequencies of heart beat and respiratory data. The integer numbers, n and m, are called as oscillatory factor. The coupling behaviours between two oscillators are resonant to each other with n:m factors between their phases.

Due to the noise effects, the stable points may shift up and down with respect to a phase locking condition and an analytic condition of synchronization can be written as:

$$\left| n\phi_I(t) - m\phi_r - \delta \right| < C,$$

where C is a constant and δ is equal to the average phase shift or a frequency entrainment. If noise is relatively small, the synchronization will show the fluctuations around phase baseline. If the phase difference between the two systems was within a certain threshold value, then constant C remained stable among n heart beats and m respiratory cycles. If at the time, t_k, a cardiac peak is spotted, indicating by R_k, then by observing its phase wrapping the phase, ϕ_I, onto an interval of [0, 2πm], denoted by $\psi_m(t_k)$, is given by

$$\psi_m(t_k) = (1/2\pi) * \mathrm{mod}(\phi_I(t), 2\pi m).$$

The derivation of all R peaks will form the transition between phase relationships of cardiorespiratory systems. The wrapping phase of the above equation leads a visual tool, called as cardiorespiratory synchrogram. By plotting ψ_m corresponding to time t_k, there are n horizontal lines with its vertical range confined from 0 to its maximum cyclic relative phase, m. The synchrogram visually shows the phase relationships between R peaks and respiratory rhythm. The best resolutions of viewing the data vary depending on the amount of data; a manually adjustment may be required. On Figure 2, a synchrogram is plotted by choosing respiratory length, m =2, from one subject of collected data.

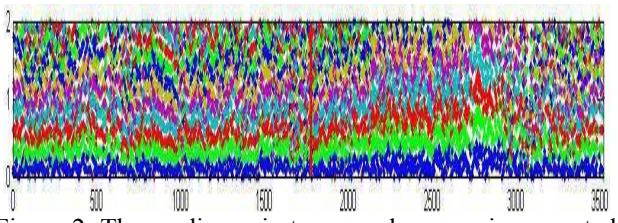

Figure 2. The cardiorespiratory synchrogram is presented from one data set. The x axis is time (3600 seconds). The respiratory window (m) is set to 2, so the maximum value of vertical axis is also 2.

One hour long cardiorespiratory data was analyzed. In our observations, long term phase variation is locked at a fixed ratio, but the variances of short-term period are relatively large. The thin line in the middle area is the happening time when the subject was reminded that experiment is going half way.

In order to quantify the degree of synchronization, instead of using graphical tool, a numerical evaluation of coupling between two oscillators is required for further defined. First, it transform from $\psi_m(t_k)$ to $\Psi_{n,m}(t_k)$, called as gamma evaluation, and then the degree of n:m synchronization is derived by

$$\Psi_{n,m}(t_k) = \mathrm{mod}(\psi_m(t_k) * n, m)$$

$$\gamma^2_{n,m} = <\cos(\Psi_{n,m}(t_k))>^2 + <\sin(\Psi_{n,m}(t_k))>^2,$$

where the bracket denotes the average value of $\Psi_{n,m}(t_k)$ over the range of selected window length. The gamma quantizes the regularity of distribution of generalized phase differences. Its range is varying from 0 to 1. The higher value it is, the stronger synchronization it will be. Higher degree of phase coupling indicates that the phases of cardiorespiratory are distributed regularly at a specific phase corresponding to the n rotations of cardiac R peaks over m epochs of respiration.

3. Experimental results

In order to compare the effects of synchronization by using different respiratory length, it had calculated the gamma values for most possible n:m combinations. The ranges of respiratory window, m, are selected from 1 to 20 respiratory epochs. In m respiratory epochs, if there are n R-peaks being spotted, then the number n will be used for gamma derivation. The technique derived the degree of synchronization for local cardiorespiratory activity. In order to get a full cyclic period for two systems, it used the respiratory length, m, as an index. It is because the number of R peaks occurring in m respiratory epochs will also be an integer number. But if it used n as index, then a full cyclic of respiration cannot be guaranteed. It has derived the gamma of the whole data sets for each subject. Figure 3 show the calculated gamma result of one subject. It is a 3D plot where x axis

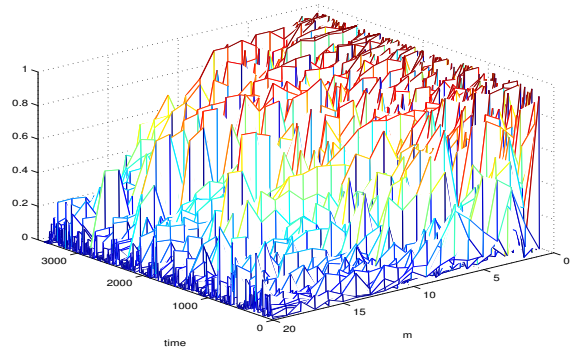

Figure 3. A 3D plot of the gamma derived from one subject. One axis is labeled by time (seconds) and the other indicates the respiratory window length m=1:20. The vertical direction is the value of gamma where its range is from 0 to 1. The higher value it is, the degree of synchronization is stronger.

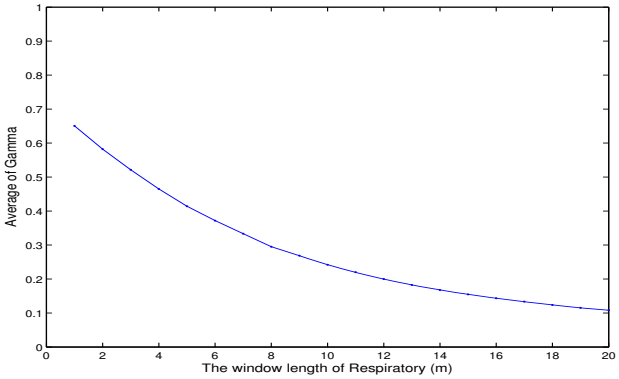

Figure 4. The average gamma values over the whole time duration of cardiorespiratory data for twenty subjects are presented. The respiratory window length, m, are chosen from 1 to 20. The vertical direction is the average value of gamma. The curve is parabolic shape declining from smaller window length to larger number.

is time and the y axis is the value of respiratory length, m.

By observing the 3D plot, it has been seen that gamma value is higher when the window length, m, is smaller. But gamma decreases rapidly when the m becomes larger. It indicates that the cardiac and respiratory systems are less or non-synchronous with each other for a long term period. But for a shorter window length, two biological systems have tendency coupling with each other. Human system may hold on a steady status for a while, but it will alter eventually when the environment changed.

For further processing, the gamma values along with the time axes for each plot had been added together with respect to the window length, m. The average of the gamma summation indicates the strength of synchronization corresponding to a fixed length, m, over the whole time duration. A 2D plot is generated to show their relationship which its horizontal axis is equal to m and the vertical one is the average gamma strength. The

range of average is still between 0 and 1. By adding all data sets, the plot of mean gamma and different window, is shown on Figure 4. The horizontal axis is respiratory window length (m=1:20) and the vertical axis is gamma. The curve of gamma is a smooth parabolic line declining from left to right side. The highest degree of gamma value occurs at the respiratory length selected by 1. Since gamma presents the degree of synchronization, it leads a preliminary conclusion that the overall synchronization of cardiorespiratory systems will decrease as the length of window of gamma processing increases. Higher synchronization is observed when a short respiratory length is applied.

If cardiorespiratory signal with fix ratio (n:m) was repeatedly appeared, in this paper, it is considered as a strong synchronous sign. It had been defined as if a n:m ratio respiratory pattern continuously appearing at least three times in the data. It is called as 'contiguous repeated pattern'. All repeated patterns are counted to compare their occurrence for all data sets. Table 1 is the number of appearances for different n:m ratio. It shows that the highest number of all subjects are at ratio n:m equal to 4:1.

Table 1. Number of n:m of contiguous repeated patterns, the row, n, indicates the number of heart beats were observed in m respiratory cycles (column).

	Respiratory Length (m)			
n	1	2	3	4
3	531			
4	2100			
5	1225	5		
6	507	139		
7	231	228		
8	75	658		
9	63	212	30	
10		190	237	
11		53	84	
12		81	118	
13		44	14	10
14		14	31	9
15		10	33	30
16			7	116

4. Discussion

In order to get the largest coherence, the calculations are used a moving window with each step overlapping one respiratory epoch. The inspections of synchrogram of collected data sets show that the synchronization of cardiorespiratory system fluctuating over time. The basic ratio of n:m holds in a short-term period, but for a long period different synchronous pattern changes. The gamma evaluation quantizes the strength of synchronization with respect to a n:m ratio. The numerical results show that the gamma quantitative method has a better indication and sensitivity for a smaller respiratory length, m. If the window length becomes larger, a less degree of synchronization it will generate. The choice of window length depends on the integrity of data. But the contiguous repeated patterns can be used to choose right window length. These patterns exhibit the most synchronized rhythm of physiological status when two systems may have a stronger coupling relationship. So it can indicate the main predominant phase locking ratio. In this study, the most significant n:m ratio is 4:1 and the next one is at 8:2. However, it is obviously that the two ratios are identical to each other. The complete knowledge of this kind phenomenon is yet waiting to explore. But the synchronization provides an ECG and respiratory screening tool for investigation their interactions.

References

[1] Blekhman I.I. Synchronization in science and technology, ASME Press, New York, 1988.

[2] Landa PS. Nonlinear oscillations and waves in dynamical systems, Kluwer Academic Publishers, Dordrecht-Boston-London, 1996.

[3] Raschke F. Coordination in the circulatory and respiratory Inspiratory timing during anaesthesia systems, In: Rensing L, an der Heiden U, Mackey MC eds., Temporal Disorder in Human Oscillatory Systems. Berlin: Springer-Verlag, 1987:152-75.

[4] Censi F, Calcagnini G, Lino S, Seydnejad S, Kitney R. Transient phase locking patterns among respiration, heart rate and blood pressure during cardiorespiratory synchronisation in humans. Med Biol Eng Comput 2000;38:416–426.

[5] Lotric MB, Stefanovska A. Synchronization and modulation in the human cardiorespiratory system. Physica A 2000;283:451–461.

[6] Kotani K, Takamasu K, Ashkenazy Y, Stanley HE, Yamamoto Y. Model for cardiorespiratory synchronization in humans. Phys Rev E Stat Nonlin Soft Matter Phys, 2002.

[7] Schafer C, Rosenblum MG, Kurths J, Abel HH. Heartbeat synchronized with ventilation. Nature 1998;392: 239–240.

[8] Mrowka R, Patzak A, Rosenblum M. Quantitative analysis of cardiorespiratory synchronization in infants. Int J Bifurc Chaos 2000;10: 2479–2488.

[9] Eldridge FL. The different respiratory effects of inspiratory and expiratory stimulations of the carotid sinus nerve and carotid body. Advances in Experimental Medicine and Biology 1978;99:325–333.

Chih-Hsiang Tsou, MD, PhD
Division of Chest Medicine,
Ren-Ai branch, Taipei City Hospital
No.10, Sec. 4, Ren-Ai Rd.,
Taipei City 106, Taiwan
Email: DAM36@tpech.gov.tw