**Chen D, Chen F, Murray A, Zheng D. Phase difference between respiration signal and respiratory modulation signal from oscillometric cuff pressure pulses during blood pressure measurement. *In: Computing in Cardiology*. 2017, Vancouver, Canada: IEEE Computer Society.**

# Phase Difference between Respiration Signal and Respiratory Modulation Signal from Oscillometric Cuff Pressure Pulses during Blood Pressure Measurement

Diliang Chen[1], Fei Chen[1], Alan Murray[2], Dingchang Zheng[3]

[1]Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, China
[2]School of Electrical and Electronic Engineering and Faculty of Medical Sciences, Newcastle University, Newcastle upon Tyne, UK
[3]Health and Wellbeing Academy, Anglia Ruskin University, Chelmsford, UK

## Abstract

*Respiration influences the oscillometric cuff pressure waveform from which blood pressure (BP) is estimated. However, there is little information available on the phase shift between reference respiration signal and respiratory modulation signal from oscillometric cuff pressure pulses (OscP) during BP measurement. This study aimed to provide this information and investigate the effect of breathing pattern on the phase difference.*

*Two manual BP measurements were performed on 20 subjects under both normal and deep breathing conditions. During linear cuff deflation, OscP and respiration signal (Resp) were digitally recorded. Respiratory modulation signal was derived from pulse interval of OscP. After filtering the Resp and respiratory modulation signal with a bandpass filter, phase shift was calculated by cross spectral analysis, and then compared between the two measurement conditions.*

*Experimental results showed that there was phase shift between Resp and respiratory modulation signal from OscP under both normal (phase difference 0.20±0.09 rad) and regular deep breathing (phase difference 0.64±0.19 rad) conditions. Statistical analysis showed that deep breathing significantly (p<0.05) increased phase shift in comparison with normal breathing.*

*In conclusion, this study demonstrated the presence of phase shift between respiration signal and respiratory modulation signal from OscP during BP measurement and that the phase shift is associated with breathing pattern.*

## 1. Introduction

It has been widely accepted that respiration is one of the main factors affecting blood pressure (BP) measurements [1-5]. Although the underlying mechanism regarding the effect of respiration on BP measurement has not been fully understood, it is generally believed that respiration influences the central venous pressure through the chest expansion and compression, and then influences stroke volume [6].

Oscillometric cuff pressure pulses (OscP) are commonly used for automatic non-invasive BP determination. Zheng et al. [6] demonstrated the modulation effect of respiration on OscP under static cuff pressure. Our recent work extended Zheng et al.'s study and showed that respiration has amplitude modulation effect on OscP even under deflating cuff pressure during standard BP measurement [7].

However, to the best of our knowledge, there is little information available on the phase shift between reference respiration signal (Resp) and respiratory modulation signal derived from OscP during BP measurement. This study aimed to provide this information and investigate the effect of breathing pattern on the phase shift.

## 2. Method

### 2.1. Experimental setup

Twenty healthy subjects (ten males and ten females; aged from 23 to 65 years) were enrolled in the study. Their mean ± SD of age, height and weight were 39±16 years, 175±8 cm and 72±10 kg, respectively. This study was carried out according to the Declaration of Helsinki (1989) of the world Medical Association, and was approved by the locally appointed ethics committee. Informed and written consent was obtained from all subjects. Anonymised data was analysed.

For each subject, there was three repeated sessions. Within each session, two manual BP measurements were performed under both normal and regular deep breathing conditions by a trained operator following the recommendations of the European Society of Hypertension [8]. A one-minute resting period was given between every two consecutive measurements within a session to allow cardiovascular stabilization.

During manual BP measurement, the linearly deflating cuff pressure signal and reference Resp signal (from a chest magnetometer for detecting chest wall movement) were digitally recorded to a computer at 2 kHz of sampling rate [9].

## 2.2. Signal processing

The procedure of obtaining the phase shift between Resp and respiratory modulation signal from OscP included three steps: (1) Resp signal processing as shown in Fig. 1; (2) OscP signal processing to obtain the respiratory modulation signal (Fig. 2); and (3) cross correlation analysis. The details of the above signal processing procedures are described below.

Figure 1 (a) shows the originally recorded reference Resp signal. Firstly, the normalized power spectrum density (PSD) of Resp was estimated by Welch periodogram between 0.1 and 0.5 Hz with the frequency resolution of 0.001 Hz. As shown in Fig. 1 (b), the peak of the normalized PSD is marked with a red star and its corresponding frequency is the respiratory frequency. The Resp signal was then filtered by a bandpass filter (central frequency: respiratory frequency, bandwidth: 0.06 Hz) and stored for cross correlation analysis in the next step.

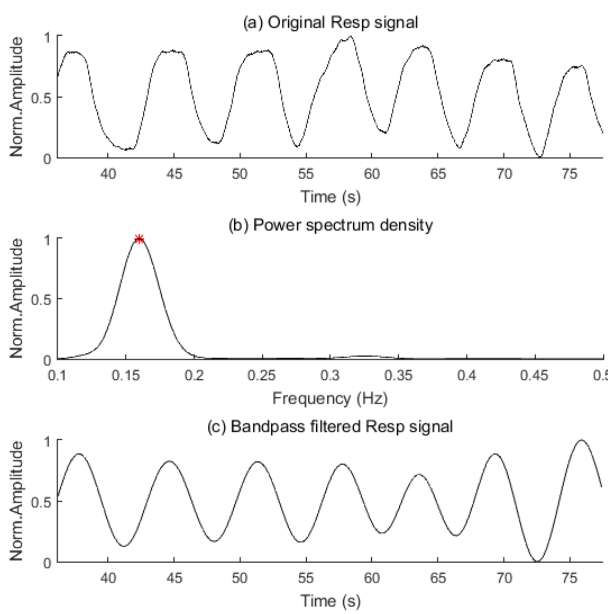


Figure 1. Reference respiration signal processing procedure. (a) The original Resp signal. (b) Power spectrum density of the original Resp signal. Red star indicates the peak of the power spectrum density, and its corresponding frequency is respiratory frequency. (c) The Resp signal filtered by a bandpass filter (central frequency: respiratory frequency, bandwidth: 0.06 Hz).

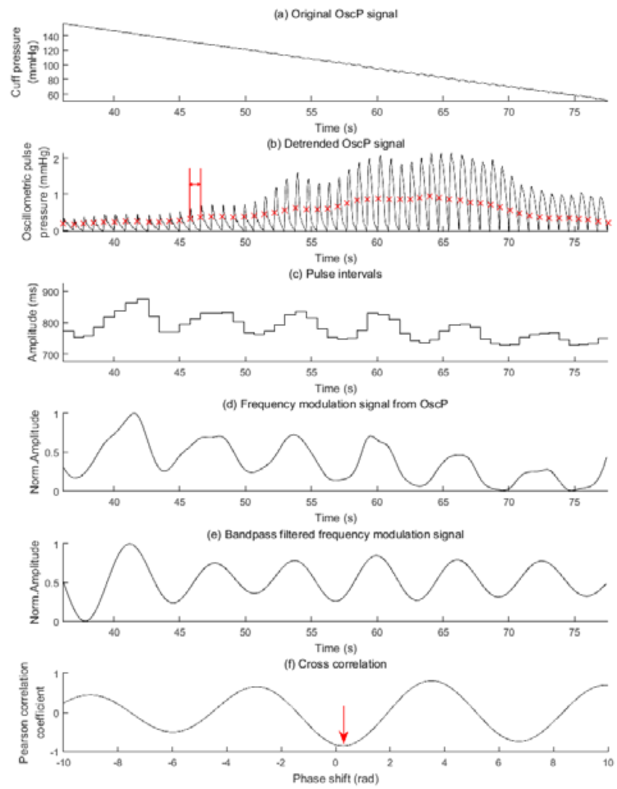


Figure 2. Oscillometric cuff pressure (OscP) signal processing and cross correlation analysis. (a) The linearly deflating cuff pressure signal. (b) The derived OscP signal. Each red x-mark in (b) indicates the maximum slope point of each OscP pulse, and the red double arrow indicates a pulse interval. (c) Stair-step graph shows the pulse interval series from OscP. (d) The normalized respiratory frequency modulation signal acquired from the pulse interval series through cubic spline interpolation. (e) Respiratory frequency modulation signal after bandpass filter. (f) Cross-correlation between filtered Resp and respiratory frequency modulation signal. The red arrow in (f) indicates the phase shift between the reference Resp signal and respiratory modulation signal.

Figure 2 (a) shows the originally recorded cuff pressure signal between 50 to 160 mmHg, and (b) shows the derived OscP pulses superimposed on the linearly deflating cuff pressure. The maximum slope points of each OscP pulse were then located by searching the peak of its first-order derivative signal, which are shown in Figure 2 (b) using red x-marks. Next, OscP pulse interval was acquired through calculating the time interval of the adjacent maximum slope points of OscP, which was used to construct the time interval series, as shown in Fig. 2 (c). The interval series was then further processed by cubic spline interpolation with a sample rate of 4 Hz to obtain the frequency modulation signal, which was then filtered by the same bandpass filter for the Resp signal.

Finally, the bandpass filtered Resp signal and the frequency modulation signal were used for cross correlation analysis. The phase shift between Resp and the frequency modulation signal was calculated as the phase difference between the valley nearest to the zero-lag point of the cross correlation function and the zero-lag point, as shown in Fig. 2 (f).

## 2.3. Statistical analysis

Results are presented as mean ± standard error of mean (SEM). The paired *t* test (with a significance level of $\alpha$=0.05) was used to assess the difference of measured BP, respiratory frequency and phase shift between the two breathing patterns (normal and deep breathings).

## 3. Results

As expected, when compared with the normal breathing condition, deep breathing significantly decreased SBP from 116 ± 2 mmHg to 111 ± 2 mmHg, DBP from 76 ± 2 mmHg to 72 ± 2 mmHg and respiratory frequency from 0.25 ± 0.01 Hz to 0.17 ± 0.01 Hz (all $p<0.001$), indicating that the experiment data were suitable for studying the effect of different breathing pattern on phase shift.

Figure 3 shows all the phase shifts between Resp and respiratory modulation signal from OscP under both normal breathing and regular deep breathing conditions. Statistical analysis showed that there was significant and positive phase shift ($p<0.05$) between Resp and respiratory modulation signal from OscP under both breathing conditions. The mean ± SEM of phase shift was 0.20±0.09 rad under the normal breathing condition and 0.64±0.19 rad under the deep breathing condition.

Statistical analysis also showed that deep breathing significantly ($p<0.05$) increased phase shift in comparison with normal breathing.

## 4. Discussion and conclusion

This study demonstrates the existence of phase shift between respiration signal and the derived respiratory modulation signal from OscP during BP measurement, where a positive phase shift means the delay of the respiratory modulation signal with respect to the respiration signal.

Zheng et al. [6] studied the phase shift between respiration signal and respiratory modulation signal from OscP under static cuff pressure condition, and also showed the existence of a positive phase shift between the two signals, which is consistent with the finding in this work.

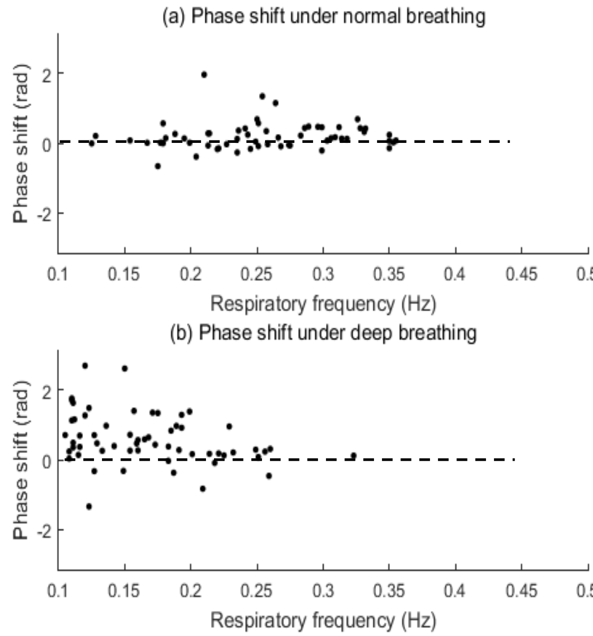


Figure 3. Scatter plots of all phase shift data between reference Resp and respiratory modulation signal from OscP under (a) normal breathing and (b) regular deep breathing conditions.

Our results also showed that deep breathing significantly increased phase shift. This agreed with Sin et al.'s study [10] where the increased phase delay between respiratory signal and respiratory modulation on beat-to-beat BP waveform was observed with decreasing respiratory rate.

In conclusion, this study demonstrated the presence of phase shift between respiration signal and respiratory modulation signal from OscP during blood pressure measurement. In addition, the phase shift was found to be associated with the breathing pattern.

## Acknowledgements


This study was supported by the National Natural Science Foundation of China (Grant No. 61571213) and by the Engineering and Physical Sciences Research Council (EPSRC) grants (reference number EP/I027270/1 and EP/F012764/1).

## References


[1] Novak V, Novak P, De Champlain J, Le Blanc AR, Martin R, Nadeau R. Influence of respiration on heart rate and blood pressure fluctuations. J Appl Physiol 1993; 74: 617-26.

[2] Radaelli A, Raco R, Perfetti P, Viola A, Azzellino A, Signorini MG, et al. Effects of slow, controlled breathing on baroreceptor control of heart rate and blood pressure in healthy men. J Hypertens 2004; 22: 1361-70.

[3] Jagomagi K, Raamat R, Talts J, Lansimies E, Jurvelin J. Effect of deep breathing test on finger blood pressure. Blood Press Monit 2003; 8: 211-4.

[4] Mori H, Yamamoto H, Kuwashima M, Saito S, Ukai H, Hirao K et al. How does deep breathing affect office blood pressure and pulse rate? Hypertens Res 2005; 28: 499-504.

[5] Laude D, Goldman M, Escourrou P, Elghozi JL. Effect of breathing pattern on blood pressure and heart rate oscillations in humans. Clin Exp Pharmacol Physiol 1993; 20: 619-26.

[6] Zheng D, Di Marco LY, Murray A. Effect of respiration on Korotkoff sounds and oscillometric cuff pressure pulses during blood pressure measurement. Med Biol Eng Comput 2014; 52: 467-73.

[7] Chen DL, Chen F, Murray A, Zheng D. Respiratory modulation of oscillometric cuff pressure pulses and Korotkoff sounds during clinical blood pressure measurement. Biomed Eng Online 2016; 15:53.

[8] O'Brien E, Asmar R, Beilin L, Imai Y, Mallion JM, Mancia G, et al. European Society of Hypertension recommendations for conventional, ambulatory and home blood pressure measurement. J Hypertens 2003; 21: 821-48.

[9] Griffiths CJ, Gilmartin JJ, Gibson GJ, Murray A. Measurement of chest wall movement; design, performance and clinical use of a four-channel magnetometer instrument. Clin Phys Physiol Meas 1983; 4: 363-71.

[10] Sin PYW, Galletly DC, Tzeng YC. Influence of breathing frequency on the pattern of respiratory sinus arrhythmia and blood pressure: old questions revisited. Am J Physiol Heart Circ Physiol 2010; 298: H1588-99.



Address for correspondence:
Prof Fei Chen
Department of Electrical and Electronic Engineering
Southern University of Science and Technology
Xueyuan Road 1088#, Xili, Nanshan District, Shenzhen, China
Email: fchen@sustc.edu.cn