A Method for Extracting Respiratory Frequency during Blood Pressure Measurement, from Oscillometric Cuff Pressure Pulses and Korotkoff Sounds Recorded during the Measurement

Diliang Chen, Fei Chen *Member IEEE*, Alan Murray, Dingchang Zheng

***Abstract*—Respiratory frequency is an important physiological feature commonly used to assess health. However, the current measurements involve dedicated devices which not only increase the medical cost but also make health monitoring inconvenient. Earlier studies have shown that respiratory frequency could be extracted from electrocardiography (ECG) signal, but little was done to assess the possibility of extracting respiratory frequency from oscillometric cuff pressure pulses (OscP) or Korotkoff sounds (KorS), which are normally used for measuring blood pressure and more easily accessible than the ECG signal. This study presented a method to extract respiratory frequency from OscP and KorS during clinical blood pressure measurement. The method was evaluated with clinical data collected from 15 healthy participants, and its measurement accuracy was compared with a reference respiratory rate obtained with a magnetometer. Experimental results showed small non-significant mean absolute bias (0.019 Hz for OscP and 0.024 Hz for KorS) and high correlation (0.7 for both OscP and KorS) between the reference respiratory frequency and respiratory frequency extracted from OscP or KorS, indicating the high reliability of extracting respiratory frequency from OscP and KorS during normal blood pressure measurement.**

I. Introduction

Multi-physiological parameter monitoring supplies medical staff with more systematic health information which contributes to the accuracy of clinical diagnosis. Respiratory frequency is one of the important physiological parameters for clinical diagnosis, and its abnormity is recognized as an indicator of patient deterioration [1-4]. Because of its importance as an indicator of deterioration, respiratory frequency is included in Early Warning Scores (EWS), which are used for physiological deterioration identification in hospital [5]. However, existing automated techniques for respiratory frequency measurement involve dedicated respiratory measurement devices which not only increase the medical cost but also make multi-physiological parameter monitoring inconvenient. For instance, spirometry needs equipment for measuring the flow of air during breathing, and a magnetometer requires a chest band for measuring changes in chest movement or volume during breathing. So is it possible to extract respiratory frequency from other easily accessible physiological signals without additional dedicated respiratory measurement hardware?

It is well known that respiratory sinus arrhythmia (RSA) is the heart rate variation associated with respiration. Typically, heart rate accelerates during inspiration and slows down during expiration [6, 7], and this is a cardiorespiratory phenomenon universally observed among vertebrates [6]. Earlier work has shown the possibility and reliability of extracting respiratory frequency from the electrocardiography (ECG) signal with algorithms designed to study RSA [8-12]. However, to our knowledge, little has been done to assess the possibility and reliability of extracting respiratory frequency from oscillometric cuff pressure pulses (OscP) and Korotkoff sounds (KorS), from which blood pressure (BP) is measured, although automatic BP measurement devices have made BP measurement more easily accessible than ECG measurement both in hospital and at home.

There are two commonly-used non-invasive ways to measure BP, i.e., auscultatory method and oscillometic method, which are based on the auscultation of Korotkoff sound and the analysis of OscP respectively. Although the genesis of KorS is still unclear, it has been long hypothesized that KorS is generated by the distension of the arterial wall associated with changing transmural pressure gradient [13-16]. When the heart is beating, blood is pumped from the left ventricle of the heart, and changes the blood volume of vessels and subsequently the pressure under the cuff. Therefore, KorS and OscP are influenced by heart beating, allowing pulse intervals to be extracted from those two signals. In other words, it may be possible to extract respiratory frequency from OscP and KorS, based on pulse interval changes during BP measurement.

Given the importance of respiratory frequency for assessing health conditions and the need to use easily accessible physiological signals for multi-physiological parameter (including respiratory frequency) monitoring, the purpose of this study was to design a pulse interval based method for extracting respiratory frequency from oscillometric cuff pressure pulses and Korotkoff sounds during clinical BP measurement.

This study was supported by the National Natural Science Foundation of China (Grant No. 61571213). It was also supported by the Engineering and Physical Sciences Research Council (EPSRC) Healthcare Partnership Award (reference number EP/I027270/1), and EPSRC standard grant (reference number EP/F012764/1).

Diliang Chen is with the Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, China (e-mail: chendl@mail.sustc.edu.cn).

Fei Chen is with the Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, China (phone: 0086-75588015878; fax: 0086-75588015878; e-mail: fchen@sustc.edu.cn).

Alan Murray is with the School of Electrical and Electronic Engineering and Faculty of Medical Sciences, Newcastle University, Newcastle upon Tyne, UK (e-mail: alan.murray@ncl.ac.uk).

Dingchang Zheng is with the Health and Wellbeing Academy, Faculty of Medical Science, Anglia Ruskin University, Chelmsford, UK (e-mail: dingchang.zheng@anglia.ac.uk).

II. Experimental Setup

The study was carried out on 15 healthy participants according to the Declaration of Helsinki (1989) of the World Medical Association. This study was approved by Newcastle and North Tyneside NHS Research Ethics Committee, and informed and written consent was obtained for all participants.

For each participant, manual systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured by a trained operator following the recommendations of the British and European Hypertension Societies [17]. The cuff pressure was inflated to 200 mmHg, and then deflated linearly at a rate of 2–3 mmHg/s. Three repeated BP measurements under normal breathing were performed in total for each participant. A one-minute resting period was given between every two consecutive measurements to allow cardiovascular stabilization.

During BP measurement, KorS was recorded by a piezo-electric microphone, with the bell-shaped stethoscope terminal connected to the microphone and placed on the antecubital fossa of the forearm, where a good signal-to-noise ratio of KorS could be acquired. OscP was derived from the cuff pressure signals, and the reference respiration signal (Resp) was obtained by a chest magnetometer for detecting chest wall movement [18]. All signals were digitally recorded at 2 kHz with 16 bits resolution.

III. Signal Processing Method

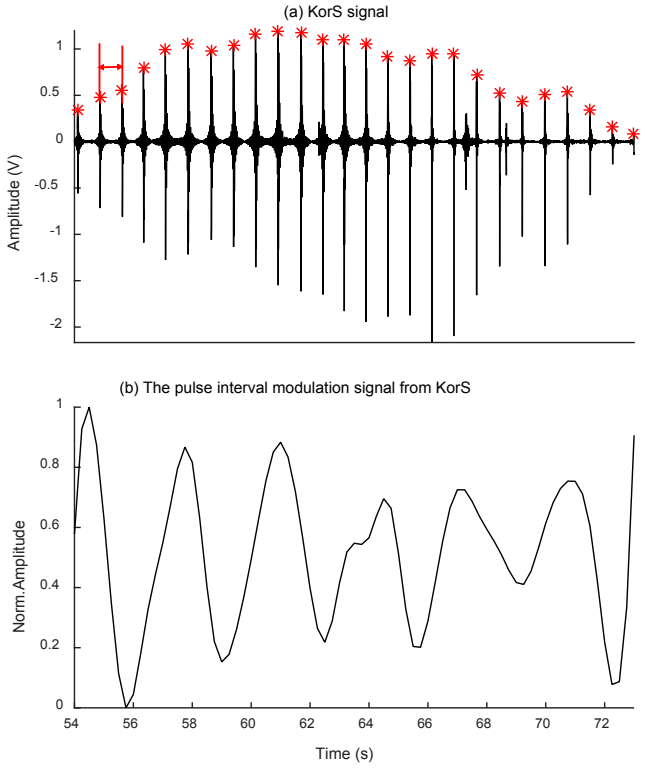

Figure 1. Procedure for extracting the pulse interval modulation signal from KorS. (a) KorS signal in the time period between SBP and DBP. Each red star indicates the peak of each KorS pulse. The red double arrow indicates a pulse interval. (b) Normalized pulse interval modulation signal extracted from KorS.

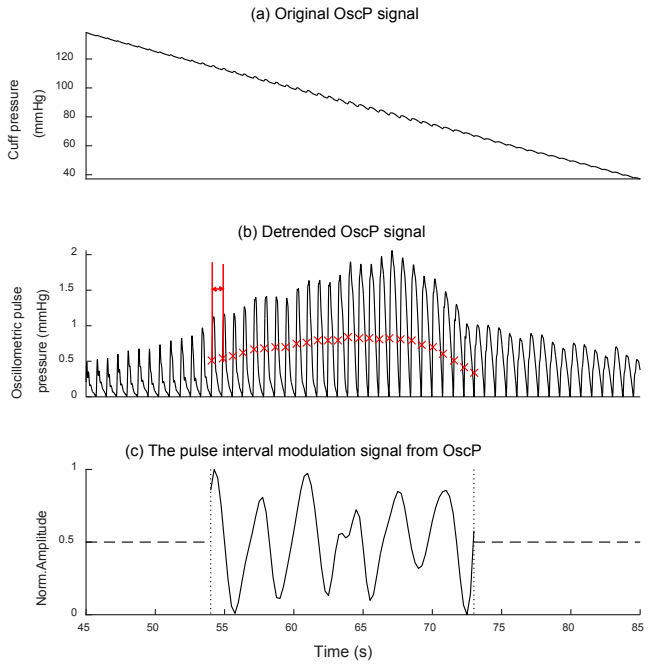

Figure 2. Procedure for extracting the pulse interval modulation signal from OscP. (a) Original OscP signal in the time interval of 45 − 85 s. (b) De-trended OscP signal. Each red x-mark indicates the maximum slope point of each OscP pulse in the time interval between SBP and DBP. The red double arrow indicates a pulse interval. (c) Normalized pulse interval modulation signal (the solid line) extracted from the data of OscP in the time period between SBP and DBP. Dashed lines indicate no signal and dotted lines indicate the time boundary of the modulation signal.

The signal processing method for extracting respiratory frequencies from KorS and OscP included two steps: (1) extracting the pulse interval modulation signals from KorS and OscP, as exemplified in Figs. 1 and 2 respectively; and (2) calculating the respiratory frequency from the power spectral density (PSD) of the corresponding pulse interval modulation signal, as shown in Fig. 3. More details on implementing each signal processing step are described below. Analysis was performed on anonymised data.

A. Pulse interval modulation signals from KorS and OscP

Figure 1 illustrates the procedure for extracting pulse interval modulation signal from KorS. The KorS signal shown in Fig. 1 (a) was acquired from one subject during BP measurement in the time period between SBP and DBP, and band-pass filtered with a 3 dB pass-band of 59–1000 Hz [19]. The peaks of each KorS pulses were located first, and red stars in Fig. 1 (a) indicate the peaks of KorS pulses. Pulse intervals from KorS signal were acquired through calculating the time intervals of the adjacent peaks of KorS. As shown in Fig. 1 (a), the red double arrow shows an example of the pulse interval calculated from KorS. Finally, the pulse interval modulation signal from KorS could be acquired by cubic spline interpolation with a sample rate of 4 Hz on the pulse interval series. This sample rate satisfies the Nyquist condition, as the normal frequency range of healthy adults under resting conditions is between 0.1–0.5Hz. Figure 1 (b) shows the pulse interval modulation signal extracted from KorS.

Figure 2 (a) shows the original OscP signal acquired during the same BP measurement as Fig. 1 in the time interval of 45–85 s for a better presentation of OscP signal. As shown in Fig. 2 (a), a cuff pressure deflation ramp is superimposed on small cuff pressure oscillations which arise from BP pulses in the arteries underlying the cuff. To make the pulse interval calculation more accurate, the cuff pressure ramp was removed through de-trending. Figure 2 (b) illustrates the de-trended OscP signal. From the data in the time interval of 45–85 s, a typical OscP signal is observed which is usually used for automatic BP measurement. In this study, only the data in the time period between SBP and DBP were used for extracting respiratory frequency. The maximum slope point of each OscP pulse in the time period between SBP and DBP was located through finding the peak of the first-order derivative. Red x-marks in Fig. 2 (b) indicate the maximum slope points of OscP pulses. Pulse intervals of the OscP signal were acquired through calculating the time interval of the adjacent maximum slope points of OscP. As shown in Fig. 2 (b), the red double arrow shows an example of the pulse interval calculated from OscP. Finally, the pulse interval modulation signal from OscP was acquired by cubic spline interpolation with a sample rate of 4 Hz on the pulse interval series. Figure 2 (c) shows the pulse interval modulation signal extracted from the data of OscP in the time period between SBP and DBP.

B. Respiratory frequency calculation

The normalized PSDs of Resp and pulse interval modulation signals from OscP and KorS were estimated by Welch periodogram between 0.1 and 0.5 Hz with the frequency resolution of 0.001 Hz. Respiratory frequency from Resp (f_R), OscP (f_O) or KorS (f_K) was calculated as the frequency corresponding to the peak of the PSD. As shown in Fig. 3, the peak of each PSD is marked with a red star and the frequency corresponding to the peak is recognized as the respiratory frequency. In this example, the respiratory frequencies extracted from OscP and KorS are both almost identical with the reference respiratory frequency [i.e., the difference is 0.004 Hz between Figs. 3 (a) and (b), and 0.009 Hz between Figs. 3 (a) and (c)], asserting the possibility of extracting respiratory frequency from OscP and KorS.

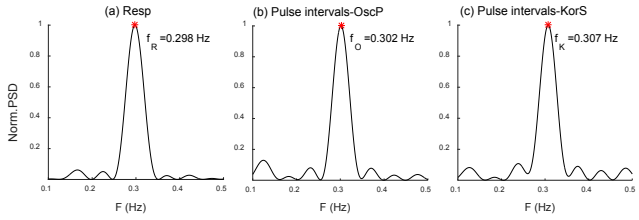

Figure 3. Normalized PSDs of (a) Resp and pulse interval modulation signals from (b) OscP and (c) KorS. Red star of each plot indicates the peak of the corresponding PSD.

IV. Data Analysis

One-way analysis of variance (ANOVA) was used to analyze the repeatability among the three repeated measurements. Bland-Altman difference plots and correlation coefficients were used to assess the agreement between f_R and f_O or f_K. Limit of Agreement (LOA) was also used, which was defined as average difference ± 1.96 times of standard deviation of difference, i.e., [μ−1.96σ, μ+1.96σ], where μ and σ denote average difference and standard deviation (SD) of difference, respectively [20]. 95% of all differences lie inside the LOA.

V. Results

The results showed that there was no statistically significant difference (all p>0.05) for the respiratory frequencies derived in this study among the three repeated recordings. This was helped by participants keeping relatively still and breathing at a relatively stable rate, which is essential for minimizing the analytic error in this study.

Bland-Altman plots in Fig. 4 show respiratory frequency estimation error of OscP and KorS in comparison with f_R during normal BP measurement. As shown in Fig. 4, most recordings (89% of f_O and 91% of f_K) agree with f_R within 0.05 Hz, indicating that it is reliable to extract respiratory frequency from OscP and KorS during normal BP measurement.

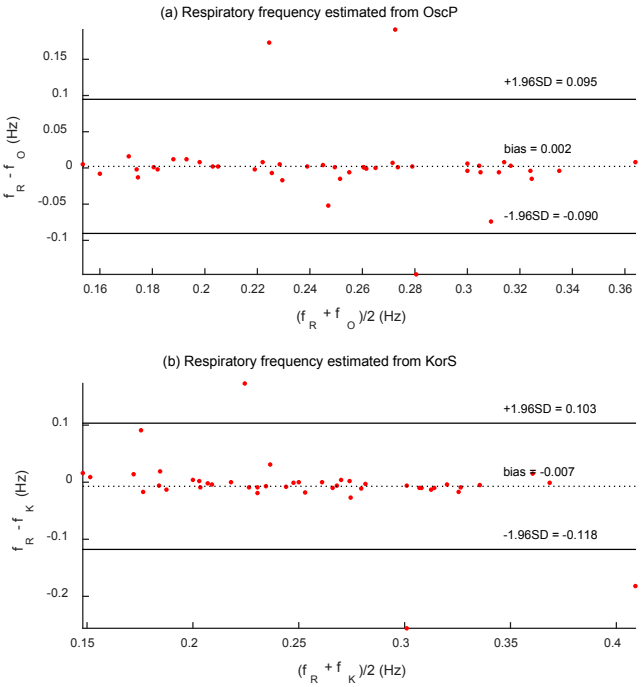

Figure 4. Bland-Altman difference plots of respiratory frequency estimation from (a) OscP and (b) KorS. Dotted black line indicates bias and solid black lines indicate 1.96-SD limits of agreement.

TABLE I. Comparison of Respiratory Frequency from OscP and KorS with the Reference Respiratory Frequency.

	correlation coefficient	mean bias [Hz]	mean absolute bias [Hz]	LOA [Hz]
f_O	0.7	0.002	0.019	[–0.090,0.095]
f_K	0.7	–0.007	0.024	[–0.118,0.103]

Table I details the parameters of correlation coefficient, mean bias, mean absolute bias and LOA for evaluating the reliability of estimating respiratory frequency with f_O and f_K. The correlation coefficients between f_R and f_O or f_K were both

0.7, indicating a high correlation between respiratory frequencies under investigation [21]. Besides, mean biases were near zero and mean absolute biases were less than 0.024 Hz, confirming the reliability of extracting respiratory frequency from OscP and KorS.

VI. Discussion and Conclusion

In this paper, we proposed a method for extracting respiratory frequency from OscP and KorS during clinical BP measurement. The method was based on the cardiorespiratory phenomenon, i.e., RSA, which is universally observed with decreased heart beat interval during inspiration and increased heart beat interval during expiration.

Note that RSA is not the only cardiorespiratory mechanism which could be used for respiratory frequency extraction. Respiration also has an amplitude modulation effect on OscP and KorS. Our former studies have confirmed the amplitude modulation effect of respiration on OscP and KorS [22-24]. However, deriving respiration based on amplitude modulation is sensitive to motion influence, making it difficult and unsuitable for respiratory frequency extraction in the condition of normal BP measurement. According to the study of Di Marco et al. [22], 60% of f_K agreed with f_R within 0.05 Hz. In this study, the performance of the pulse interval based method was better (i.e., 91% of f_K agreed with f_R with 0.05 Hz or less), because pulse intervals extracted from OscP and KorS might be less impacted by noise.

Pulse intervals of OscP in this study were calculated as the intervals of the adjacent maximum slope points but not peaks, because the top segment of OscP pulses was relatively flat and peaks extracted from the OscP pulses may be easily affected by noise, which may influence the accuracy of pulse interval estimation. It would be worth investigating the difference between approaches for pulse interval calculation in a future study.

In conclusion, this work presented a method for extracting respiratory frequency from oscillometric cuff pressure pulses and Korotkoff sounds, from which blood pressure could be measured, during clinical blood pressure measurement. Experimental results showed that the proposed method provided an accurate estimation of respiratory frequency with small mean absolute bias (0.019 Hz for OscP and 0.024 Hz for KorS) and high correlation (0.7 for both OscP and KorS) between reference respiratory frequency and respiratory frequency extracted from OscP or KorS, providing a solution for multi-physiological parameter (including respiratory frequency) monitoring.

References

[1] J.F. Fieselmann, M.S. Hendryx, C.M. Helms, D.S. Wakefield, "Respiratory rate predicts cardiopulmonary arrest for internal medicine inpatients," *Journal of General Internal Medicine*, vol. 8, no. 7, pp. 354–360, 1993.

[2] J. Kause, G. Smith, D. Prytherch, M. Parr, A. Flabouris, K. Hillman, "A comparison of antecedents to cardiac arrests, deaths and emergency intensive care admissions in Australia and New Zealand, and the United Kingdom—the ACADEMIA study," *Resuscitation*, vol. 62, no. 3, pp. 275–282, 2004.

[3] D. Goldhill, A. Mcnarry, G. Mandersloot, A. Mcginley, "A physiologically-based early warning score for ward patients: the association between score and outcome," *Anaesthesia*, vol. 60, no. 6, pp. 547–553, 2005.

[4] M. Cretikos, J. Chen, K. Hillman, R. Bellomo, S. Finfer, A. Flabouris et al., "The objective medical emergency team activation criteria: a case–control study," *Resuscitation*, vol. 73, no. 1, pp. 62–72, 2007.

[5] C. Orphanidou, S. Fleming, S.A. Shah, L. Tarassenko, "Data fusion for estimating respiratory rate from a single-lead ECG," *Biomedical Signal Processing and Control*, vol. 8, no. 1, pp. 98–105, 2013.

[6] F. Yasuma, J. Hayano, "Respiratory sinus arrhythmia: why does the heartbeat synchronize with respiratory rhythm?" *Chest*, vol. 125, no. 2, pp. 683–690, 2004.

[7] P. Grossman, E.W. Taylor, "Toward understanding respiratory sinus arrhythmia: Relations to cardiac vagal tone, evolution and biobehavioral functions," *Biological Psychology*, vol. 74, no. 2, pp. 263–285, 2007.

[8] C. Mason, L. Tarassenko, editors. "Quantitative assessment of respiratory derivation algorithms," in *Proc. 23rd Annual International Conf. Engineering in Medicine and Biology Society,* 2001.

[9] J.F. Thayer, J.J. Sollers III, E. Ruiz-Padial, J. Vila, "Estimating respiratory frequency from autoregressive spectral analysis of heart period," *IEEE Engineering in Medicine and Biology*, vol. 21, no. 4, pp. 41–45, 2002.

[10] D. Cysarz, R. Zerm, H. Bettermann, M. Frühwirth, M. Moser, M. Kröz, "Comparison of respiratory rates derived from heart rate variability, ECG amplitude, and nasal/oral airflow," *Annals of Biomedical Engineering*, vol. 36, no. 12, pp. 2085–2094, 2008.

[11] A. Schäfer, K.W. Kratky, "Estimation of breathing rate from respiratory sinus arrhythmia: comparison of various methods," *Annals of Biomedical Engineering*, vol. 36, no. 3, pp. 476–485, 2008.

[12] P. Langley, E.J. Bowers, A. Murray, "Principal component analysis as a tool for analyzing beat-to-beat changes in ECG features: application to ECG-derived respiration," *Biomedical Engineering, IEEE Transactions on*, vol. 57, no. 4, pp. 821–829, 2010.

[13] E.P. Mccutcheon, R.F. Rushmer, "Korotkoff sounds. An experimental critique," *Circulation Research*, vol. 20, no. 2, pp. 149–161, 1967.

[14] M.E. Tavel, J. Faris, W.K. Nasser, H. Feigebaum, C. Fisch, "Korotkoff sounds. Observations on pressure-pulse changes underlying their formation," *Circulation*, vol. 39, no. 4, pp. 465–474, 1969.

[15] A. Ur, M. Gordon, "Origin of Korotkoff sounds," *American Journal of Physiology -- Legacy Content*, vol. 218, no. 2, pp. 524–529, 1970.

[16] R. Venet, D. Miric, A. Pavie, D. Lacheheb, "Korotkoff sound: the cavitation hypothesis," *Med Hypotheses*, vol. 55, no. 2, pp. 141–146, 2000.

[17] E. O'Brien, R. Asmar, L. Beilin, Y. Imai, J.M. Mallion, G. Mancia et al., "European Society of Hypertension recommendations for conventional, ambulatory and home blood pressure measurement," *J Hypertens*, vol. 21, no. 5, pp. 821–848, 2003.

[18] C.J. Griffiths, J.J. Gilmartin, G.J. Gibson, A. Murray, "Measurement of chest wall movement; design, performance and clinical use of a four-channel magnetometer instrument," *Clinical Physics and Physiological Measurement*, vol. 4, no. 4, pp. 363–371, 1983.

[19] J. Allen, T. Gehrke, J.J. O'sullivan, S.T. King, A. Murray, "Characterization of the Korotkoff sounds using joint time–frequency analysis," *Physiological measurement*, vol. 25, no. 1, pp. 107, 2003.

[20] R. Yousefi, M. Nourani, S. Ostadabbas, I. Panahi, "A Motion-Tolerant Adaptive Algorithm for Wearable Photoplethysmographic Biosensors," *Biomedical and Health Informatics, IEEE Journal of*, vol. 18, no. 2, pp. 670–681, 2014.

[21] M.J. Campbell. Statistics at square two. Blackwell; 2006.

[22] L.Y. Di Marco, D. Zheng, A. Murray, "Effects of deep breathing on blood pressure measurement in healthy participants,"*Computing in Cardiology,* vol. 39, pp. 9–12, 2012.

[23] D. Zheng, L.Y. Di Marco, A. Murray, "Effect of respiration on Korotkoff sounds and oscillometric cuff pressure pulses during blood pressure measurement," *Med Biol Eng Comput*, vol. 52, no. 5, pp. 467–473, 2014.

[24] D. Chen, F. Chen, A. Murray, D. Zheng, "Respiratory modulation of oscillometric cuff pressure pulses and Korotkoff sounds during clinical blood pressure measurement in healthy adults," *BioMedical Engineering OnLine,* 15:53, 2016.