Assessing the Challenges of a Pulse Wave Velocity Based Blood Pressure Measurement in Surgical Patients

Guanqun Zhang, Scott A. McCombie, Richard Greenstein, and Devin B. McCombie

Abstract—**Development of a continuous noninvasive blood pressure (cNIBP) monitor that is unobtrusive to patients is an attractive alternative to the cuff based measurements performed on medical-surgical floors in the hospital. Pulse wave velocity (PWV) provides a means to continuously monitor blood pressure in these patients. However, a PWV based cNIBP monitor faces a number of challenges in order to accurately measure blood pressure. In our study, we investigated some of the challenges faced by a body-worn cNIBP monitor (i.e. ViSi Mobile) on data collected on patients undergoing surgery. Results indicated that 1) pulse arrival time (PAT) values from ViSi Mobile were well correlated with PAT values obtained from an invasive reference; 2) the reciprocal of the PAT measurements were linearly correlated with blood pressure but the calibration curve was altered by administration of certain vasoactive substances; and 3) there are deterministic correlations between systolic pressure, diastolic pressure and the corresponding mean arterial pressure over a wide range of blood pressure values.**

I. Introduction

Arterial blood pressure is an important vital sign for assessing the stability of post-operative patients in the hospital. Blood pressure in this patient population is typically measured at regular time intervals using an automated oscillometric cuff or during routine spot checks performed by members of the clinical staff. Regular use of an inflatable cuff is obtrusive to the patient and prevents them from getting adequate sleep. Additionally, infrequent periodic measurements may not detect early signs of deterioration in recovering patients. An unobtrusive monitor that provides continuous, non-invasive blood pressure (cNIBP) would be a welcome alternative to conventional spot check monitors.

Pulse wave velocity (PWV) provides an ideal candidate for unobtrusive cNIBP monitoring. During each cardiac cycle, contraction of the heart creates a pressure pulse wave that propagates along the arterial tree from proximal to distal sites. The velocity of the pulse wave depends on arterial blood pressure [1]. Pulse arrival time (PAT) is a popular method for measuring PWV since it can be measured easily, continuously, and noninvasively [2]–[5]. PAT is usually determined as the time delay between an ECG QRS complex and the onset of a subsequent distal pressure waveform measured with an arterial catheter or a photoplethysmogram (PPG) waveform. However, PAT not only consists of a pressure dependent vascular transit time but also a pre-ejection period (PEP) comprised of the electromechanical delay of the heart and the isovolumic contraction time of the left ventricle.

Although PWV has achieved much attention in academic research and has shown potential as a method for indirectly tracking blood pressure[4], [5], several issues have limited its commercial success.

First, how can a cNIBP monitor capture a timing measurement that is highly correlated with the velocity of a pressure pulse? True PAT values can only be measured between an ECG QRS complex to the subsequent onset of a pressure waveform at sites such as the radial artery. However, most non-invasive approaches have used fingertip based PPG sensors to measure PAT. Fingertip PPG sensors measure pulsatile activity in the capillary beds underlying the measurement site and timing measurements derived from these sensors may provide inadequate correlation with pressure pulse velocity. As an alternative to a fingertip sensor an optical sensor that targets an artery such as the princeps pollicis artery at the base of the thumb could potentially provide PAT values that are better correlated with true PAT. It is of interest to compare the consistency of timings achieved by two approaches.

Second, how can a cNIBP monitor establish a unique calibration equation for each patient that is valid over a wide range of arterial blood pressure values? Inflation of a blood pressure cuff on the arm ipsilateral to the optical sensor is known to cause an increase in PAT that is correlated with the cuff pressure. It has been suggested that a cuff based interrogation of PAT could provide individual calibration [6]. It is of interest to evaluate the relationship between PAT, blood pressure, and a cuff based interrogation on patients with dynamic blood pressures.

Third, how do vasoactive drugs affect a previously established calibration curve? PWV is dependent on the elastic modulus of the arterial wall and on vessel geometry according to the Moens-Koertewig equation [7]. Contraction and relaxation of skeletal artery smooth muscle in response to vasoactive substances can alter these properties but how much error will this create in a PWV based cNIBP monitor? It is of interest to evaluate the affects of vasoactive drugs on a calibration curve.

Last, how can a PWV based monitor provide systolic pressure (SP), diastolic pressure (DP), and mean arterial pressure (MAP) based on a single PAT measurement? It is accepted clinical practice to measure systolic and diastolic blood pressure in post-operative patients. Cuff-based

Research supported by Sotera Wireless, Inc.

G. Zhang is with Sotera Wireless, Inc., San Diego, CA 92121 USA (e-mail: guanqun.zhang@soterawireless.com).

S. A. McCombie is with Sotera Wireless, Inc., San Diego, CA 92121 USA (e-mail: scott.mccombie@soterawireless.com).

R. Greenstein is with Palomar Medical Center, Escondido, CA 92029 USA (e-mail: greengas1@gmail.com)

D. B. McCombie is with Sotera Wireless, Inc., San Diego, CA 92121 USA (phone: 858-373-4821; e-mail: devin.mccombie@soterawireless.com)

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

oscillometric blood pressure monitors achieve this by determining MAP by fitting an envelope of pressure pulses, and then estimating SP and DP using empirical approximations, such as the fixed ratio approach [8], [9]. Could a similar strategy be used for PAT based monitors and how would these fixed relationships for SP and DP evolve under changing hemodynamic conditions?

II. Methods

A. The ViSi Mobile System

The ViSi Mobile System is a wireless, body-worn vital sign monitor designed by Sotera Wireless, Inc. The system consists of a wrist module, an upper arm module, a cuff module and a chest module (Figure 1).

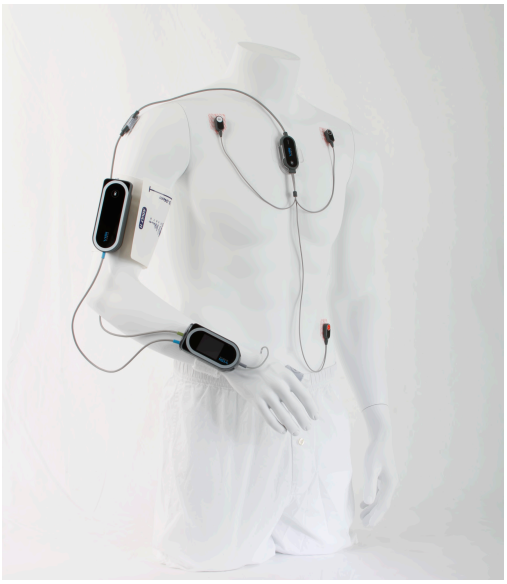

Figure 1. ViSi Mobile attached to the body with a 3-lead ECG cable.

The device is FDA approved to measure heart rate, pulse rate and SpO_2 at the base of the thumb, respiration rate, skin temperature, traditional NIBP, and cNIBP. All data collected by ViSi are wirelessly transmitted via Wi-Fi to a remote patient data server for observation and analysis.

B. Experimental Data

The study was performed on two patients undergoing carotid endarterectomy surgery at Palomar Medical Center, Escondido, CA under IRB approval and having provided informed consent.

During the course of surgery patient one was administered hydralazine, phenylephrine, and nitroglycerine to regulate their hemodynamic state. Patient two was administered ephedrine, and labetalol to regulate their hemodynamic state. Both subjects were transported to PACU after surgery.

ECG and pressure waveforms were recorded by the Biopac System MP150 (BIOPAC Systems, Inc., Goleta, CA) with ECG amplifier (ECG100C) and transducer amplifier (DA100C). ECG electrodes of Biopac were placed on the trunk and a blood pressure transducer (Argon Medical Devices, Athens, TX) was inserted into the left radial artery. Meanwhile, ECG electrodes of ViSi were placed next to Biopac's electrodes. ViSi's wrist transceiver was worn on the right wrist, and the PPG sensor was wrapped at the base of the right thumb. The subject remained near supine during the surgery to avoid hydrostatic difference on both arms. Both Biopac and ViSi data were collected at the sampling frequency of 500 Hz.

C. Data Analysis

ViSi Mobile automatically annotated onsets of ECG and PPG signals, and wirelessly transmitted them to the central server. ViSi PAT was determined as the time delay from an ECG R peak to the maximal second derivative of the subsequent beat of PPG waveform [10]. Post-processing algorithms were employed for extracting fiducial points on waveforms collected by Biopac. For example, SP, DP and MAP were estimated from the radial pressure waveform and R peak was detected from the ECG waveform, respectively. Radial PAT values were estimated between ECG R peak and radial arterial pressure waveform using identical strategies as ViSi Mobile (Figure 2). Erroneous records due to movement were excluded.

III. Results

A. Noninvasive ViSi PAT comparing with invasive radial PAT

Figure 3 depicts the time series of PAT values from Subject 2, in which ViSi PAT analogously corresponds the trend of radial PAT. It is noteworthy that 1) PAT values from two approaches are not identical since PAT values were estimated by two approaches from two different arms; and 2) Radial PAT has better precision than ViSi PAT since the radial catheter utilized an invasive measurement of blood pressure waveform while ViSi is indirectly estimating PAT from a pulse oximeter.

B. Calibration of PAT and MAP from the invasive radial blood pressure measurements

MAP measured in Subject 1 from the radial catheter positively correlated with the reciprocal of PAT, as shown in Figure 4.

In addition, data aggregated into two groups indicating different slopes and offsets. The lower group is mainly from samples collected under the interventions of hydralazine, nitroglycerine and phenylephrine, while the upper group represents data collected from the rest data of the surgery.

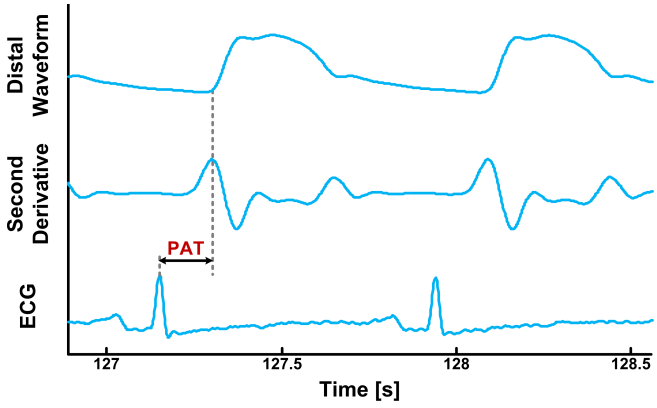

Figure 2. The measurement of PAT.

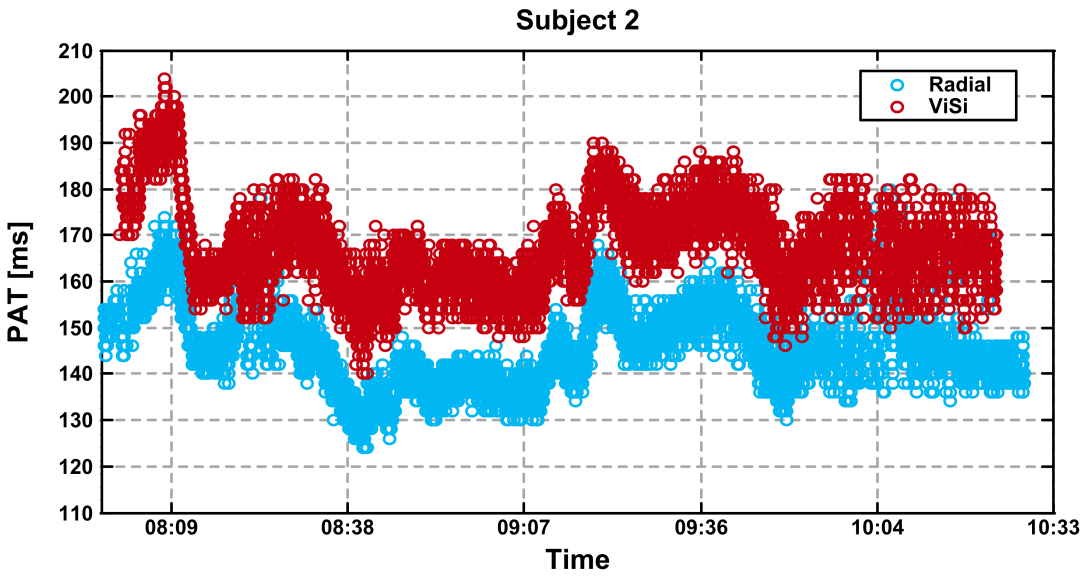

Figure 3. Time series of PAT values from invasive radial blood pressure waveform and noninvasive ViSi measurements.

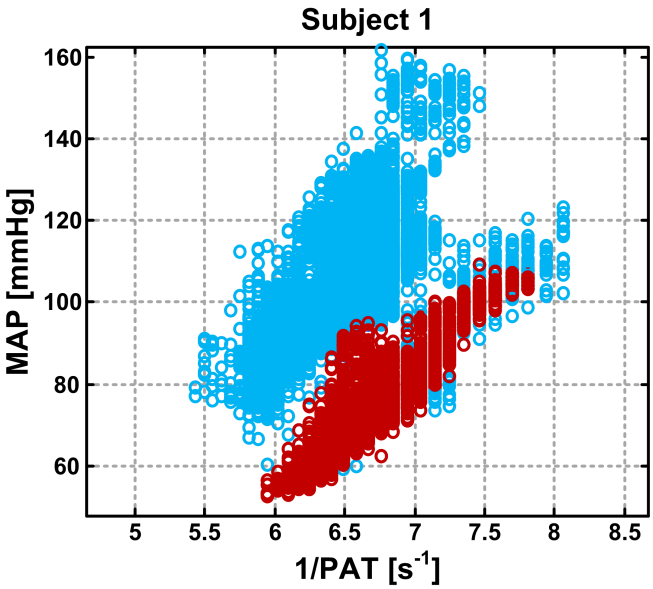

Figure 4. Correlation between MAP and PAT from invasive radial blood pressure measurements. Red samples represent data collected during interventions of hydralazine, phenylephrine and nitroglycerine. Blue samples are the rest data of the surgery.

C. *Correlation between DP or SP and MAP from the invasive radial blood pressure measurements*

Figure 5 plots that both SP and DP are positively correlated with MAP in both subjects, according to the radial blood pressure. Pressure of both subjects varied over wide range during the surgery. In Subject 1, DP: 39 - 117 mmHg, MAP: 54.5 – 161 mmHg and SP: 74.6 – 234 mmHg. In Subject 2, DP: 35.1 – 77.8 mmHg, MAP: 48.4 - 117 mmHg and SP: 90.5 – 178 mmHg. Both SP and DP tightly showed an approximate linear correlation with MAP, although SP is slightly curvilinearly correlated with MAP in Subject 1.

IV. Discussions

We performed a study for investigating the adequacy of PAT in tracking blood pressure during hemodynamic instabilities in an operating room. Data were both collected by an invasive reference and a body-worn ViSi Mobile system for noninvasive comparison. Results are concluded as: 1) PAT noninvasively measured by ViSi is in substantial agreement with the invasive reference, despite an offset; 2) PAT inversely correlated with MAP, but slope and intercept of the correlation can vary due to vasomotor tone in peripheral arteries and 3) DP and SP obtained at the radial artery are essentially in consistent correlation with MAP over wide pressure range. Since ViSi Mobile has recently received the FDA clearance for cNIBP monitoring, we will conclude quantitative analysis including more subjects in our follow-up studies.

Our study indicates that the calibration between PAT and MAP could change when administrated with vasoactive interventions, which alter vascular smooth muscle tone. A previous study reported that PAT could significantly increase with smooth muscle relaxation [7], which can be more prominently observed in measurements from peripheral arteries. Likewise, the calibration can also be affected by vasoconstrictors. We would suggest that recalibration of cNIBP be necessary when administrated with vasoactive agents.

The oscillometric fixed ratio method determines MAP, SP and DP by occluding brachial artery using a cuff worn on the upper arm [8], [11]. Although no universally applicable relationship exists for deriving SP or DP from a singular MAP measurement, the tight correlation in our data indicates the feasibility of approximating DP or SP from MAP with the use of analytical equations. Usually, DP has better correlation with MAP than SP, which is more significantly affected by wave reflection [12]. Multiple formulas have been proposed before [13], [14], and the efficacy can be compared. More dynamic sophisticated models, such as the Windkessel model, the tube-load model, have higher degree of freedoms, and can

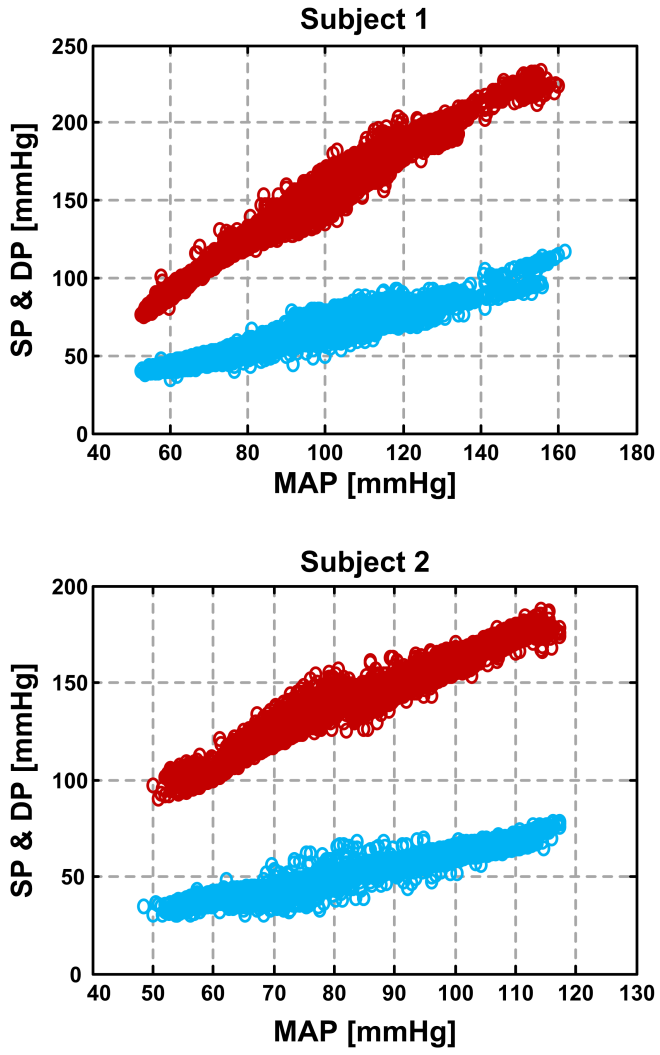

Figure 5. SP and DP vs. MAP from invasive radial blood pressure measurements

thus adaptively adjust to more challenging situations [15].

The accuracy of PAT in tracking with blood pressure can be further improved with the removal of PEP. PEP is composed of the ventricular electromechanical delay and isovolumic contraction, and it can be affected by varying preload, afterload and myocardial contractility. Therefore, PEP could nontrivially affect PAT and become a confounding factor in tracking blood pressure [16]. We plan to upgrade the ViSi Mobile System that is capable of detecting PEP in future releases.

ACKNOWLEDGMENT

The authors thank Janel Chaltis, R.N., for support of data collection in Palomar Medical Center.

REFERENCES

[1] J. C. Bramwell and A. V. Hill, "The velocity of the pulse wave in man," *Proc. R. Soc. London Ser. B*, vol. 93, no. 652, pp. 298–306, 1922.

[2] C. Ahlstrom, A. Johansson, F. Uhlin, T. Länne, and P. Ask, "Noninvasive investigation of blood pressure changes using the pulse wave transit time: a novel approach in the monitoring of hemodialysis patients.," *J. Artif. Organs*, vol. 8, no. 3, pp. 192–7, Jan. 2005.

[3] J. Y. A. Foo, C. S. Lim, S. J. Wilson, G. R. Williams, M.-A. Harris, and D. M. Cooper, "Pulse transit time ratio as a potential marker for paediatric crural and brachial blood pressure index.," *J. Hum. Hypertens.*, vol. 21, no. 5, pp. 415–7, May 2007.

[4] J. E. Naschitz, S. Bezobchuk, R. Mussafia-Priselac, S. Sundick, D. Dreyfuss, I. Khorshidi, A. Karidis, H. Manor, M. Nagar, E. R. Peck, S. Peck, S. Storch, I. Rosner, and L. Gaitini, "Pulse Transit Time by R-Wave-Gated Infrared Photoplethysmography: Review of the Literature and Personal Experience," *J. Clin. Monit. Comput.*, vol. 18, no. 5–6, pp. 333–42, Dec. 2004.

[5] M. Y. Wong, C. C. Poon, and Y. T. Zhang, "An evaluation of the cuffless blood pressure estimation based on pulse transit time technique: a half year study on normotensive subjects.," *Cardiovasc. Eng.*, vol. 9, no. 1, pp. 32–8, Mar. 2009.

[6] X. F. Teng and Y. T. Zhang, "Theoretical study on the effect of sensor contact force on pulse transit time.," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 8, pp. 1490–8, Aug. 2007.

[7] A. J. Bank and D. R. Kaiser, "Smooth muscle relaxation: effects on arterial compliance, distensibility, elastic modulus, and pulse wave velocity.," *Hypertension*, vol. 32, no. 2, pp. 356–9, Aug. 1998.

[8] L. A. Geddes, M. Voelz, C. Combs, D. Reiner, and C. F. Babbs, "Characterization of the oscillometric method for measuring indirect blood pressure.," *Ann. Biomed. Eng.*, vol. 10, no. 6, pp. 271–80, Jan. 1982.

[9] G. Drzewiecki, R. Hood, and H. Apple, "Theory of the oscillometric maximum and the systolic and diastolic detection ratios.," *Ann. Biomed. Eng.*, vol. 22, no. 1, pp. 88–96.

[10] Y. C. Chiu, P. W. Arand, S. G. Shroff, T. Feldman, and J. D. Carroll, "Determination of pulse wave velocities with computerized algorithms.," *Am. Heart J.*, vol. 121, no. 5, pp. 1460–70, May 1991.

[11] J. Liu, J.-O. Hahn, and R. Mukkamala, "Error mechanisms of the oscillometric fixed-ratio blood pressure measurement method.," *Ann. Biomed. Eng.*, vol. 41, no. 3, pp. 587–97, Mar. 2013.

[12] W. W. Nichols and M. F. O'Rourke, *McDonald's Blood Flow in Arteries: Theoretical, Experimental and Clinical Principles*, 5th ed., no. 6341. A Hodder Arnold Publication, 2005, p. 616.

[13] D. Chemla, V. Castelain, S. Provencher, M. Humbert, G. Simonneau, and P. Hervé, "Evaluation of various empirical formulas for estimating mean pulmonary artery pressure by using systolic pulmonary artery pressure in adults.," *Chest*, vol. 135, no. 3, pp. 760–8, Mar. 2009.

[14] M. Razminia, A. Trivedi, J. Molnar, M. Elbzour, M. Guerrero, Y. Salem, A. Ahmed, S. Khosla, and D. L. Lubell, "Validation of a new formula for mean arterial pressure calculation: the new formula is superior to the standard formula.," *Catheter. Cardio. Inte.*, vol. 63, no. 4, pp. 419–25, Dec. 2004.

[15] G. Zhang, J.-O. Hahn, and R. Mukkamala, "Tube-load model parameter estimation for monitoring arterial hemodynamics.," *Front. Physiol.*, vol. 2, Jan. 2011.

[16] G. Zhang, M. Gao, D. Xu, N. B. Olivier, and R. Mukkamala, "Pulse arrival time is not an adequate surrogate for pulse transit time as a marker of blood pressure.," *J. Appl. Physiol.*, vol. 111, no. 6, pp. 1681–6, Dec. 2011.