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Noninvasive Tracking of Systolic Arterial Blood Pressure Using Pulse Transit Time Measured with ECG and Carotid Doppler Signals with Intermittent Calibration

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Summary : We have developed a non-invasive blood pressure measurement system using pulse transit time (PTT) from the heart to the common carotid artery, measured by using an electrocardiogram (ECG) R-wave and carotid arterial Doppler signals at the anterior neck. In this study, we examined the validity of our system by comparing PTT derived systolic blood pressure (Dopp_SBP) with invasive radial systolic arterial pressure (Inv_SBP) with calibration every 15 min in the ICU setting.

Methods: 17 patients under invasive mechanical ventilation in the ICU were studied. Carotid arterial flow via an 8-MHz Doppler flow probe, ECG, and radial arterial pressure signals were transferred to a personal computer at a rate of 1 kHz and processed to calculate Dopp_SBP from PTT using our own calibration formula.

Results: We recorded 3,770 pairs of Inv_SBP and Dopp_SBP in 17 patients. Inv_SBP ranged from 213 to 82 mmHg, and Dopp_SBP from 185 to 71 mmHg. The Bland-Altman plot of the comparison between Inv_SBP and Dopp_SBP revealed limits of agreement of –20.1 to 17.7 mmHg (mean difference, –1.2 mmHg). There was a statistically significant close linear correlation between Inv_SBP and Dopp_SBP ($y = 0.9494x + 7.5171$, $R^2 = 0.8471$, $p < 0.0001$).

Conclusions: The results of the present study show that our system using Doppler ultrasound flow and ECG signals, is feasible for systolic blood pressure tracking over a longer interval if it is combined with intermittent calibration.

Key words : Doppler flow meter, blood pressure, monitor

Introduction

Non-invasive blood pressure (NIBP) measurement and continuous heart rate measurement with electrocardiography (ECG) are standard monitoring methods used during anesthesia and intensive care. However, NIBP measurement with a shorter interval (e.g., every minute) or continuous blood pressure measurement are often desired in acute settings during anesthesia and intensive care unit (ICU) management. Previous studies have used photosensor-derived or pulse oximetry-derived pletysmograms for detecting the pulse wave at the periphery; however, although pletysmographs are easy to obtain with these devices, no blood pressure tracking systems with these devices are commercially available.

While propagation of the arterial pulse through arteries that are structurally different, i.e. the aorta versus the small arteries, is affected by aging, sympathetic tone, blood volume, and many other factors, the pulse from the heart to the carotid artery is propagated through structurally homogenous large arteries. Therefore, we speculated that pulse propagation may be modeled with a simple mathematical equation; i.e., the Moens-Korteweg equation. Because the photo-sensor and pulse oximeter probe are not appropriate for detecting the pulse wave at the carotid artery, we applied a Doppler flow probe to detect the pulse wave at this location. A Doppler flow probe at the neck has an advantage over the pletysmograph in the periphery because the pulse wave is robust even when severe peripheral vasoconstriction occurs as during hypotension.

We have shown that pulse transit time (PTT) from the heart to the common carotid artery, measured by using an ECG R-wave and Doppler flow probe attached at the anterior neck, has a moderate but significant correlation with systolic arterial pressure ($R^2 = 0.46$) in the previous study.[1] In this study, we aimed to examine the validity of our system when combined with calibration every 15

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minuntes in the ICU setting. We used this system to test estimated systolic blood pressure (Dopp_SBP) versus invasive radial systolic arterial pressure (Inv_SBP), which was also used to calibrate the system.

Materials and Methods

The institutional ethical committee reviewed the protocol and approved the study (#1166). After written informed consent was obtained from the patients' relatives, 17 patients (mean age 71 years) under invasive mechanical ventilation in the ICU were included in the study. In each patient, radial arterial blood pressure had been continuously monitored via a 20-gauge catheter. Carotid blood flow wave was obtained via an 8-MHz Doppler flow probe attached to either side of the anterior neck and connected to the flow meter (DVM-4300, Hadeco, Japan). Carotid blood flow, ECG, and systolic arterial pressure signals were recorded from each patient using a data recorder (Sony, PC204AX, Tokyo) for 30 to 60 min. The stored data were transferred to a personal computer through a 16-bit AD interface at a rate of 1.0 kHz and processed with our own software. Briefly, the software measures PTT, which is defined as the time delay between the ECG R wave peak and the maximum upstroke of the carotid blood flow wave. The software then displays the averaged curves of ECG, arterial pressure, and carotid flow in combination with a digital display of PTT every 10 s, to an accuracy of 1 ms. PTT was converted to Dopp_SBP as follows.

Calculation of systolic blood pressure (Dopp_SBP) from PTT

PWV is given by the Moens-Korteweg equation (1)

$$PWV = \sqrt{\frac{\Delta E \cdot h}{2r \cdot p}} \quad (1)$$

where ΔE is the incremental elastic modulus of the vessel wall, h is the wall thickness, r is the arterial radius, and ρ is the blood density.

There is an inverse relationship between PTT and PWV as follows:

$$PTT \propto \frac{1}{PWV} \quad (2)$$

According to equations (1) and (2) and assuming that h and r are constant in a given patient, PTT is thought to change proportionally to the square root of the incremental elastic modulus of the vessel wall, which correlates with pressure changes. We found the following relationship between PTT and SBB in a previous study[1)]

$$SBP = \frac{A}{PTT^2} + B, \ (R^2 = 0.46) \quad (3)$$

where $A = 7.0 \times 10^5$ and B = 49.6. Units of SBP and PTT are presented in millimeters of mercury (mmHg) and milliseconds (ms), respectively.

In this study, we performed a one-point calibration every 15 minutes. While A was considered constant at 7.0×10^5, B was updated by assigning PTT and Inv_SBP to the equation (3). Dopp_SBP was converted from the PTT averaged every 10 seconds using equation (3).

Statistical analysis

Data were presented as mean ± SD. Linear regression analysis was performed between Dopp_SBP and Inv_SBP. The difference between Dopp_SBP and Inv_SBP was assessed by calculating the mean bias and the limits of agreement (± 2SD mean bias) based on the method of Bland and Altman. The threshold of statistical significance was defined as $P < 0.05$.

Results

We obtained 3,770 pairs of Inv_SBP and Dopp_SBP from 17 patients, resulting in approximately 10 h of total data recording. Inv_SBP ranged from 213 to 82 mmHg (125 ± 24 mmHg), and PTT ranged from 165 to 77 ms (115 ± 14

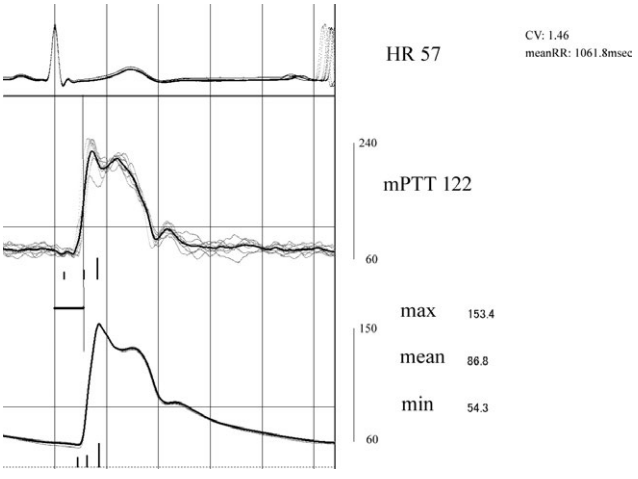

Figure 1. From top to bottom, the averaged electrocardiogram, Doppler flow and arterial pressure signals. These signals were transmitted to a PC at a rate of 1.0 kHz. PTT was defined as a time delay between the ECG R wave peak and the maximum upstroke of the carotid blood flow wave (straight line with arrows). Our software calculates the averaged PTT (mPTT) from the averaged curves of ECG and carotid blood flow signals, heart rate (HR) and the averaged maximum, mean and minimum arterial pressure, every 10 seconds to an accuracy of 1 millisecond. In the figure, mPTT shows 122 milliseconds.

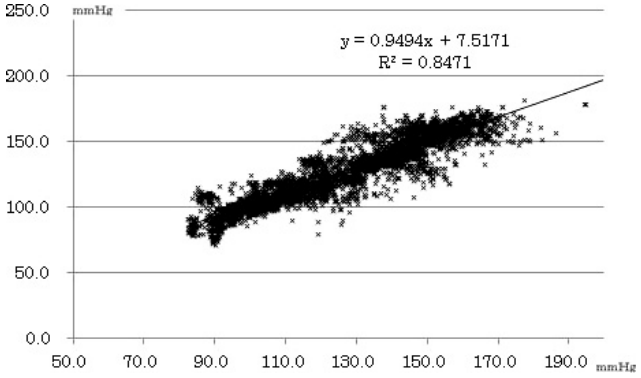

Figure 2. Correlation of Dopp_SBP (PTT-derived systolic arterial pressure, x-axis, mmHg) with Inv_SBP (radial systolic arterial pressure, gold standard, y-axis, mmHg). There is a significant linear correlation between the two values ($P < 0.0001$).

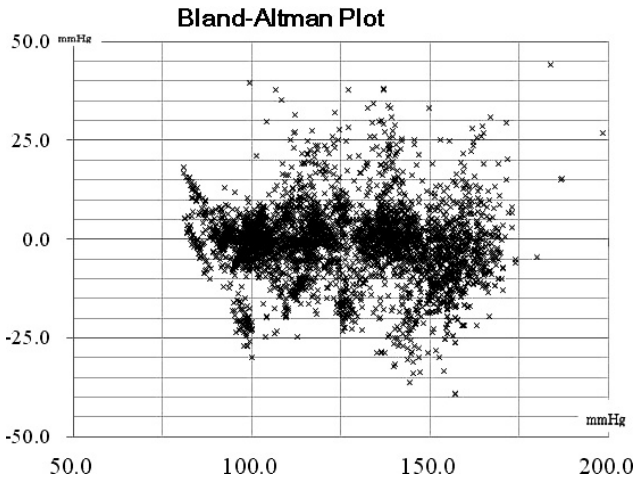

Figure 3. Bland-Altman plot. Differences between Dopp_SBP (PTT-derived systolic arterial pressure, mmHg) and Inv_SBP (radial systolic arterial pressure, gold standard, mmHg) are plotted against the mean of the two values.

ms), resulting in Dopp_SBP in the range of 185 to 71 mmHg (126 ± 24 mmHg). There was a statistically significant close linear correlation between Inv_SBP and Dopp_SBP ($y = 0.9494x + 7.5171$, $R^2 = 0.8471$, $p < 0.0001$) (Fig. 1). The Bland-Altman plot of the comparison between Inv_SBP and Dopp_SBP revealed limits of agreement of –20.1 to 17.7 mmHg (mean difference, –1.2 mmHg) (Fig. 2).

Discussion

This clinical study, which enrolled 17 adult patients for approximately 10 h, demonstrated a good correlation between Inv_SBP and Dopp_SBP, suggesting the usefulness of our non-invasive system with intermittent calibration for systolic blood pressure (SBP) tracking during a longer interval.

Because previous studies[2,3] showed that PTT-derived non-invasive blood pressure correlates better with SBP than with mean or diastolic blood pressure, and SBP is a more reliable parameter for hemodynamic management, we validated our system only with SBP (radial arterial pressure). This study, thus, does not provide any information on the correlation of PTT with the mean or diastolic arterial pressure.

Although Kim et al.[2] recently reported the feasibility of beat-to-beat tracking of SBP using an ECG-R wave and pulse oximeter pletysmography during anesthesia induction, its utility during a longer period remained undetermined. In their system, PTT is subject to changes in vasomotor tone and pre-ejection time.

Changes in vasomotor tone in the peripheral arteries induced by blood pressure fluctuations may modify the stiffness of the wall in the peripheral arteries, thereby causing disparity between arterial pressure and PTT. In contrast, our system is less influenced by changes in vasomotor tone because the carotid artery is a large, straight artery containing mostly elastic and fibrous tissues as opposed to the peripheral artery, which is rich in smooth muscle.[4] This difference may have a nontrivial effect during longer periods of SBP tracking.[5]

On the other hand, our system has a theoretical limitation: it contains the pre-ejection time in the measured PTT. It may be a source of errors in converting PTT to SBP in this system, because traveling distance is significantly shorter in our system (heart to carotid artery vs. heart to finger) and thus the ratio of the pre-ejection period (PEP) to the PTT is greater in our system than in Kim's system. The true PTT from the aortic valve to the detector site of the carotid artery can be obtained by subtracting the PEP from the measured PTT, if PEP is measured simultaneously with impedance cardiography. PEP has long been used as a non-invasive marker of left ventricular systolic function in a variety of cardiac diseases; however, it requires multiple electrodes and is inherently labile to electromagnetic interference. Therefore, it is not practical to incorporate impedance cardiography into our uncomplicated system, which is designated for use in operating rooms or the ICU. Likewise, incorporation of a precordial phonocardiogram into our system can obtain the PEP. It would, however, interfere with use in the operating room.

Interestingly, Proenca et al.[6] did not find a correlation between true PTT and SBP in a population of young patients, although they determined true PTT by subtracting the PEP derived from impedance cardiography from a PTT obtained from the ECG R peak and the pulse measured at

the fingertip. They speculated that the inaccuracy of PEP through impedance cardiography as well as the changes in the radius of the arterial trees in this population may be responsible for the absence of a correlation between the two variables. They proposed that improved accuracy of PTT and PEP measurements is needed in future research. In our system, we averaged the PTT every 10 seconds instead of using a beat-by-beat PTT to calculate Dopp_SBP. We presume that this procedure may have also contributed to a relatively good correlation between Dopp_SBP and actual SBP (Inv_SBP) in this study, thereby demonstrating the possibility of blood pressure tracking for longer periods.

In the equation (3), constant B contains the PEP in addition to a delay for measuring the time of carotid blood flow by the Doppler flow meter, the latter is considered constant. We attempted to reduce the error caused by the changes in the PEP by calibrating frequently (i.e., every 15 min) and introducing updated constant B in the equation (1) for the conversion from PTT to SBP. Frequent calibration enabled us to track SBP for a longer period. Although the accuracy of the system increases with more shortened calibration intervals, frequent cuff inflation increases can be inconvenient. Therefore, the calibration interval must be determined in concert with two parameters. In addition, to use our system in the clinical setting, it must be incorporated with an automated blood pressure device and be able to intermittently calibrate SBP.

Application of the Doppler flow probe has limitations in clinical use. Although automatic detection of the ECG R-peak is robust, carotid Doppler flow signals are easily affected by nontrivial artifacts such as changes in the Doppler flow probe position and movement of the patient's neck despite fixation of the probe with adhesive tape. This system is therefore more suitable for use in the operating room or in patients under deep sedation in the ICU, where the position of the patient's neck is more likely to be stationary. Some experience is required to detect the appropriate carotid flow signals with Doppler flow probes. These characteristics of the Doppler flow probe contrast with the pulse oximeter probe. Further development of a simple and easy-to-use Doppler flow probe with a wide angle for detecting flow signals is desirable for any non-invasive SBP tracking system using a Doppler flow probe based on our principle.

In conclusion, the results of the present study show that our system, which uses Doppler ultrasound flow signals from the carotid artery and ECG signals, is feasible for SBP tracking over a longer interval if it is combined with intermittent calibration, i.e. every 15 minutes, and an automatic non-invasive blood pressure monitor.

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