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Advancements In Monitoring Blood Pressure And Reduction Of Cardiovascular Risk

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Abstract
The most common cause of cardiovascular disease (CVD) is hypertension. It is one of the most prominent diseases of the body, stroke, and organ failure. During a medical check-up, it is one of the most important signs measured in a patient. Accurate measurement of blood pressure is vital in the prevention and treatment of blood pressure-related diseases. Blood pressure (BP) estimation strategies have significant disadvantages, as non-invasive estimations are non-continuous whereas invasive measurements are kept to in-hospital utilization. One of the major problems, especially in operating rooms and in monitoring devices, is the continuous measurement of blood pressure changes using cuffs. Innovations were set up to manage the measurement of BP for the past long time. Currently, cuffless noninvasive blood pressure measurements can be divided into techniques that use only the PPG sensor and techniques that use a combined approach, i.e., PPG sensor and ECG. The hybrid approach is mainly based on PTT or PAT. This article provides a new perspective on blood pressure monitoring and management. This research aimed to investigate the literature on designing blood pressure monitoring to provide useful recommendations for increasing the accuracy of blood pressure measurement. The disadvantages and advantages of blood pressure measurement methods and choosing the best, most accurate, and efficient method of blood pressure measurement have been reviewed in related articles.

Keywords: *Blood Pressure, Hypertension, Oscillometric Measurement, Photoplethysmograph (PPG), Pulse Transit Time (PTT)*

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I. Introduction

High blood pressure (BP), cigarette smoking, diabetes mellitus, and lipid abnormalities are major modifiable risk factors for cardiovascular disease (CVD). It is also a main risk factor for heart failure, and myocardial and vascular disease (1). Most hypertensive patients are not aware of their high blood pressure. The negative effects of high blood pressure can cause various risks that can even result in death. This indicates that blood pressure must be measured as accurately as possible and the patient's motivation must be kept as high as possible. Accurate monitoring of BP depends on how effectively it is managed (2).

There are two ways to measure blood pressure. The first one is monitoring ambulatory blood pressure and arterial blood pressure measurement method and the second one is monitoring ambulatory blood pressure which is a non-invasive method to measure the blood pressure continuously for 24 or 48 hours. It is a diagnostic test to assess the presence of hypertension during routine daily activities and sleep. The arterial blood pressure measurement method is most commonly measured through a sphygmomanometer. Sphygmomanometers historically used mercury height to reflect circulatory pressure(3). Oscillatory strategies are exceptionally well suited to observing blood pressure at the brachial artery when patients are calm(4). Sphygmomanometer cuffs can effortlessly be joined and expelled by the patient. In any case, the oscillations utilized to determine the systolic and diastolic pressures are highly influenced by low-frequency mechanical vibrations, particularly those produced by movements during everyday physical action (5).

Recently, several studies have proposed different sphygmomanometers. Singh et.al proposed a system that continuously measures the patient's blood pressure and temperature and transmits these values to the physician via a wireless connection(6). In the other study, a wireless blood pressure monitor was developed that uses an Android-based smartphone as the display device (7). In this article, materials and methods of measuring blood pressure are discussed in section 2. Investigating pressure sensors is also described in this section. Next, section 3 reviewed related works as well as a summary of kinds of literature based on new technologies. It is worth noting that there is an increasing number of articles with the analysis and analysis of pressure measurement methods and the use of machine and deep learning techniques for BP estimation. Since the overview paper is about the blood pressure sensors technically and checking the accuracy of these sensors, such studies are not discussed in detail.

II. Materials And Methods

Methods of measuring blood pressure

Pressure measured during contraction of the heart is expressed as SBP and pressure measured during relaxation of the heart is expressed as DBP. Normal values for SBP and DBP are 120 mmHg and 80 mmHg, respectively(5). Invasive and non-invasive are two different methods for measuring blood pressure. Invasive methods require skin penetration but non-invasive methods do not require skin penetration. Instead, blood pressure is measured by blocking blood flow through the arm with an air-filled cuff. The most common of these non-invasive methods are oscillometric methods. Table 1 shows summary of common blood pressure measurement techniques.

Table 1. Summary of current blood pressure measurement techniques

Technique	Method	Accuracy	Usability
Auscultatory	Non invasive	Gold standard	Clinics or hospital
Palpatory	Non invasive	poor	Emergency situations
Oscillometry	Non invasive	Good	Clinics or hospital
[1]PTT/[2]PAT	Non invasive	Controversial	Useable for all sciences

Auscultator and Palpatory Measurement

Auscultator method: To measure arterial blood pressure using Korotkoff's auscultatory technique, a sphygmomanometer and stethoscope are needed. Sphygmomanometer is a device used to hear and amplify the sounds of the body and consisting of aneroid or mercury sphygmomanometer. The auscultator strategy for BP recording is considered as a gold standard to monitor BP in patients as well as within the healthy cares(8).

In this strategy the cuff is swelled to a level over blood vessel pressure. As the cuff is slowly collapsed, the pressure is noted at which sounds created by the blood vessel pulse waves Korotkoff sounds show up and vanish once as stream through the artery resumes. The appearance of the primary Korotkoff sound is the greatest pressure produced amid each cardiac cycle the systolic pressure. The level of pressure at which the sounds vanish forever. As the pressure is diminished amid collapse of the occluding cuff, the Korotkoff sounds alter in quality and escalated. Figure 1 shows the auscultator measurement. Advantages of the auscultatory method are similarity to conventional clinical blood pressure measurements; and accurately to detecting systolic and diastolic blood pressure at the onset and disappearance of sounds.

Figure 1: Auscultatory method aneroid sphygmomanometer with stethoscope

Palpatory method:

In this method, the cuff inflates rapidly to 70 mmHg, and increases by 10 mm Hg increments. The bladder of cuff places over brachial artery and wrap cuff hardly around the arm and the first three fingers palpates the radial pulse. During deflation, the level of pressure at which the pulse disappears and subsequently reappears will be systolic blood pressure. The advantages of palpation method involve feeling the pulse at

[11] Pulse Transmit Time

[2] Pulse Arrival Time

certain points in the body to estimate blood pressure. The advantages of the method are that it does not require a stethoscope, it is convenient and easy to use, and its equipment is easily available. Danish et al. (2020) did cross-sectional research about blood pressure measuring by auscultatory technique. They have compared two methods BP records of the auscultatory method and palpatory method. They concluded that the palpatory method can assess BP with accuracy.

A different between systolic pressure taken in palpatory and auscultatory methods is identification of systolic blood pressure by palpatory method helps one to avoid a lower systolic reading by auscultatory method if there is an auscultatory gap. It also minimizes the discomfort of over inflating the bladder of the cuff.

Oscillometric Measurement

The oscillometric technique is used in blood pressure measuring devices in clinics, hospitals and home use. New wristband devices use the same method for blood pressure. In this method, less discomfort and muscle compression is caused than mercury sphygmomanometers(9).

There have been many studies in the literature examining the oscillometric measurement of blood pressure. This method has simplified blood pressure measurement and eliminated the need for specialist training.(10-17). Automated oscilloscopes have a variety of algorithms, transducers, inflation and deflation rates, cuff sizes, and materials, which can affect the blood pressure estimate. This can lead to significant differences in estimates of systolic and diastolic blood pressure compared with auscultation results in the same patient.

Pulse Transit Time/ Pulse Arrival Time

All evidences vividly show the importance of continuous BP monitoring for diagnosing cardiovascular diseases and evaluating hypertension control (18-22). To improve the weaknesses of cuff blood pressure measurement, many research studies have been published using different techniques on the pressure sensor such as Pulse Transit Time (PTT), Pulse Arrival Time (PAT) and pulse wave analysis (23-26). PTT is a parameter related to the cardiovascular system and is extracted with the help of ECG signal and photoplethysmography wave and from its linear relationship with blood pressure, blood pressure is continuously measured (27-29). PCG and ECG serve as the suggested timing reference for achieving PTT and PAT indices (30, 31). PTT can be easily estimated as the proximal timing and distal arterial pressure. Therefore, PTT can provide continuous, non-invasive, cuff-free. Indeed, many have followed PTT as a BP marker (32-35). PAT can be calculated by the sum of PTT and the pre-ejection period (PEP) delay:

$$PAT = PTT + PEP \qquad (1)$$

Where PEP is the time elapsed to convert ECG signal to open the aortic valve(36). Because of its complexity when several physiological signals are needed to receive PEP value, the use of PAT to estimate BP is gaining popularity. However, the use of PAT is still controversial(35, 37). In this section, we intend to review procedures to enable reliable control of relationship BP and PTT/PAT (38-40). Using the calibration method, the measured PTT can be converted using an appropriate model for arterial pressure. The proximal waveform can be measured by photoplethysmography (PPG) (24, 41-46), pressure sensors, cardiography (ICG) (47-50), ballistocardiography (BCG) (51-55), seismography (SCG) (56-58), etc.

Blood Pressure Sensors

For designing a blood pressure, determining a suitable pressure sensor is one of the most common things. For a quick comparison of the blood pressure sensors, they are investigated in table 2.

Table 2. Investigating Pressure Sensors

sensor	Type of sensor	Dimensions(mm)	Accuracy (%)	Range	Unique Features	Typical applications	procedure
 **SDX05D4**	Non-invasive	2.29	+/-1 %	034.47k Pa	Low-cost Small size	Medical equipment	By oscillometric method through an artery during cuff deflation
 **MP3v5050**	Non-invasive	11.33 x 11.33 x 12	2.5%	0-50kPa	High quality High volume Biocompatibility Technical support	Level detectors Medical diagnostics Pressure switching Blood-pressure measurement	By oscillometric method through an artery during cuff deflation

 **AP3xx044K GNIBP**	Non-invasive	001 x 9 x772	2.5%	0-44kPa	Low noise/ Single point pressure/ High level output	Medical application	Piezoresistive chip by amplifying a low-level signal from sensing chip by compensating temperature
 **MAX32664**	Non-invasive	35 x17	3.3%	0-49 kPa	High precision Low noise	Medical application Wearable medical portable	Measuring BP, SPO2 and heart rate through the finger contact
 **MEAS 1620**	Invasive	11.43 x 8.13 x 4.20	1.0%	30 to 300 mmHg	Low-cost , disposable design	Disposable blood pressure, surgical procedures, ICU, medical instrumentation	Designed to be used with automated assembly equipment and can be dropped directly into a customer disposable blood pressure
 **Bmp180**	Non-invasive	12 x 10 x 2	0.1%	300 to 1100hPa		Weather forecast Leisure and sports	Connected directly to a microcontroller via IC bus

III. Review On Literatures

In this regard, detailed studies have been conducted on a set of sensors in different works. For example, Izzuddin Bin Mohd Sani (2013) designed a blood Pressure monitoring system. The MPX5700DP pressure sensor and Atmega328 microcontroller are used for manufacturing the system. The process was measured the blood pressure by oscillometric method. It was started with the motor pump inflating the cuff, then stopped. After that, the cuff was deflating gradually where the systolic and diastolic pressure was determined. After the deflation process reaching certain low pressure, the air valve released the air inside the cuff and the cuff completely deflated(59). Abdulkadir et al. (2017) described the development of PIC-Microcontroller based fully-automatic blood pressure monitoring system with GSM communication so that patients could monitor a patient's blood pressure (BP) and heart rate from a remote location without requiring being physically present. Traditionally, measuring a blood pressure is used by mercury sphygmomanometers; however, understanding the mercury sphygmomanometer should be done by expert and is manual. Later, oscillometric devices often referred to as automatic devices are introduced; automatic blood pressure devices do not require observer participation beyond placing the cuff on the arm and noting the digital blood pressure readout. In this article, PIC16F877A microcontroller was used to interface the blood pressure module to the GSM modem, blood pressure and heart rate module were used to read the blood pressure and heart rate. Then the result displayed on an LCD and used GSM for communicating the result by SMS directly to the health personnel's mobile phone. Figure 2 shows the overall of a system block diagram (60).

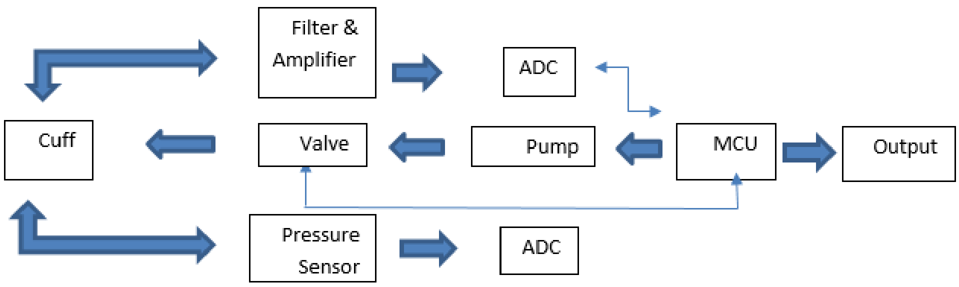

Figure 2. The general architecture of a blood pressure monitoring block diagram

In another study, İlha (2016) developed an automatic blood pressure measurement device to perform measurement on the arm. Resistor-Capacitor (RC) and digital filters were preferred to process and filter signal. The obtained results showed that a prediction accuracy of 94.67%, 92.51% and 97.68% could be achieved for systolic and diastolic blood pressure and heart rate values, respectively (61). Sivasankari et.al proposed a Wi–Fi based wireless sensor network for monitoring purpose. Each of them requires a periodic monitoring of vital parameters and correct treatments based on this data. Atmega328 microcontroller were used for continuous monitoring. In this case several sensor units were considered. Namely, temperature sensor, heart beat rate sensor, human blood pressure sensor(62).Lopez (2012) also illustrated the usage of an essential blood weight screen utilizing Freescale items. The blood weight screen could be executed utilizing any of the Freescale restorative situated MCUs: Kinetics MK53N512 and Flexis MM individuals MC9S08MM128 and MCF51MM256 (63).

All things considered, it is essential to know basics of electronic, analog, and advanced circuits. Application of different types of pressure sensors, task and methods in different literature survey have summarized in Table 3.

Table 3. Literature survey of the recent pressure sensors including their construction and working principle

Author(s)	Task	Microcontroller	Pressure sensor	Method
Izzuddin Bin Mohd Sani (2013)(59)	Manufacturing a blood pressure monitoring system	Atmega328 	MPX5700DP 	Oscillometric
Abdulkadir et al.(2017))(60)	The development of PIC-Microcontroller based fully-automatic blood pressure monitoring system with GSM communication	PIC16F877A 	MPX5050GP 	Oscillometric
İlhan (2016)(61)	Development of Blood Pressure (BP) Measurement Device Using The Curve Fitting Method	STM32F407 	MPX5050GP 	The Curve Fitting Method
Sivasankari et al. (2016)(62)	Arduino Based Human Health Care Monitoring and Control System	ATmega328 	SDX05D4 	Oscillometric
Lopez et al. (2012)(63)	The implementation of a basic blood pressure monitor using Freescale products	TWR-9S08MM, TWR-MCF51MM and TWR-K53	MPV3V5050 	Oscillometric
Edwan et al. (2020)(64)	Designing BP monitoring system through Arduino-Android Platform	ATmega328 	PSG010 	Oscillometric

According to the review of the literature, Atmega328 microcontroller is more suitable option for designing a blood pressure. It has 14 digital input/output pins, 6 analogue inputs, a 16 MHz crystal oscillator, a USB connection ,a power jack, an ICSP header, and a reset button. Notes that out of 14 digital input/outputs pins, there are 6 of them can be used as PWM outputs. The analogue inputs are connected with built-in ADC where capable to convert or quantize 0 V to V analogue input into 1024 level digital input (0 to 1023, 9 bits)(64) .

The MPXx5050 series are used in more for designing a blood pressure monitoring. These series output pressure range is 0 to 50 kPa. They are easy to use. They are designed for a wide range of application and have high level output signal.

Review on New technologies for blood pressure monitoring and management

Cardiovascular diseases (CVD) have become a complex issue. Utilizing manufactured insights approaches to test this complexity will likely reveal imperative unused highlights of CVD pathophysiology that may not be anticipated by routine procedures alone. Measuring blood pressure can be an essential step in the prevention of CVD (65). BP lowering can reduce the risk of CVD (66-68).

There are new techniques for monitoring blood pressure. One of the new technologies is the Penaz finger-cuff method (23, 69-72) which detects arterial pulsation in a finger using a photo-plethysmograph (PPG) under a pressure cuff. Kao et al. [2017] also developed a cuffless wireless optical blood pressure (BP) sensor. The device used photoplethysmography (PPG) technology to read changes in blood volume in blood vessels in real time and calculate blood pressure. The system was used a red-light LED with a wavelength of 660 nm, and the readout circuit was included a preamplifier, bandpass filter, programmable gain amplifier (PGA), Arduino unit for computation, and Bluetooth module for wireless communication. A notebook or mobile phone was also used to display continuous blood pressure readings and performed statistical analysis/results. The passband is 0.3 to 3.4 Hz and the adjustable gain range is 60 to 80 dB. As a result, the signal-to-noise ratio (SNR) was improved, enabling accurate estimation of BP. Eight subjects participated in the experimental validation, and the obtained blood pressure values were compared with those of a commercially available Omron sphygmomanometer. The maximum error of the experimental results was ±6mmHg, which is less than 8mmHg and meets the requirements of Advancements in Medical Equipment (AAMI). Their study was a pioneer in reporting stable and accurate blood pressure estimates with handheld cuffless optical devices(73). Zhang et al. [2020] reported a flexible sensor system for monitoring human health parameters such as human pulse wave, blood pressure, and heart rate. In the circuit design, the STM32F103C8T6 chip was chosen as the lower computer control core. Based on the ARM Cortex-M3 core, it was a 32-bit microcontroller with a built-in RISC core running at 72MHz and high-speed memory. To ensure accuracy, the sensor was filled with a melamine sponge covered with nano-conducting graphene material as the conductive layer, and the Ecoflex material acted as a flexible substrate(74). Tarifi et al. [2023] used of PPG for monitoring blood pressure. The models were trained on 890 h of data from 1669 patients in the MIMIC-III database. Feature-trained artificial neural networks predicted the systolic blood pressure to 5.26 ± 6.53 mmHg (mean error ± standard deviation), the diastolic blood pressure to 2.96 ± 3.31 mmHg, and the mean arterial pressure to 3.27 ± 3.55 mmHg(75) . A comparison of blood pressure and pulse pressure values obtained by oscillometric and central measurements from experiments showed that the developed prototype could attain an accuracy of 94.67% and 92.51% for SBP and DBP values, respectively, compared to those obtained from sphygmomanometers. Also, an accuracy rate of 97.68% was observed for heart rate. A photoplethysmogram (PPG) is based on pulse oximetry by detecting changes in the volume of peripheral blood circulation(76-78) .Figure 2 shows the overall of a system block diagram using a photo-plethysmograph (PPG).

Figure 2. The overall of a system block diagram using a photo-plethysmograph (PPG)

Some of researchers obtained pulse transit time (PTT) based on PPG(79, 80). In this regard, Liu et al. proposed the concept of finding waveforms associated with instances. This is an approach that minimizes the effects of atypical pulse waves on blood pressure measurements. Its method improved blood pressure measurement accuracy by 58%. Sampling frequency was used to derive PTT pulse wave velocity. A new blood pressure measurement model was proposed based on the statistical model of pulse wave velocity and blood pressure measurement accepted by the medical community. Finally, they validated the pulse wave-based real-time blood pressure measurement system by comparing it with the real situation(81). Masqsood et al. [2021] conducted an analysis of feature extraction techniques for blood pressure estimation by using PPG signals. They found that the deep learning models got better performance than all traditional machine learning methods(82). Table 4 shows summary of literatures based on new technologies.

Table 4. Summary of literatures based on new technologies

Author(s)	Task	Signals	AI algorithm	Result
Kao et al. [2017] (73)	8 subjects	PPG (photoplethysmograph)	Self- adaptive Signal Processing	Maximum error: ± 6 mmHg
Zhang et al. [2023] (74)	Computer samples	PPG	CNN	Error≤3%

Tarifi et al [2023] (75)	MIMIC-II database (1669 patients)	PPG	Machine Learning models	Error for systolic: 5.26 ± 6.53 mmHg Error for diastolic: 2.96 ± 3.31 mmHg
Jian-Qiang et al. [2018] [23]	800 samples	PW (Pulse Wave) and ECG	ML (Machine Learning)	Accuracy: 58%
Ibrahim & Jafari [2022] (83)	4 subjects	PPG	CNN (convolutional neural network): Autoencoder, 6 Bio-Z sensors	Error for diastolic: 0.5 ± 5.0 mmHg Error for systolic: 0.2 ± 6.5 mmHg
Mou et al. [2021] (84)	MIMIC-II database	PW (Pulse Wave)	CNN-LSTM	Accuracy: up to 30.41%
Panwar et al. [2020] (85)	MIMIC-II database	PPG	LRCN (Long-term Recurrent Convolutional Network)	An average NMAE of 0.09 (DBP) and 0.04 (SBP) mmHg for BP
Tan et al. [2022] (86)	120 Samples	PW	DP (Deep Learning)	Error≤ 4 mmHg
Eom et al. [2020] (87)	15 subjects	PTT	DP	Error for systolic: 4.06 ± 4.04 Error for diastolic: 3.33 ± 3.42
Masqsood et al. [2021] (88)	MIMIC-II database	PPG	Bi-LSTM	Error for systolic: 3.68C4.28 mmHg Error for diastolic: 5.34C5.25 mmHg

IV. Discussion And Result

The biggest drawback of the oscillometric method for measuring blood pressure is that it measures the DBP values with less accuracy than SBP values. The main drawbacks are (1) Sensitive to movements; (2) Having the accuracy of blood pressure systolic and diastolic to the algorithm used; and (3) Difficulty reading some oscillometric curves accurately. Therefore, an automatic blood pressure measurement device was developed to perform measurement from the arm. The RC and digital filters were preferred as signal processing and filtering methods. The other technique to measure blood pressure electronically is Pulse Transit Time technique (PTT). This technique is introduced to design a cuff-less blood pressure monitor. Two types of pulse wave are usually paired and PTT is extracted from the both types. This technique is able to determine the systolic and diastolic pressure continuously too. If the smallest average error is 4.91 mmHg. The PTT techniques are not ready for BP measurement. This is one of the biggest weaknesses of the technique. We also reviewed various theoretical methods in PPG signals. We concluded that the technology is not yet mature, but it is anticipated that in the near future, accurate, continuous BP measurements may be available from mobile and wearable devices given their vast potential. Table 5 shows drawbacks and benefits for blood pressure monitoring and management.

Table 5. Drawbacks and benefits for blood pressure monitoring and management.

Method	Notes	Drawbacks	Benefits	Accuracy
Oscillometric	Cuffed device	1.Sensitive to movements 2. Having the accuracy of blood pressure systolic and diastolic to the algorithm used 3. Difficulty reading some oscillometric curves accurately	The main advantages are (1) possibility of BP measurement when the Korotkoff signal is poor; (2) measurement of the mean arterial BP; and (3) no need of a microphonic sensor.	A reasonably accurate
PTT/PPG+ CNN	Cuffless	Cost, requires physician oversight	1.Improves medication adherence 2. Less patient discomfort than cuffed devices, measuring blood pressure remotely 3. Useful in resource limited areas	High accuracy

V. Conclusion

Noninvasive cuffless blood pressure measurements can be divided into techniques that use only the PPG sensor, or combined approaches. PTT is the time a blood pressure wave travels between two points in the body and is inversely correlated with BP. PAT is defined as the time interval between the electrical activation of the heart and the arrival of the pulse wave to a location in the peripheral body. It can be measured using two sensors, an ECG sensor and a PPG sensor. In this paper, we investigated the different technologies that monitor BP and relationship related to BP estimation for PTT/PAT. From the proximal and distal waveforms, it highlights the advantages and disadvantages of combining different factors that could provide us with PTT or PWV information for designing a blood pressure. The use of PTT or PAT can be a useful technique to achieve accurate hemodynamic estimates. They are the most effective methods for the non-invasive assessment of arterial stiffness and cuffless BP estimation. In addition, the investigation also addressed various technical challenges, such as blood pressure sensors requirements and advancement in new technologies. Drawbacks and benefits for blood pressure monitoring and management was also reviewed. To overcome some of these challenges, researchers introduced more accurate hybrid methods. They concluded that many challenges will be solved using of the machine and deep learning models and the measurement accuracy for estimating blood pressure will be higher. The CNN models had achieved a higher accuracy rate in researchers' research. In the CNN-LSTM model, a convolution layer and a pooling layer were used to perform features from PW data. Then two hidden layers of LSTM were used for further training. They defined two groups of qualities. The test results based on the MIMIC dataset showed that the proposed methods were close to or better than the existing BP estimation methods.

In summary, future developments of BP devices will likely require collaborative efforts of biomedical engineering, computer science, electrical engineering, and medical disciplines. We hope that home, smart and continuous BP monitoring will be realized in the near future. Through advances in designing, care can be significantly reduced and our quality of life greatly increased.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.