A wireless wearable body sensor network for continuous noninvasive blood pressure monitoring using multiple parameters

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Abstract: - Blood pressure is a significant vital sign; blood pressure monitoring has a great significance to determine the health status of parents. This paper proposes a continuous, non-invasive blood pressure monitoring system concept, which requires a minimum of calibrations. Using the changes in Pulse Transit Time (PTT) to derive changes in blood pressure is a new method to detect the continuous non-invasive blood pressure monitoring. The system proposed is also based on this method, but different from other systems, which use electrocardiograph (ECG) signal and photoplethysmography (PPG) signal to obtain the PTT. In this paper a new method is introduced with two PPG sensors located at different positions to obtain the PTT. The sensor is placed on the fingertip and the other one on the ear lobe. The optical signals obtained from the sensors will be sent to a micro-processor. According to the time difference of the pulse arrived between the sensors, micro-processor can calculate the PTT time and then the current blood pressure value with the predefined algorithm is calculated. Blood pressure values can be sent to a variety of terminals present in the wireless network, such as mobile phone, PC and medical monitoring systems. The two micro PPG sensors and a microprocessor form a wearable wireless sensor network on the body of the patient, this network will not disturb the patient's daily life and can achieve 24-hour continuous blood pressure monitoring. For the algorithm to estimate the changes in blood pressure from PTT time, researchers in previous studies tend to focus on finding the linear relationship between PTT and the changes in blood pressure. This paper considers the PTT as a unique parameter and also takes into account other vital signs of the patient such as height, weight, age, gender, body temperature, heart rate, etc., as these factors have an effect on blood pressure changes too. More experiments have to be performed and large amount of data has to be collected to develop the algorithm. The mathematical software Matlab and the available statistical methods will be adopted to analyze these data to obtain a precise algorithm for calculation of the correlations between blood pressure and multiple parameters. In future, more sensors can be added in this network such as ECG, Electroencephalography (EEG), etc., which can extend into a complete human vital signs monitoring system.

Key-Words: - Blood pressure, Continuous, Noninvasive, Multiple parameters, Wireless, Sensor Network

1 Introduction

Blood pressure (BP) is a very important vital sign, not only in the diagnosis of cardiovascular disease, but also in first aid.

Hypertension is a very common disease in industrial countries. In Germany, approximately every second adult suffers from hypertension [1]. In addition to high BP, low BP can also damage the human body functions. Therefore, BP has important significance for health monitoring.

Conventional methods of BP monitoring can be divided into direct and indirect ways. In direct way, the pressure sensor must be implanted in artery, it can continuously monitor BP, but the operation is complicated and difficult acceptable from patients. The indirect way is the mercury sphygmomanometer, the current gold standard for BP measurement. It is widely used in clinical practice and it is simple, fast, painless and easy acceptable from patients, but the continuous monitoring cannot be achieved.

In recent years, a large amount of research activities were made for non-invasive continuous BP monitoring. Compared to other methods, the new PTT method shows excellent results in many studies. [6 - 17] The basic principle of these studies is:

1. Use an ECG sensor and a PPG sensor to get the PTT
2. Measure BP at same time
3. Gather date from volunteers
4. Estimate the linear relationship between BP and PTT

Because individual differences of PTT and BP are large, it is difficult to model for estimating BP of unspecified people. [6] This paper describes a wireless wearable sensor network for continuous monitoring of BP. The system is also based on the PTT method as many other studies, but will use two PPG sensors to get PTT. In the system, not only the PTT, but also other signs of patient will be observed, such as height, weight, age, gender, body temperature, heart rate, etc. Bluetooth sensors will be integrated in the network, thereby creating the wireless communication between network and peripheral devices, like mobile phone, laptop and medical monitoring system.

2 BP Estimation

To estimate BP there are the following methods, which are widely used or still under development.

2.1 Direct, invasive, continuous

This method uses in artery implanted pressure sensor to get the changes of BP. It is very exact and continuous, but because of its complexity, it must be operated by a skilled physician in a hospital, and easy lead to bleeding, thrombosis, infection and nerve injury.

2.2 Indirect

2.2.1 Noninvasive, non-continuous

- Auscultation Method (Mercury sphygmomanometer)
- Oscillometric Method

These two methods are widely used as standard methods in ambulant clinic. Mercury sphygmomanometer is even seen as gold standard for BP estimation. They are easy to use, fast and not expensive, but they must be also operated by a skilled physician, and are non-continuous.

2.2.2 Noninvasive, continuous, with cuff

- Tonometric method
- Vascular Unloading Method
- Finapres method, volume-clamp methodology

These methods have been sufficiently developed in recent years. Some mature products based on Finapres already appeared in the market. [5] But they all need cuff - which press the local area of body, which leads to comfortlessness. The cuff must be deflated after a certain period of time or the placement of cuff has to be changed, so it is not really continuous BP monitoring.

2.2.3 Noninvasive, continuous, without cuff

2.2.3.1 NIR CCD camera

With this method, the change of vessel diameter could be obtained by NIR CCD camera in each cardiac cycle. The relationship between the change of vessel diameter and the change of BP will be evaluated. This method is just in first phase – image analysis, the result is not yet reported, whether accurate BP can be got using this method.

2.2.3.2 Pulse Transit Time, PTT

In recent years, many studies show that it is a safe, non-invasive, accurate method for continuous BP measurement. [6 - 17]

3 Overview of studies based on PTT method

3.1 The theory of PTT

In 1809, Thomas Young derived the pulse wave propagation velocity in blood flow with ignoring the blood viscosity, namely Young's velocity [2]. In 1878, Moens amended the Young's velocity according to the experimental results. In the same year, Korteweg derived the calculation formula for pulse wave velocity, which is as same as Young's velocity in special condition. So Young's velocity was known as the Moens-Korteweg equation. [3, 4]

$$v = \sqrt{\frac{gEa}{\rho d}} \qquad (1)$$

v is the pulse wave velocity, g is acceleration of gravity, E is the elastic modulus of vascular wall, a is vascular wall thickness, ρ is the blood density, d is the vessel diameter.

The elastic modulus of blood vessels has an exponential relationship with BP:

$$E = E_0 e^{\gamma P} \quad (2)$$

P is BP (mmHg), γ is a coefficient for vascular characterization, value between 0.016 ~0.018 (mmHg-1)

So the followed equation can be determined：

$$\Delta P = -\frac{2}{\gamma T}\Delta T \quad (3)$$

It means that if the blood vessel elasticity remains unchanged, then changes in BP are proportional to the pulse transit time. Thus the changes in BP can be estimated by measuring changes in plus transit time. The studies for continuous BP estimation using PPT method are based on this theory.

3.2 Studies for on PTT based method and wireless network

Asada et al. used 2 PPG-sensors along an artery to get the PTT, and a sensor was integrated to measure the acceleration in three dimensions, so that the position of the hand could be calculated at any time (Fig. 1). With the information of hand position, the system could correct the value of BP automatically. [7]

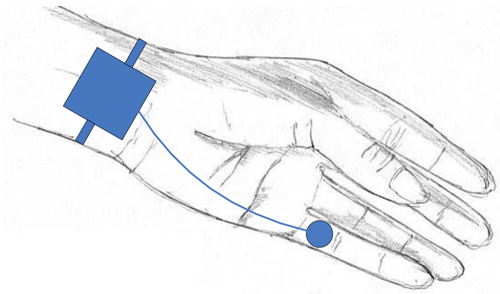

Fig. 1 A wearable BP monitor with acceleration sensor

Yan Chen et al. acquired pulse waves with two clip-type infrared light transducers which are utilized for ear and toe. A mathematical model can be proposed using two different pulse wave velocities (PWVs) from ear and toe. The results of clinical trials show that the mean deviation and standard deviation of SBP and DBP measurement by PWV have met the test standard in ANSI/AAMI SP10. [8]

Shriram, R. et al. have developed a system for systolic BP (SBP) measurement using PTT (Fig. 2). The equation for BP calculation from PTT is:

$$BP = \frac{1}{\alpha}\left[\ln\left(\frac{L^2 dP}{E_0 h}\right) - 2\ln(PTT)\right] \quad (4)$$

The results of twenty three healthy subjects show that the standard deviation was around 3 mmHg. [9]

Zurek, P. et al. would compare two systems of BP monitoring. The first system measures the wide changes of the blood vessels with NIR CCD camera (Near Infra-Red). The second system would be based on the PTT. The study is still in develop phase. [10]

Youngsung Kim and Jeunwoo Lee have developed a wrist type device for the continuous noninvasive BP monitoring based on PTT. The device can connect to the PDA phone by wireless connection. Its error rate is higher than the commercial product, but it is a novel attempt which can approach the reliability of traditional BP measurement product. [11]

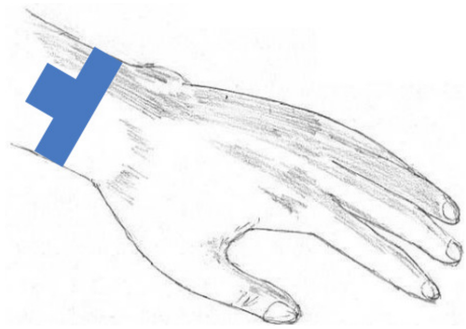

Fig. 2 Wrist type device

Fiala, J. et al. implanted the PPG sensor inside the body to estimate BP by measuring the PTT. Most of PTT based systems for BP measurement contain PPG sensors positioned on body surface. It can be influenced by ambient light, movement and temperature. With the use of an implanted sensor, such problems can be minimized or eliminated entirely. [12]

Mahmood, N.H. et al. have recorded the values of Pulse Wave Transit Time (PWTT) and SBP in three experiments. After analyzing all the experiment conducted, three different mathematical equations for calculation SBP from PWTT were obtained from three experiments:

$$y = 0.086x + 95.15 \quad (5)$$

$$y = -0.172x + 156.0 \quad (6)$$

$$y = -0.347x + 208.5 \quad (7)$$

The accuracy of derived BP values was low in comparison to the conventional method. [13]

Fortino, G. and Giampà, V. have proposed an overview of PPG-based techniques and methods for non-invasive and continuous BP measurement. They have also imagined a wireless Body Sensor Networks (BSNs) for remote continuous cardiac monitoring. However, there are several issues for development of the BSNs. [14]

Da Xu et al. have optimized the approach to calculate PWV. The approach was tested to estimate diastolic BP of six humans and the results showed that, the root-mean-squared-error is less than the corresponding error of the conventional method. [15]

Da He et al. proposed the site behind the ear as a location for continuous and wearable vital signs monitoring. The quality of PPG and Ballistocardiogram (BCG) signals which are obtained from minor sensors behind the ear is as well as the signal quality of traditional measurement. The signal information of PPG and BCG could be used for monitoring of heart rate, blood oxygenation, cardiac heart output and BP. [16]

Nitzan, M. hat reviewed the methods for non-invasive BP measurement. The sphygmonanometry is most accurate noninvasive method in comparison to other conventional methods. But it requires a well-trained examiner and is only made in doctor's office. A new method using PPG signal to detect BP pulses during cuff deflation is proposed for BP measurement. The method has potential to offer an accurate automatic BP measurement. [17]

4 Wearable body sensor network

Most of current medical care systems are fixed equipment that obtains signals from the sensors on the human body surface through the cable. These systems severely limit the patient's comfort and mobility. With the development of technology is possible to manufacture minor, wireless sensor. Therefore, using the small, wireless sensors to construct a wearable body sensor network for monitoring human vital signs has become a hot research topic.

Gallego, J. et al. would construct a wearable system for physiological signals monitoring like ECG, NIBP (Non Invasive BP), daily events, and oxygen saturation (SpO2). The system contains several intelligent modules that are integrated by a coordinator. The coordinator can communicate with modules per a wireless personal area network (WPNA) using MiWi P2P protocol and ZigBee module. [18]

Baozhi chen et al. have devised a Wireless Body Area Networks (WBANs) for reliable and continuous collection of patient vital signs. The system has minimum added RF (Radio Frequency) interference and provides a better performance than conventional wireless communications protocols. [19]

However, wireless communication has to face more errors than wired communication. This is basically the direct result of wireless channel characteristics such as multi-path, transmission interference, and signal fading. [20] So that the wireless technologies are not enough developed in health care & medical fields. Pandli P.K. et al. has recently presented a new approach to improve the Bluetooth technology with an additional safety layer to achieve safe communication for safety systems. [21] With the new approach, the Bluetooth technology could meet the safety request for medical care systems.

5 Wireless wearable sensor network for BP monitoring using multiple parameters

BP is regulated by the autonomic nervous system and hormones. The stock volumes, vascular resistance, viscoelasticity of blood vessels, blood volume and blood viscosity have effect on the level of BP.

There are the following physical factors, which can also influence BP:

- Age: The older, the worse the viscoelasticity of blood vessels. Therefore, the systolic BP has a tendency to rise, so the elder are more susceptible to the hypertension.
- Gender: In general, men's BP is about 5-10mm Hg higher than women's.
- External temperature: The higher external temperature will stimulate the peripheral vasodilation, thus decreasing BP. On the contrary, BP will be increased.
- Body temperature: The peripheral blood vessels will contract when body temperature is low, thus increasing BP. On the contrary, BP will be decreased.
- Posture: Because of gravity, the different posture will lead to the different BP.

- Eating habits: Eating too much salt will lead to hypertension, as sodium can cause the peripheral bold vessels to contract. Too much sugar and fat will cause obesity, which is a risk factor to hypertension.
- Emotions: In the excitement, tension, anxiety and pain, BP will increase.
- Metabolism: During the day, the metabolism is hyperactive for the working, eating, movement and other activities, BP will also increase. At night, the metabolism and activities are reduced, so BP keeps relatively at a low level.
- Smoking: Large amounts of nicotine can cause BP decreasing, thus a small amount causing BP to increase.
- Alcohol consumption: A small amount of alcohol will increase BP, large amount decrease therefore BP.

In recent years, PTT-based non-invasive continuous blood pressure monitoring system has been extensively researched. Most researchers were trying to find the linear relationship between PTT and BP, but they did not take into account the above factors. Only Chen et. al used multiple parameters to develop the relationship between PTT and BP. [6] But they have only chosen weight, arm length, height, arm circle, BMI and BMI_Kg as parameters, and only measured the systolic BP, so this study is not enough fully.

In this study, more physical factors, such as age, gender, temperature, weight, height, heart rate and BMI will be included for the evaluation. Not only the systolic BP but also the diastolic BP will be measured, in order to find the accurate complex relationship between multiple parameters and BP.

Previous studies are aimed to find the relationship between PTT and BP, and there are already several mathematical functions to be reported. However, it is relatively complex to find the relationship between multiple parameters and BP, so selecting an appropriate mathematical method for the success of experiment is very important. A variety of statistical methods will be compared in the study, such as artificial neural network (ANN), multiple regressions and support vector machine (SVM). The best algorithm will be chose to calculate the mathematical relationship between multiple parameters and BP.

The remote, wearable medical monitoring system can greatly improve the success rate of medical treatment and not affects the daily life of patient. The wearable, wireless BP monitoring system is the key component for realizing the remote, wearable medical monitoring system.

The in this study purposed BP monitoring system will consist of three sensors and a central coordinator. Two PPG sensors, one on the ear lobe, another on the fingertips, with a temperature sensor and the central coordinator form a star network. The benefit of star network is that a sensor can be simply replaced without the need to replace the entire system when the sensor has errors, so it is easy to detect faults and to remove parts. Star network can be also easily expanded with more sensors, like ECG, EEG sensors, to improve the performance of the entire medical monitoring system.

The sensors will be manufactured using micro sensor techniques, and the central coordinator will be manufactured using microprocessor and low energy consumption techniques. That the sensors are connected and powered by the central coordinator helps to reduce the size of the sensors. The use of micro sensors and microprocessor in coordinator make a wearable body sensor network possible, which will not affect the patient's daily life.

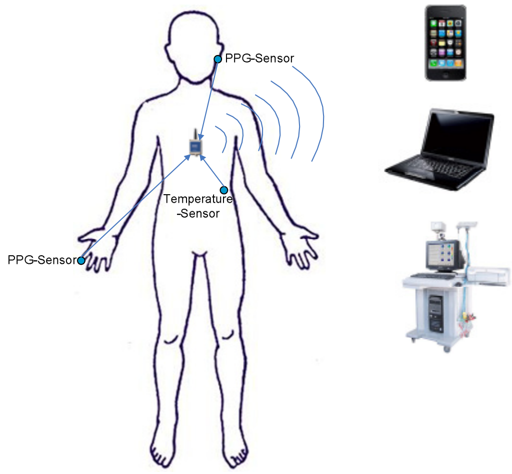

Fig. 3 A wireless wearable body sensor network for noninvasive continuous BP monitoring

The two PPG sensors will collect the pulse information sent by wire transmission to the central coordinator. The coordinator can calculate the PTT according the differences of pulse peak arrival time between two PPG sensors. The PTT, with the temperature data collected by the temperature sensor, as well as other predetermined information, such as age, gender, BMI etc. will be concentrated in the coordinator to develop the instant BP value.

The wire transmission between sensors and coordinator lead to the safe, stabile and rapid data transmission.

In the core of the star network – the central coordinator a Bluetooth sender will be integrated. With Bluetooth wireless technology, the coordinator can send the instant BP value to a mobile terminal such as laptop, smart phone or medical device (Fig. 3). The new approach of Pandli et al. [21] will be used for the Bluetooth communication, in order to improve the safety of wireless transmission. Through the wireless function the family members or physician of patient can acquire his BP value at all time. Some warning values of BP could be set in the coordinator, when BP exceeds those values, the alarm will be given to other terminals or direct showed in the coordinator. This function could help the patient himself, or his family members and physicians to take immediately proper medical treatment in a crisis.

The microprocessor of the central coordinator will be schemed out on Field Programmable Gate Array (FPGA). The mathematical algorithm for calculating BP from multiple parameters will be implemented into Very High Speed Integrated Circuit Hardware Description Language (VHDL) code integrated in FPGA. With this structure, the processing speed of microprocessor can be ensured on the hand, and on the other it is more convenient for updates and maintenance in the future.

6 Conclusion

This paper discussed the PPT-based methods for noninvasive continuous BP monitoring. Most relevant studies have showed good results, which indicated that this is a feasible method to realize the non-invasive continuous BP monitoring. This paper also presented a PTT-based, using multiple parameters method to determine BP value. Additionally, the paper described a safety wearable body sensor network using new safe Bluetooth transmission protocol. This network can monitor the changes in BP without influencing the daily life of patient and can give alarm in an emergency. Such network could greatly improve the quality of the medical treatment.

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