Wireless Chest Wearable Vital Sign Monitoring Platform for Hypertension

G. Janjua, D. Guldenring, D. Finlay, *Member*, *IEEE* and J. McLaughlin, *Member*, *IEEE*

***Abstract* — Hypertension, a silent killer, is the biggest challenge of the 21st century in public health agencies worldwide [1]. World Health Organization (WHO) statistic shows that the mortality rate of hypertension is 9.4 million per year and causes 55.3% of total deaths in cardiovascular (CV) patients [2]. Early detection and prevention of hypertension can significantly reduce the CV mortality.**

We are presenting a wireless chest wearable vital sign monitoring platform. It measures Electrocardiogram (ECG), Photoplethsmogram (PPG) and Ballistocardiogram (BCG) signals and sends data over Bluetooth low energy (BLE) to mobile phone–acts as a gateway. A custom android application relays the data to thingspeak server where MATLAB based offline analysis estimates the blood pressure. A server reacts on the health of subject to friends & family on the social media - twitter.

The chest provides a natural position for the sensor to capture legitimate signals for hypertension condition. We have done a clinical technical evaluation of prototypes on 11 normotensive subjects, 9 males 2 females.

I. Introduction

Hypertension or high blood pressure (BP) is a stressed arterial state, where blood continually exerts increased pressure on arterial walls. In normal adults, when the heart contracts the amount of pressure exerted on arteries wall by blood is 120mmHg, called systolic blood pressure (SBP). When the heart relaxes the amount of pressure exerted on arteries wall by blood is 80mmHg, called as diastolic blood pressure (DBP). Hypertensiveness increases health risks especially to heart and to vessels in kidneys and brain.

Hypertension is a silent killer with no visible symptoms. As per WHO, over 1 in 5 adults have the hypertensive condition and its complications cause a major number of impediments in cardiovascular patients. Most common conditions are myocardial infarction, stroke, renal failure and death - if not diagnosed and treated properly. Joint National Committee (JNC) stated in its 7th report that obliviousness is over 30% in afflicted patients and 40% of hypertensive patients are not getting the treatment [3].

This study presents research on a chest wearable cuffless blood pressure monitoring system that measures arterial stiffness by calculating pulse transit time (PTT). ECG, PPG and BCG signals estimate blood pressure with semi-supervised learning method.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 676201.

Chest position is most stable and right signal acquisition position for signal stability and legitimacy. Signals measured at the chest are less prone to artifact and PTT from carotid arteries provides the aortic stiffness which is a true indicator for hypertension.

For every measurement, the server receives the data from the subject's mobile phone which is wirelessly connected to the chest strap. We have conducted the clinical technical evaluation on 11 healthy individuals (9 males & 2 females).

The object of research were to 1) design a wireless wearable vital sign monitoring platform, 2) to look for non-invasive BP measurement method, 3) to investigate novel legitimate position for arterial stiffness measurement and 4) to a conduct clinical technical evaluation for prototype.

II. Background

An overview of wearable techniques used in the development of cuffless blood pressure monitors is discussed here.

A ring - comprising PPG and accelerometer sensors are used to measure transmural pressure based on finger blood flow waveforms and positioned by using the wiener model. The ring is calibrated by using the hydrostatic pressure variation available in the arm positions to heart level [4].

Two in-line PPG Sensors are used on the wrist and little finger to measure pulse transit time (PTT). It uses the principal of optical absorption of incident wavelength due to volumetric blood flow. The height sensor is used for catering hydrostatic variation on the arm positioning with reference to heart level [5].

Two in-line polyvinylidene difluoride (PVDF) piezoelectric sensors are used on the forearm to estimate pulse wave velocity (PWV). It measures the mechanical pulsation of volumetric blood flow in the radial artery [15].

The most commonly used technique, PPG, and the ECG sensor are used to measure pulse arrival time (PAT). Different locations are used for PPG sensor placement like the forehead, index finger and on the back of ear etc. PPG waveform reference points for PAT ranges from a foot to peak in the waveform [6 - 13].

Also, PPG, ECG & BCG sensors are used at the mastoid location - back of the ear. In this technique, PTT is calculated between the peak of BCG J-wave and PPG 1st derivative. Electronics is anchored on the ear and data is transmitted wirelessly to the PC and estimation of mean arterial pressure (MAP) is estimated using the regression algorithm of PTT [14].

III. PROCEDURE

A. Sensor Location

Attenuation of pulsatile flow is due to aorta elasticity - stiffer the artery more reflection in blood flow thus more pressure on the heart pumping. Aortic stiffness is a legitimate indicator for hypertension and showed highest CV mortality when compared to other arterial stiffness [16]. So, we have selected the chest position for wearable vital sign monitoring platform. On chest ECG signals are less prone to motion. Second, the equal distance at right and left common carotid arteries for PPG and BCG sensors from the heart. By equal distance, we are able to measure the PTT optomechanically.

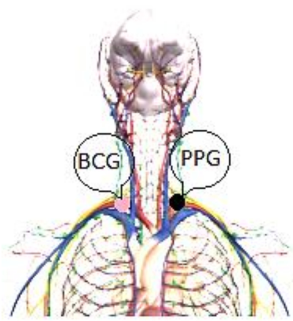

Figure 1: Left carotid artery with PPG sensor and Right carotid artery with BCG sensor

B. Sensors Selection

For wearable platform, ECG, BCG and PPG signals are ideal sensors for vital signs monitoring. These sensors are power efficient and miniature in size. ECG provides vital information of heart useful for critical diagnostic. PPG gives valuable information on blood flow, oximetry, and arterial augmentation index. BCG gives the mechanical pulsation and when it combines with PPG, the 1st derivative gives arterial stiffness.

C. PPG wavelength selection

To measure carotid artery blood flow, we have used the infrared (940nm) sensor PPG due to good penetration in the skin. Red and Green wavelengths have lesser depth and not suitable for measuring carotid volumetric flow [17].

D. PPG 1st derivative selection

PPG 1st derivative is the least affected point waveform due to reflection artifact created by bifurcation and/or arterial stiffness. Foot and peak of waveform get an artifact from reflected wave and may lead to false positive easily.

E. PWV effecting parameter

PWV varies with age, height and ethnicity in normotensive patients, so we took special consideration in gathering datasets by gathering a group of people of age ±7 years. To avoid bias in the dataset, when transversely compared to hypertensive patients, we have kept the same age group.

F. MAP estimation fact

The estimation of mean arterial pressure (MAP) is not suitable based on PTT compared to SBP or DBP [19]. We have estimated the SBP and DBP from PTT in subject groups.

G. PTT is not surrogate of PAT

In a clinical study, it is well-established fact that PAT showed incapability to track changes in BP compared to PTT [18].

IV. EMPIRICAL EQUATION

Moens-Korteweg equation models PWV to arterial distensibility based on Newton's second law as:

$$PWV = \sqrt{\frac{Eh}{2\gamma\rho}} \quad (1)$$

Young's modulus exponential fit for canine artery described by Hughes relation as:

$$E = E_o \, exp^{\alpha p} \quad (2)$$

By solving eq.1&2 we have the empirical equations for transmural pressure as:

$$P = \frac{1}{\alpha}\ln\left(2r\rho\frac{\Delta X^2}{E_o h}\right) - \frac{2}{\alpha}\ln(PTT) \quad (3)$$

Where r = carotid Artery inner radius, h = carotid artery wall thickness, ρ = blood viscosity, E_o = young's modulus and ΔX = heart to carotid distance.

$$P = \frac{C1}{\alpha} - \frac{2\ln PTT}{\alpha} \quad (4)$$

We have been able to track changes in blood pressure by driving the relationship between correcting factor and a log of pulse transit time. Transformations use numerical range estimation specific to individual subject's blood variation.

V. HARDWARE AND SOFTWARE

Wearable vital signs monitoring system uses the internet of things (IoT) architecture. We have developed the belt which takes the vital signs and transmits over BLE. The device gets paired with the subject's personal mobiles on custom BLE profile, NIBP. The custom android application takes data from belt and relays to server and serves the purpose for user interaction. Data communication to/from a mobile device is on secure connection with thingspeak server. The server runs the data offline analysis in MATLAB environment and estimated the blood pressure which is reacted to twitter for subject's physician and friend list.

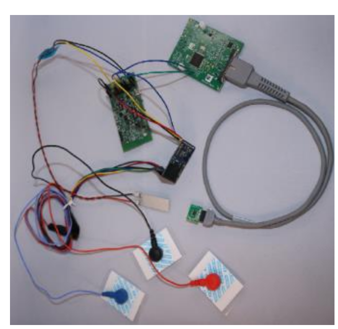

Figure 2: Prototype hardware

A. *Hardware*

For ECG data acquisition, we have used medlab ECG module, EG04000, is interfaced over universal asynchronous receive and transmit (UART) port. For data transmission, we have used the Broadcom BCM20737s system on a chip which has a cortex-M series micro-controller (MCU) and used as a master controller of the belt. ECG module is interfaced to UART of MCU at 115,200 baudrate with level shifter as BLE MCU works at 1.8V and ECG module works at 3.3V. Piezoelectric sensor by Measurement Specialist is interfaced with charge and voltage mode circuitry to MCU analog-to-digital converter (ADC).

For PPG data acquisition, we have used OSRAM optics module, SFH7050 is interfaced to Texas Instrument (TI) analog front end AFE443. AFE4403 is suitable for pulse oximetry front as it can drive the LED and have a trans-impedance amplifier for the light sensor. Also, AFE4403 equipped with a programmable amplifier for gain controls. AFE is interfaced to TI MSP430 MCU which is secondary MCU (SMCU). SMCU configures PPG and waits for signals from MCU for data acquisition. SMU is an interface to Fujitsu MB85RC256V 256K flash over the Serial peripheral interface (SPI) to store data.

We have used Saft LSH20 3.6 V Primary lithium-thionyl chloride (Li-SOCl2) to power the prototype. In parallel, have developed wireless charging solution by using TI bq51003 wireless power receiver and linear charger bq25100. The wireless charging system is Qi compliant charger. System micro schematic model is as.

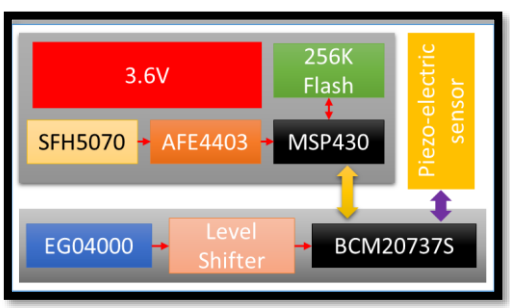

Figure 3: System Architecture

B. *Firmware*

Operation occurs in the following sequence:

1- On power-up, BLE MCU enable BLE profile
2- MCU configures ECG module for all parameters
3- On power-up, SMCU configures PPG module
4- SMCU polls for signal from MCU
5- MCU check the device pairing with mobile phone app
6- MCU waits for message from mobile phone app to start acquisition
7- As it starts taking ECG & BCG signal data at same instant sends signal SMCU to acquire PPG signal
8- Once MCU get 85-byte of ECG than sends notification message to mobile phone
9- BCG data is sent after the ECG data
10- Acquisition runs for 10 second
11- Once SMCU gets the trigger it captures data from PPG and save in flash for 10 seconds
12- Once data transmission finishes in MCU then it reads FRAM and send the PPG data notification messages
13- System goes to sleep afterward
14- if any error, MCU sends an error code to the mobile application

C. *Android application*

We have used appinventor2 for android application development. For user interface in the app there are three buttons and heart Icon. Scanning for Bluetooth devices is done by clicking scan button. On scanning, a screen with available devices pops-up and on selection the belt device with name NIBP it starts paring process. In the background, it completes the pairing and once done heart icon starts beating. On the press of measure button on belt, the app receives the command from the wireless device to start data reception. On reception of first 85-byte array, it checks the data type. ECG, BCG and PPG data is sent via web post for ‘channel 1’, ‘channel 2’, ‘channel 3’ on thingspeak server, respectively.

Error handling function displays the error as it occurs on the display screen. Disconnect button is used to unpair the device and exit button is to exit the application. Apps icon and interface are shown as.

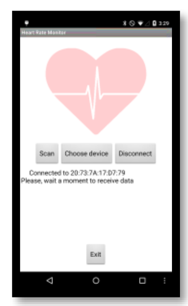

Figure 4: App user interface (UI)

Thingsview is a open access app for view the thingspeak channel data on to mobile and we have used it for displaying user data analytic and blood pressure estimate.

C. *Server*

We have used the thingspeak.com server to receive data for ECG and PPG signals. Have assigned channel 1 for ECG data, channel 2 for BCG data and channel 3 for PPG (for setting up channel visit www.thingspeak.com). MATLAB offline analysis runs by logging into server and results are displayed in form of graph as shown:

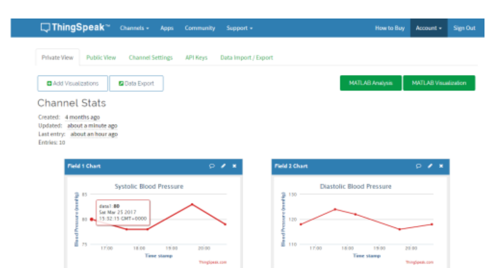

Figure 5: Server View

C. MATLAB analysis

MATLAB algorithm works as below:

1- On ECG signals pre-processing done to remove the data noise from it.
2- Pans-Tompkins algorithm is used for R-wave detection
3- Low pass filter is used on PPG signal for removing the noise
4- Then 1st order derivative is applied on PPG signals and peak are detected and marked
5- On BCG signal peak are detected and marked
6- Time difference is calculated between PPG 1st derivative and BCG j-wave peak which gives PTT value
7- Then have used equation 3 to get blood pressure value
8- SBP and DBP values are estimated based on linear regression
9- Bland-Altman (BA) shows the system compliance to central blood pressure

A graph for analysis is as shown:

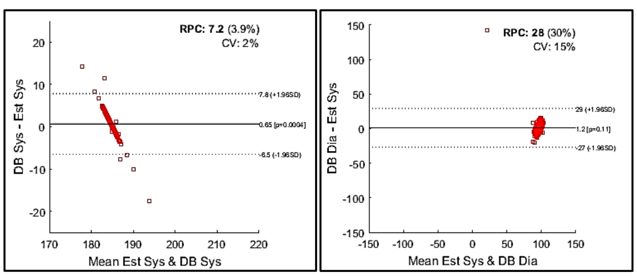

Figure 5: PTT on top left, Transformation on top right, BA SBP on bottom left & BA DBP (bottom right)

VI. CONCLUSION

This work has presented a novel wireless chest wearable vital sign monitoring platform. Aortic arterial stiffness provides a good estimation of SBP compared to DBP. Bland-Altman analysis showed that the device algorithm is compatible with Grade C of British Hypertensive Society standards for SBP estimation.

REFERENCES

[1] Patricia M Kearney, Megan Whelton, Kristi Reynolds, Paul Muntner, Paul K Whelton, and J. He, “Global burden of hypertension--analysis of worldwide data,” Lancet, vol. 365, pp. 217–223, 2005.

[2] W. H. Day, “World Health Day 2013,” A Glob. Br. Hypertens., p. 9, 2013.

[3] A. V Chobanian, “The Seventh Report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure” JAMA, vol. 289, no. 19, p. 2560, 2003.

[4] S. Committee, I. Engineering, and B. Society, IEEE Standard for Wearable Cuffless Blood Pressure Measuring Devices. 2014.

[5] A. Marinkovid, A. Marinkovid, H. H. Asada, T. Supervisor, and L. Anand, “Reconstructing the Blood Pressure Waveform using a Wearable,” 2007.

[6] D. B. McCombie, “Development of a wearable blood pressure monitor using adaptive calibration of peripheral pulse transit time measurements,” Dspace.Mit. Edu, 2008.

[7] H. Gesche, D. Grosskurth, G. Küchler, and A. Patzak, “Continuous blood pressure measurement by using the pulse transit time: Comparison to a cuff-based method,” Eur. J. Appl. Physiol., vol. 112, no. 1, pp. 309–315, 2012.

[8] G. Jeong, K. Yu, and N. Kim, “Continuous Blood Pressure Monitoring using Pulse Wave Transit Time,” Measurement, pp. 2–5, 2005.

[9] S. Ye, G. Kim, and D. Jung, “Estimation of systolic and diastolic pressure using the pulse transit time,” World Acad. Sci., pp. 726–731, 2010.

[10] R. Magjarevic, N. A. Abu Osman, F. Ibrahim, W. A. B. Wan Abas, H. S. Abdul Rahman, H.-N. Ting, E. B. M. Tamil, N. H. Kamarudin, R. Salleh, and a. M. Tamil, Measuring Blood Pressure Using a Photoplethysmography Approach, vol. 21, no. DECEMBER. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008.

[11] C. Yu, J. Janousek, E. Sheridan, D. L. McAuslan, H. Rubinsztein-Dunlop, P. K. Lam, Y. Zhang, and W. P. Bowen, “Optomechanical magnetometry with a macroscopic resonator,” IEEE Sens. J., vol. 14, no. 10, pp. 3490–3497, Oct. 2015.

[12] S. Fuke, T. Suzuki, K. Nakayama, H. Tanaka, and S. Minami, “Blood pressure estimation from pulse wave velocity,” 35th Annu. Int. Conf. IEEE EMBS, pp. 6107–6110, 2013.

[13] S. Mazaheri, “A Comparative Review of Blood Pressure Measurement Methods Using Pulse Wave Velocity,” Icsima, 2014.

[14] E. S. Winokur, “Single-Site, Noninvasive, Blood Pressure Measurements at the Ear using Ballistocardiogram (BCG), and Photoplethysmogram (PPG), and a Low-Power, Reflectance-Mode PPG SoC,” 2013.

[15] JMcLaughlin, MMcNeill, B Braun and P DMcCormack, “Piezoelectric sensor determination of arterial pulse wave velocity” Physiol.Meas. 24 (2003) 693–702

[16] P. Salvi, “Pulse Wave how vascular hemodynamic effect blood pressure” springer, 2012.

[17] A. Alzahrani, S. Hu and V. A. Peris “A Comparative Study of Physiological Monitoring with a Wearable Opto-Electronic Patch Sensor (OEPS) for Motion Reduction” Biosensors 2015, 5, 288-307.

[18] G. Zhang, M. Gao, D. Xu, N. B. Olivier, and R. Mukkamala1 “Pulse arrival time is not an adequate surrogate for pulse transit time as a marker of blood pressure” J Appl Physiol 111: 1681–1686, 2011.

[19] W. Nichols, M, O'Rourke, C. Vlachopoulos “McDonald's Blood Flow in Arteries, Theoretical, Experimental and Clinical Principles” CRC press, 2011.