NON-INVASIVE, CONTINUOUS, PULSE PRESSURE MONITORING METHOD

Makiko Kuwahara, Ehsan Yavari, *Member, IEEE,* and Olga Boric-Lubecke, *Fellow, IEEE*

Abstract— **Many individuals suffer from ailments such hypertension that require frequent health monitoring. Unfortunately, current technology does not possess the ability for unobtrusive, continuous monitoring, requiring the examinee maintain uncomfortable and/or restrictive positions. This paper proposes estimation of pulse pressure based on pulse transient time determined from one non-contact, and one contact sensor: Doppler radar for non-contact detection of heart beat, and piezoelectric finger pulse sensor. The time delay between heart beat and finger pulse was determined using MATLAB software, and pulse wave velocity (PWV) was calculated. Finally, subjects' pulse pressure estimated using PWV was found to be in good agreement with pulse pressure measured using an off the shelf sphygmomanometer by reading and taking difference of systolic and diastolic blood pressure.**

I. Introduction

Center for disease control (CDC) estimates that about one third of adults have high blood pressure or hypertension, and one third prehypertension. High blood pressure increases the risk for heart attack and stroke, which are leading causes of death; heart attacks account for 23.5% of all deaths [1] while strokes account for nearly 6% of all deaths [2] in the United States. It is reported that pulse pressure is also a significant indicator of diabetes and cardiovascular disease [3]. Non-invasive, at home health monitoring for heart condition and blood pressure, pulse pressure could be an essential key to reducing mortality rates.

It has been reported that blood pressure can be estimated from the speed at which the arterial pressure wave travels, called pulse wave velocity (PWV) [4]. PWV can be obtained by measuring time delay between pulse wave peaks at two arterial sites, known as pulse transient time (PTT), at a known distance. Blood pressure estimation using PTT and PWV has been demonstrated using contact sensing methods such as Electrocardiography (ECG) and photoplethysmography (PPG) [9]. However, it may not always be possible or desirable to have two sensors attached to the body. In [8], blood pressure estimation was proposed using a single physiological non-contact Doppler radar measurement of heartbeat induced chest displacement. However, this measurement requires control over subject position that may not always be practical. In [9], it was demonstrated that PTT can be measured using two Doppler radars: one to measure heartbeat signal from the chest, and the second one from the wrist. While these results are promising, the choice of Doppler radar for wrist pulse measurement does not seem to be advantageous. In this paper, we propose to research a continuous, non-invasive method of estimating pulse pressure based on PTT, with one contact sensor in conjunction with a second non-contact sensor. Pulse pressure is obtained by following equation.

$$PP = BP_{systolic} - BP_{diastolic} \tag{1}$$

We propose to use non-contact sensor based on Doppler radar to detect heart pulse at a distance, and one contact sensor to detect pulse on left arm. These are the first reported blood pressure measurements based on PTT measured using Doppler radar for heart signals, and piezo-electric sensor for finger pulse signals. The proposed configuration has the potential for practical implementation where non-contact measurement can be made with sensor embedded into the environment, or with a mobile communication device, and the contact measurement can be provide with a wearable device, such as a watch with pulse measurement capability.

II. Methodology

Doppler radar physiological monitoring has been demonstrated for detecting cardiopulmonary signals at a distance [6]. Radio waves sent from the Doppler radar are modulated by the displacement of human chest, due to respiration and heart beats. This displacement can be demodulated to reveal heart rate and timing of heart events. It has also been demonstrated that heart signals can be obtained from different body orientations with respect to the radar, including front, back and sides. While Doppler radar can detect arterial pulse at any body site, the pulses originating from the heart have the largest displacement, and are thus dominant in the demodulated signals. This principle was used to obtain the timing of heartbeat pulses in [9]. In this paper, the peaks of this signal will be to determine PTT, in conjunction with a contact sensor on left arm.

M. Kuwahara is with the Electrical Engineering Department, University of Hawaii at Manoa, Honolulu, HI 96822 USA (e-mail: makikoku@hawaii.edu).

E. Yavari is with Adnoviv LLC, Honolulu, HI 96822 USA (e-mail: ehsan@adnoviv.com).

O. Boric-Lubecke is with the Electrical Engineering Department, University of Hawaii at Manoa, Honolulu, HI 96822 USA, (e-mail: olgabl@hawaii.edu).

As the heart beats blood is pumped through the arteries throughout the body to deliver the oxygen, and as the body

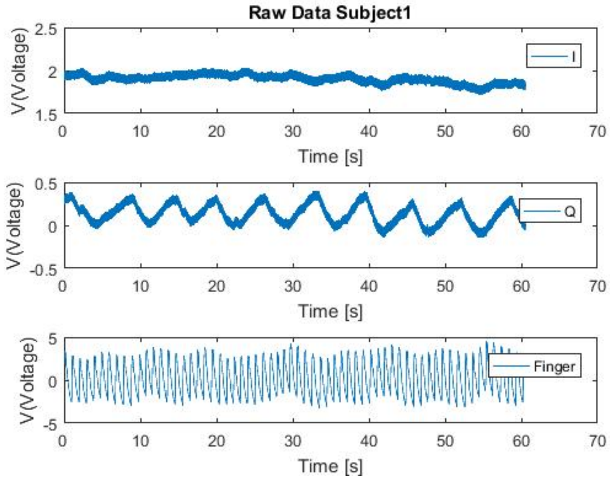

Figure.1 Preliminary data of radar(I,Q) and piezo(finger).

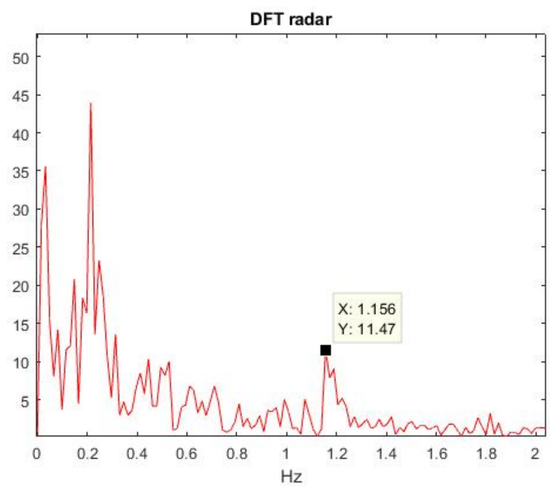

Figure.2 DFT of linearly demodulated radar signal.

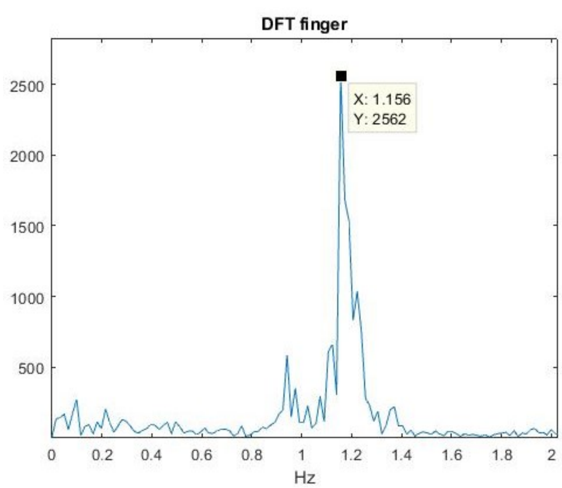

Figure.3 DFT of finger signal.

breathes oxygen-depleted, blood is circulated back towards the heart through the veins to receive the oxygen the lungs had obtained. The pressure exerted on the arteries and veins by the circulating blood can be detected as pulse at many sites of the body using piezo-electric sensors, including upper arm, wrist, and finger. If the timing of the pulse peaks is compared from different sites, PTT can be determined for various body segments. In this work, we will compare peak timing between Doppler radar heartbeat signal obtained from the chest, and the finger pulse measured using a piezo-electric sensor. By measuring the physical distance of the path that blood travels from the heart to the finger, PWV can be calculated.

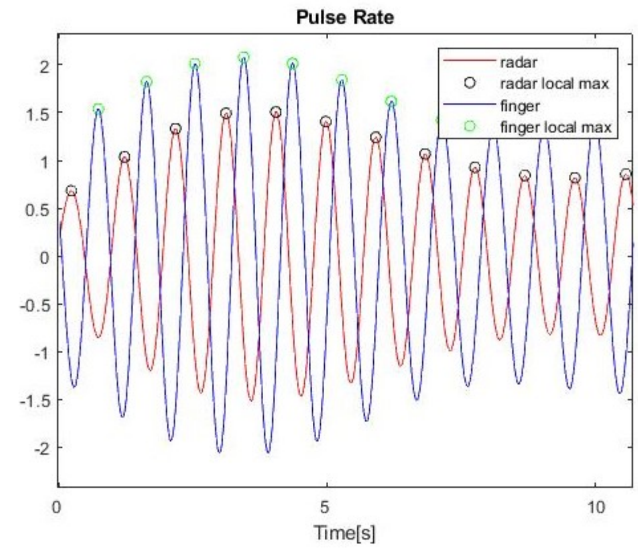

Figure.4 Pulse rate of radar and finger.

III. EXPERIMENTAL SETUP

The testing procedure begins with establishing a pulse pressure control measurement for the subject and trial using an aneroid sphygmomanometer by taking difference of systolic and diastolic blood pressure. Basic clinical routine was followed for using the aneroid sphygmomanometer to reduce possible errors- for example blood pressure was taken in a calm resting position and a resting period of at least 5 minutes was issued between blood pressure readings including when testing with the Doppler radar. For finger pulse, UFI 1010 finger pulse sensor is used to detect a pulse peak on left index finger. Data was collected on five human subjects with the following sequence: physical measurement of distance between heart and left index finger, BP measurement, Doppler radar measurement with finger pulse (one minute), second Doppler radar measurement with finger pulse (one minute), second BP measurement. Human subjects were seated at about 1 meter away from Doppler radar.

For quadrature radar setup with DC offset cancellation, HP 83640B signal generator is used operating at 2.4 GHz with 10-dBm output power. The reference signal is divided into I/Q channels by a 90-degree splitter on the receiver side. A 0-degree divider splits the received RF signal into two channel signals with the same phase and amplitude. Two identical Minicircuits ZFM4212 mixers are used to down-convert the received signal into baseband. Due to DC coupling, baseband signals have large DC values which limit baseband gain and saturates the amplifiers. a 16 bit Digital to Analog Converter (NI 6280) is used to generate DC level corresponding to the measured DC offset and subtracted from baseband signals before amplification. After DC cancellation, signals are low pass filtered, amplified with Stanford Research SR560 low-noise amplifiers and recorded by a data acquisition device with 100-Hz sampling rate. Finger pulse is recorded simultaneously.

Fig.1 shows preliminary data output of each sensor. Doppler radar sensor is used to collect two channel (I and Q) data from heartbeat of a human subject. After I and Q are linearly demodulated [6], DFT are taken both for radar and finger signal in order to estimate frequencies for the bandpass filtering. The example results are shown in Fig.2 and Fig.3. The first group of peaks shown on the DFT radar plot is a frequency band for respiration. The next peak we can observe around 1Hz is for the pulse rate which we need for estimating pulse pressure. We can also observe the peaks for both radar and finger exactly corresponds to each other at the same frequency.

Figure shows linearly demodulated [6] filtered output of heartbeat collected using Doppler radar and filtered output of piezo-electric sensor on finger. Time delay between peaks can be observed. In Fig. 4, radar signal was scaled multiplying by 400. By determining the time delay between heart and tip of finger, the blood flow rate was determined.

IV. Data Analysis

In order to observe the relationship between radar signal and piezoelectric sensor finger pulse signal, findpeaks function in MATLAB was used to find the peaks of each signal's local maximum points. Fig.4 shows the output of using this method on our data. This allows us to find the peaks in the signals and thus obtain the distance in samples between each peaks. PTT and PWV are used in calculating pulse pressure using a linear regression model between control variables and calculated variables. We can find the time delay PTT by first subtracting peak locations in the radar and finger pulse dividing by sampling frequency. Since we acquire multiple heart beats in our signals we can average over this difference. For this, the following formula summarizes this approach.

$$PTT_{RF} = \frac{\sum_{i=1}^{n} t_R - t_F}{n} \tag{2}$$

Here the variables t_R, t_F is the peak locations in the radar and finger pulse found via MATLAB. To calculate PWV, the length between each device is divided by respective PTT. Following equation describes calculating PWV where L denotes the length (in meters) between the same areas denoted by R, and F as in previous equation.

$$PWV_{RF} = \frac{nL_{RF}}{\sum_{i=1}^{n} t_R - t_F} \tag{3}$$

The time delay estimated can be used with the distance of a subject's heart to finger physical parameters of the devices in contact for measuring our data to figure out the speed of the blood flow. In this experiment, measure tape was used and this is shown in Fig.5.

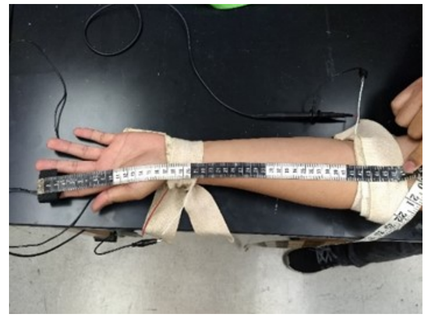

Figure.5 Measuring a subject for the length between devices.

Finally, we correlate PWV obtained using this measurement to the actual pulse pressure measured using traditional sphygmomanometers and digital blood pressure devices shown in Fig.6. In this experiment, pulse pressure measured before the experiment was correlated with the both experiment. The PWV was calculated for generating the linear regression model. Each PWV is compared to the control measurement recorded to gain a reference for the linear regression model.

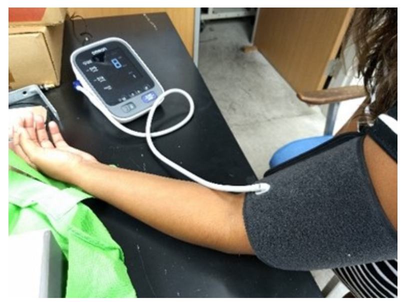

Figure.6 Taking blood pressure of a subject using a digital sphygmomanometer.

The data was displayed as a scatter plot with the x-axis as PWV and y-axis as real pulse pressure to establish a line of best fit to formulate a linear equation [5]. Pulse pressure should then follow the equation:

$$PP = a * PWV + b \tag{4}$$

where the variables a and b are the slope and y-intercept respectively of the best fit line generated by least squares estimation used in linear regression. In order to obtain linear regression model, we collected data samples from five subjects. PTT and PWV are calculated for each subject. At last, these values are used for linear regression and the universal parameters for estimating the pulse pressure were obtained.

V. Experimental Results

The PWVs were used for generating the universal linear regression model. Each PWV is compared to the control measurement recorded for each trial to gain a reference for the linear regression model. The data was displayed as a scatter plot with the x-axis as PWV and y-axis as real pulse pressure to establish a line of best fit to formulate a linear equation [5]. This plot is shown in Fig.7. Pulse pressure should then follow the equation.

The universal equations we obtained were

$$PP = 0.16 * PWV + 31 \quad (5)$$

Here, unit of PWV is in meter per second.

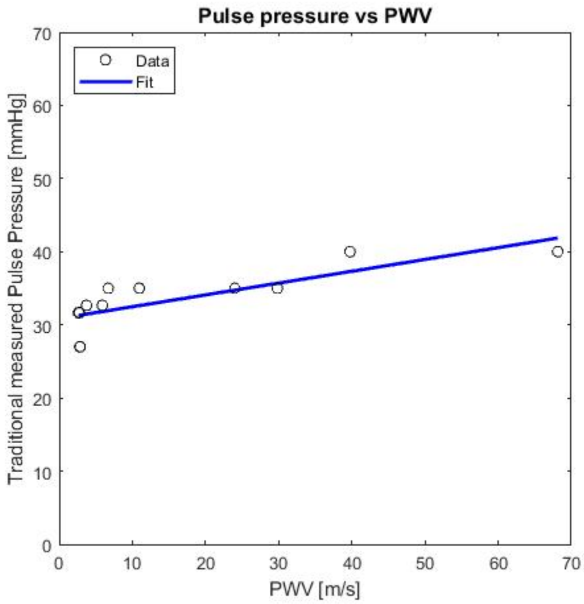

Figure.7 Universal Systolic Pulse Pressure using Linear Regression.

VI. CONCLUSION

In this paper a new method of non-invasive pulse pressure monitoring using Doppler radar and one contact sensor was proposed. PTT was measured from Doppler radar obtained heart beat and finger pulse measured using piezo-electric sensor. PWV correlation with pulse pressure was established, and pulse pressure was estimated with accuracy within 4 mmHg for five human subjects.

TABLE I. PRE-EXPERIMENT SBP AND DBP MEASUREMENT.

BP [mmHg]			
Subject	Measured SBP	Measured DBP	Pulse Pressure
Subject 1	109	71	38
Subject 2	95	67	28
Subject 3	112	79	33
Subject 4	112	80	32
Subject 5	128	99	29

TABLE II. PERCENT ERROR OF MEASURED AND ESTIMATED PULSE PRESSURE OF FIRST AND SECOND EXPERIMENTS.

Subject # - Experiment#	Measured PP [mmHg]	Estimated PP [mmHg]	Error [mmHg]
Subject 1-1	38	37.3600	0.6400
Subject 1-2	38	41.9029	3.9029
Subject 2-1	28	31.4582	3.4582
Subject 2-2	28	31.4496	3.4496
Subject 3-1	33	34.8400	1.8400
Subject 3-2	33	32.7519	0.2481
Subject 4-1	32	31.4236	0.5764
Subject 4-2	32	31.4437	0.5563
Subject 5-1	29	31.5976	2.5976
Subject 5-2	29	31.9433	2.9433

REFERENCES

[1] "Heart Disease Facts." cdc.gov. Center for Disease Control., 28 November 2017. Web 11 April 18.

[2] "Stroke Statistics" strokecenter.com. Stroke Center., n.d. Web. 11 April 2018.

[3] M. Domanski et al, "Cardiovascular risk assessment using pulse pressure in the First National Health and Nutrition Examination Survey (NHANES I)," NHANES I. Oct. 2001.

[4]

[5] Y. Zheng et al, "An Armband Wearable Device for Overnight and Cuff-Less Blood Pressure Measurement," IEEE Transactions on Biomedical Engineering, University of China. Vol. 61, No. 7, Jul. 2014.

[6] N. Kumar et al, "Cuff-less BP Measurement using a Correlation Study of Pulse Transient Time and Heart Rate," 2014 International Conference on Advances in Computing, Communications and Informatics (ICACCI), New Delhi, India. 14 Jul. 2014.

[7] C. Li, V. M. Lubecke, O. Boric-Lubecke and J. Lin, "A Review on Recent Advances in Doppler Radar Sensors for Noncontact Healthcare Monitoring," in IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 5, pp. 2046-2060, May 2013.

[8] T. Katsuura, S. Izumi, M. Yoshimoto, H. Kawaguchi, S. Yoshimoto and T. Sekitani, "Wearable pulse wave velocity sensor using flexible piezoelectric film array," 2017 IEEE Biomedical Circuits and Systems Conference (BioCAS), Turin, 2017, pp. 1-4.

[9] H. Zhao et al, " Non-contact Beat-to-beat Blood Pressure Measurement Using Continuous Wave Doppler Radar," 2018 International Microwave Symposium (IMS), Pennsylvania, USA. 10 Jun. 2018.

[10] M. Tang et al, " Noncontact Pulse Transit Time Measurement Using a Single-Frequency Continuous-Wave Radar," 2018 International Microwave Symposium (IMS), Pennsylvania, USA. 10 Jun. 2018.