Noninvasive Continuous Blood Pressure Monitoring Based on Wearable Radar Sensor with Preliminary Clinical Validation

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***Abstract*—This paper proposes a novel sensing system for noninvasive and continuous estimation of blood pressure (BP), which is based on a custom designed wearable 120 GHz Doppler radar sensor. With radar signals detected from brachial artery at the elbow, the moving trajectory of the pulses can be accurately demodulated with micrometer accuracy, and thus the reflective pulse transit time (RPTT) can be obtained for the prediction model to estimate blood pressure. Clinical trials have been launched with invasive blood pressure as reference. The experimental results show a great performance of the designed wearable radar sensor in the detection of weak pulse signatures. Compared to the ground truth of the invasive blood pressure, the estimated blood pressures by radar have mean errors below 3 mmHg for most subjects. The results reveal the possibility for the proposed radar-based BP estimation technique to be employed inside and outside the clinic, such as applications in the vast internet-of-things (IoT) and in-home health monitoring.**

***Keywords*—radar, millimeter wave, blood pressure, RPTT.**

I. Introduction

As an indicator of cardiovascular system function, blood pressure is one of the important physiological signatures to be measured in the clinic. The digital sphygmomanometer with upper arm cuff is now the most popular device for blood pressure monitoring. However, the cuff-style monitor is flawed, for it does not support a real-time continuous blood pressure detection, and its inflating process causes discomfort.

Sleeveless methods that use distal pulses, pulse transit time (PTT), and pulse wave velocity (PWV) to measure continuous blood pressure are increasingly being applied in home healthcare monitoring. Many studies believe that the PTT and PWV are potential substitutes for BP, because there is a short-term correlation between the three factors [1]-[2]. One of the most trending sleeveless BP measuring approach using distal pulses is based on Photoplethysmography (PPG) [2], which utilizes the change in light absorption to detect pulse volume change waveform, but the approach may be interfered by tattoos and sweats [3]. Approaches measuring BP with PTT and PWV are also popular, in which PTT are detected by a combination of electrocardiography (ECG) and PPG [4], accelerometer and PPG [5], and so on. However, multi-sensor for PTT and PWV detection is still inconvenient to wear, and the approaches mentioned above are all contact measurement. Radar based BP measuring approaches gradually draw attention [6]-[7] for its noncontact and high sensitivity, but improvements are to be made in accuracy and miniaturization. Clinical trials are rarely seen.

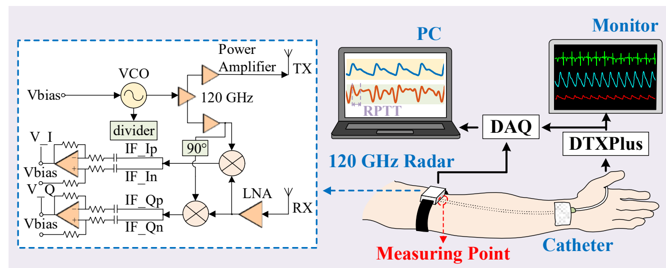

Fig. 1. Schematic diagram of the proposed blood pressure estimation technique in clinical trials. Inset: block diagram of the designed wearable radar sensor.

Therefore, a novel wearable radar sensing system for noninvasive and continuous estimation of blood pressure is proposed in this paper. With working frequency at 120 GHz, the custom designed interferometric radar sensor not only increases the detection precision, but also has a small size. Conveniently, the real-time continuous BP estimation is achieved by the use of RPTT that is contained in the distal pulses, requiring only one sensor. The proposed BP estimation technique have been preliminarily validated in clinical trials with the professional medical device of the invasive BP sensor as reference.

II. System and Theory

Fig. 1 shows the schematic diagram of the proposed blood pressure estimation technique in clinical trials. Patients keep their arms straight with palms facing upward, and a transducer set for medical invasive blood pressure measurement called DTXPlus is set up. DTXPlus has one end connected to a monitor, and the other end connected to the arterial catheter that reaches the brachial artery. The blood pressure signals for reference standard are collected by a data acquisition card (DAQ) from the transmission wire between DTXPlus and monitor. Meanwhile, the 120 GHz radar sensor with concentrated energy and high frequency is used to obtain the pulse wave signals from the brachial artery at the elbow, which is almost the same place detected by both invasive and noninvasive methods. The radar sensor continuously transmits electromagnetic signals to the human body, and the throb of the artery modulates the electromagnetic waves in the phase and the backscattered signals return to the radar receiver. For comparison later, the radar outputs are acquired by the DAQ in synchronization with the blood pressure signals.

With displacements of micrometer-level, the distal pulses are so weak to be accurately detected that it calls for high sensitivity which can be achieved with millimeter-wave frequencies. Therefore, the interferometric radar sensor system is custom designed to work at 120 GHz, whose wavelength is only 2.5 mm, so the sensor system is available to antennas-in-package (AiP), greatly reducing the system size. The block diagram inserted in Fig. 1 shows the composition of the 120 GHz radar sensor system, mainly including a radar front end and an intermediate frequency (IF) amplifier circuit. The radar front end is based on a radar transceiver TRX_120_001 from Silicon Radar GmbH, and the IF amplifier circuit is designed to increase the SNR level of the radar outputs.

The distal pulse is a low-frequency motion of less than 3 Hz that modulates the radar signal in phase. Therefore, accurate demodulation of the phase information is the essence to extract the pulse signal. The modified differential and cross multiply (MDACM) algorithm [8] is applied to linearly demodulate the phase information so as to extract the body motions in this paper. The relative displacement demodulated from the phase can be expressed in discrete form as

$$X[n] = \frac{\lambda}{4\pi}\sum_{k=2}^{n} I[k-1]\,Q[k] - I[k]Q[k-1]. \tag{1}$$

As long as the displacement of the body motion is obtained, the distal pulse waveform can be reconstructed. The pulse waveform is a combination of a forward wave and a reflected wave, and RPTT can be acquired by extracting the time interval of the first and the second peak in one cycle of the pulse signal. Since RPPT is found linearly related to PTT [9], BP can be estimated as follows, replacing PTT with RPTT.

Firstly by the Moens-Korteweg (MK) equation

$$PWV = \sqrt{\frac{Eh_0}{2\rho R_0}} \tag{2}$$

and Hughes equation

$$E = E_0 \exp(\xi P), \tag{3}$$

main blood pressure (MBP) can be obtained as [10]

$$MBP = MBP_0 + \frac{2}{\gamma}\ln\left(\frac{PTT_0}{PTT}\right), \tag{4}$$

where E is the elastic modulus, h_0 is the arterial thickness, R_0 is the arterial radius, ρ is the blood density, ξ is the arterial material coefficient, MBP_0 and PTT_0 is the average values of training set. As for γ, it is the key value to be obtained, so as to estimate the blood pressure of a certain person.

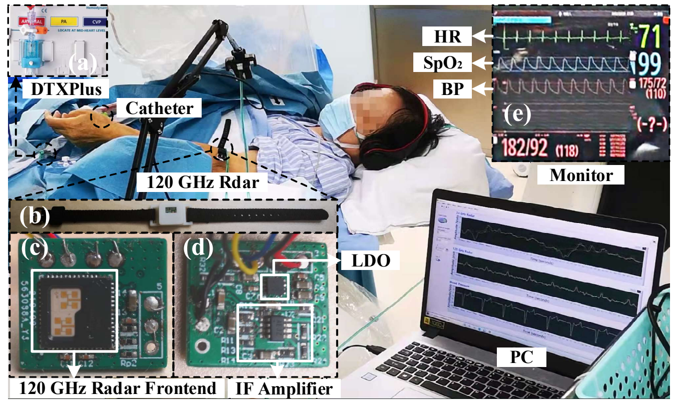

Fig. 2. Experimental setup: (a) the main pressure transducer of the DTXPlus; (b) outer packing of the 120 GHz radar sensor system; (c) top view of the radar; (d) bottom view of the radar; (e) the simultaneous monitor screenshot.

Then from the Bramwell-Hill equation

$$PWV = \sqrt{\frac{V \cdot \Delta P}{\rho \cdot \Delta V}}, \tag{5}$$

pulse pressure (PP) can be obtained as

$$PP = PP_0 \cdot \left(\frac{PTT_0}{PTT}\right)^2, \tag{6}$$

where ΔP is equal to PP and PP_0 is also the average values of training set.

Finally, according to

$$MBP = \frac{1}{3}SBP + \frac{2}{3}DBP, \tag{7}$$

$$PP = SBP - DBP, \tag{8}$$

systolic blood pressure (SBP) and diastolic blood pressure (DBP) can be expressed as

$$DBP = \frac{1}{3}SBP_0 + \frac{2}{3}DBP_0 + \frac{2}{\gamma}\ln\left(\frac{PTT_0}{PTT}\right) - \frac{SBP_0 - DBP_0}{3}\left(\frac{PTT_0}{PTT}\right)^2, \tag{9}$$

$$SBP = DBP + (SBP_0 - DBP_0)\left(\frac{PTT_0}{PTT}\right)^2, \tag{10}$$

where SBP_0 and DBP_0 are the average values of training set.

III. Experiment and Results

Experiments were carried out in the operating room with permission, patients with cardiovascular diseases were tested for several minutes after operations. Fig.2 shows the experimental set up, in which the invasive system DTXPlus and the arterial catheter were already set by surgeons for intraoperative observation, and the 120 GHz radar was placed at the patient's elbow. The radar signals and pressure signals were collected for about 2 minutes in every trial. Fig. 2 (a) is a

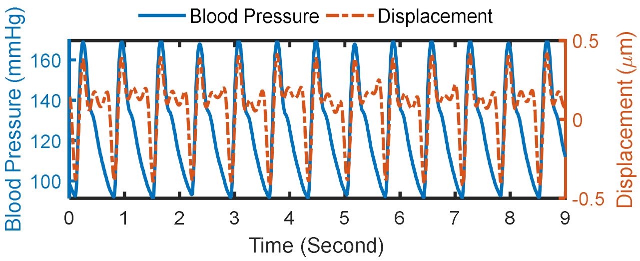

Fig. 3. Blood pressure waveform and pulse waveform of the brachial artery.

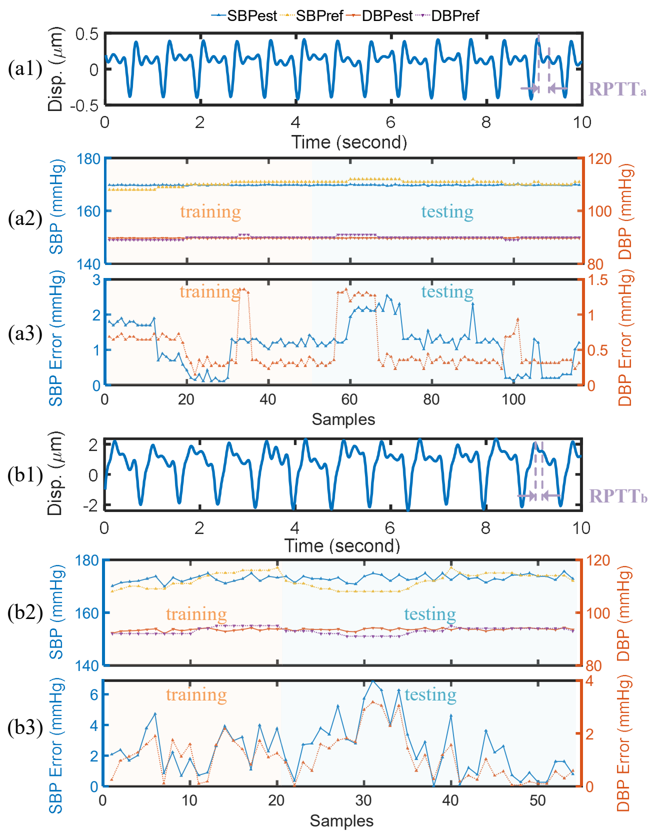

Fig. 4. The estimated and reference blood pressure of two patients: (a) small fluctuation; (b) large fluctuation.

supplementary picture of the DTXPlus, which is the main component as a pressure transducer. The radar sensor system is designed to be a highly compact 4 layer PCB with a size of 15.24 mm × 17.043 mm × 1.6 mm, whose radar front end is designed on the top side of the PCB as shown in Fig. 2 (c) while the voltage input and IF amplifier circuit are on the bottom side as shown in Fig. 2 (d). The whole radar system is packaged by a small 3D printed box for easy wearing as shown in Fig. 2 (b). Fig, 2 (e) shows the monitor screen connected to DTXPlus, simultaneously displaying heart rate (HR), peripheral oxygen saturation (SpO2), and BP.

Fig. 3 shows the blood pressure waveform that is obtained by integrating the signals collected form DTXPlus output for reference, and the demodulated radar signal that represents the brachial artery pulse waveform. The result demonstrates the same amplitude trend and period of the two waveforms, indirectly showing the high accuracy of the radar system.

Table 1. Experimental results of 7 subjects.

Subject	SBP (mmHg)			DBP (mmHg)		
	reference	estimation	mean error	reference	estimation	mean error
1	120.4 ± 1.2	120.2 ± 0.1	0.9	65.6 ± 0.9	65.3 ± 0.1	0.7
2	141.0 ± 1.6	140.2 ± 0.3	1.5	81.3 ± 2.0	80.5 ± 0.6	1.8
3	152.0 ± 2.0	150.4 ± 0.3	2.1	53.9 ± 1.0	53.2 ± 0.5	1.0
4	151.2 ± 2.0	153.4 ± 0.3	2.8	65.6 ± 1.8	67.2 ± 0.2	2.2
5	170.5 ± 1.1	169.8 ± 0.1	1.1	89.9 ± 0.6	89.7 ± 0.1	0.5
6	172.0 ± 2.9	173.0 ± 1.3	2.5	93.1 ± 1.3	93.6 ± 0.5	1.1
7	176.1 ± 1.1	175.6 ± 0.1	0.9	73.1 ± 1.0	72.3 ± 0.1	1.0

Since each pulse corresponds to a RPTT, SBP, and DBP, the real-time continuous BP estimation can be achieved by acquiring every RPTT of pulse waveforms and converting them to SBP and DBP through prediction model. Fig. 4 (a) shows an example that the RPTT, reference SBP and DBP of the first 50 pulses were taken as a training set for linear fitting, thus obtaining γ value for the testing set of the rest 66 pulses to estimate BP. Fig. 4 (a1) is a 10-second segment from the pulse waveform, from which RPTT can be extracted. Fig. 4 (a2) shows a comparison of the reference and estimated BP values, and the corresponding errors are shown in Fig. 4 (a3). The testing errors are larger than those in the training set, but all the errors are below 2.6 mmHg. Fig. 4 (a) are results of a patient who has a small blood pressure fluctuation less than 4 mmHg. Errors of those who have larger blood pressure fluctuation will increase as shown in Fig. 4 (b), however, the mean errors are still below 3 mmHg. Experimental results of 7 subjects are selected for display in Table 1.

IV. Conclusion

In this paper, a noninvasive and continuous blood pressure estimation technique based on a novel 120 GHz miniaturized radar is proposed. RPTT can be extracted from the linearly demodulated radar signals to estimate blood pressure through prediction model. Clinical experimental results illustrate a great performance of the sensor system in vital sign detection, and the estimated BP have low errors compared to the reference values. Since the technique applies to various body regions that have a strong pulse, it is possible for the sensing system to be integrated into different forms for applications inside and outside the clinic.

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