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Single-Channel Impedance Plethysmography Neck Patch Device for Unobtrusive Wearable Cardiovascular Monitoring

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ABSTRACT **Background:** Wearable and unobtrusive sensing devices are rapidly evolving for long-term cardiovascular monitoring. However, most of the cardiovascular device requires multi-channel physiological signals acquisition, especially in continuous blood pressure (BP) measurement using pulse transition time (PTT) based methods. The multi-devices implementation could impede wearable applications. **Objective:** This study developed a wearable neck patch device using single-channel impedance plethysmography (IPG) sensing for cardiovascular monitoring, including continuous BP and heart rate (HR) measurement. **Methods:** IPG-based BP model was derived based on the Bramwell-Hill equation. A patch IPG device was designed and installed above the carotid artery of the subject neck. To validate the BP and HR functions of our device, the Bland-Altman plots were performed to evaluate the estimation error between the reference and the proposed devices within 20 healthy subjects. **Results:** The BP performance indicates that systolic BP (SBP) estimation error was -0.16 ± 2.97 mmHg and 2.43 ± 1.71 mmHg in terms of mean error (ME) and mean absolute error (MAE), and 0.09 ± 3.30 mmHg and 2.83 ± 1.68 mmHg for diastolic BP (DBP) estimation. Moreover, the HR accuracy has the ME and MAE of 0.02 ± 0.17 bpm and 0.14 ± 0.08 bpm; mean percentage error (MPE) and mean absolute percentage error (MAPE) obtained 0.04 ± 0.23 % and 0.19 ± 0.12 %. Based on statistical results, the BP and HR function of our device satisfied with AAMI/ANSI criteria below 5 ± 8 mmHg and ± 5 bpm or ± 10%. **Conclusion:** This study implemented a wearable neck patch device with single-channel IPG acquisition that provided two significant cardiovascular parameters of continuous BP and HR, and its performance agreed with standard criteria based on validation with reference sensors. **Significance:** The proposed proof-of-concept IPG neck patch device has a high potential for wearable applications and low-cost manufacturing in cardiovascular monitoring.

INDEX TERMS Cardiovascular monitoring, impedance plethysmography, and neck patch device

I. INTRODUCTION

Cardiovascular diseases (CVDs) are a category of a symptom that involves heart and blood vessel functions. According to the World Health Organization (WHO) statistics, CVDs are the main cause of death, which takes an estimated 17.9 million lives per year. CVDs are categorized as a chronic disease such as hypertension and arrhythmia that requires long-term observation for cardiovascular functions. The wearable device with unobtrusive measurement can allow prolonged monitoring and avoid discomfort to achieve long-term cardiovascular monitoring. Recently, many studies proposed different wearable technologies to monitor vital cardiovascular parameters such as continuous BP and HR, including wrist, chest, and ear-worn, and neck patch devices, as shown in **Fig. 1**. Wang *et al.* [1] demonstrated a wrist-worn piezoelectric system for beat-to-beat BP monitoring. A piezoelectric sensor was placed above the

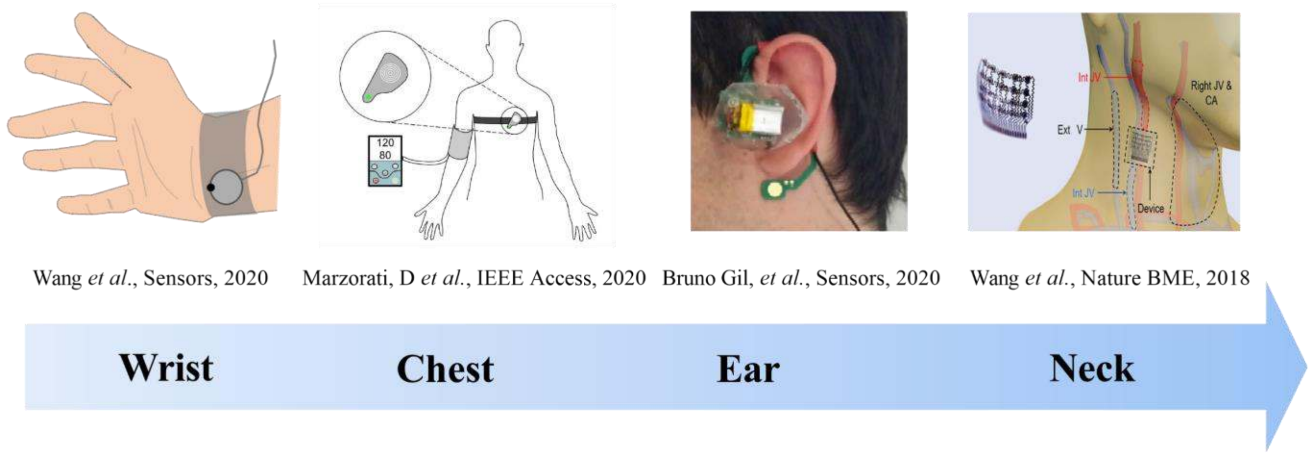

FIGURE 1. Previous work for the wearable cardiovascular devices, including wrist, chest, ear, and neck worn devices [1]-[4].

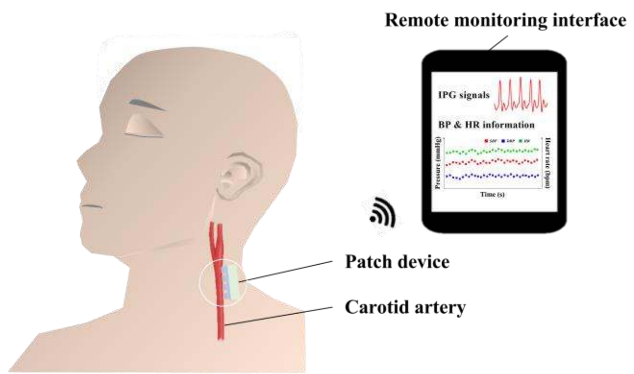

FIGURE 2. The continuous BP and HR can be extracted from the carotid artery using a single-channel IPG patch device.

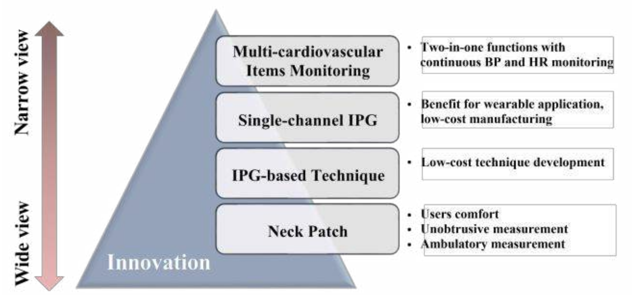

FIGURE 3. Innovation for our proposed device has some advantages, including a small neck patch implementation for users comfort, IPG technique development for low-cost manufacturing, single-channel physiological measurement for wearable application, and multi-cardiovascular items monitoring.

radial artery of the wrist to measure the pressure pulse wave (PPW) and the beat-to-beat systolic BP (SBP) and diastolic BP (DBP) change were extracted by feature points in PPW. Davide Marzorati *et al.* [2] developed a chest wearable apparatus for continuous BP measurement. The photoplethysmography (PPG) and phonocardiogram (PCG) sensors were implemented and installed on the chest belt. The pulse transition time (PTT) was obtained by PPG and PCG sensors in two measurement sites. PTT has a high correlation with BP that reveals the arterial compliance, according to the Moens-Korteweg (M-K) model. Bruno Gil *et al.* [3] presented an ear-worn device to measure HR and sweat parameters using ECG bipolar sensor around both ears and impedance sensors. Wang *et al.* [4] designed a wearable ultrasound patch to measure PPW signals from the carotid artery.

Despite significant progress in wearable cardiovascular systems, multiple channel physiological measurement that impede extensive application. For example, the PTT-based BP monitoring must rely on two-channel physiological signals acquisition such as a combination of ECG and PPG devices [5] or double PPG sensors [6]. Fatemehsadat Tabei *et al.* [7] utilized two-channel PPG signal measurements from the subject's index fingers to calculate PTT for BP estimation. However, the multi-devices that could cause device complexity and inconvenience in wearable applications.

To this end, this study aims to develop a cardiovascular neck patch device using single-channel impedance plethysmography (IPG) measurement. Compared to multi-IPG sensors for PTT-based BP monitoring [8], the proposed IPG device with one-channel physiological measurement can extract the vital cardiovascular parameters from the carotid artery, including continuous BP and HR. The remote monitoring interface was implemented on a computer and receives the BP and HR data via a wireless function, as shown in **Fig. 2**. The innovation of this study is to develop a single-channel IPG neck patch device for two-in-one cardiovascular monitoring with significant advantages, including a neck-worn device for unobtrusive measurement, low-cost manufacturing by IPG technique, and wearable application by single-channel physiological measurement, as shown in **Fig. 3**.

The rest of this paper is organized as follows. Section II introduces the IPG based BP model, sensing device design, and experiment protocol and validation method. In Section

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III, the experiment results for BP feature points extraction and the accuracy of BP and HR are presented. In Section IV and V, the discussions and conclusion of this study are drawn.

II. METHODS

The IPG-based BP model demonstrated the relationship between impedance and arterial pressure. A sensing device was implemented to validate the proposed model. For further validating the cardiovascular functions (BP and HR) of our device, this study proposed the validation protocol using reference devices to evaluate the physiological measurement accuracy of our proposed device.

A. IPG BASED BP ESTIMATION MODEL

The IPG measurement is a non-invasive sensing technique that was commonly applied in medical diagnoses to depict the impedance characteristics of the artery induced by small changes in the arterial blood volume during the systolic and diastolic phases. Nyboer *et al.* [9] first introduced the bio-impedance method as an alternative to invasive procedures to assess peripheral vascular function. The changes in the blood flow in extremities were detected by non-invasive IPG technique.

The impedance of carotid artery Z(t) can be detected under continuous alternating current excitation, according to ohm's raw as (1), (2), and **Fig. 4(a)**. Where L, A, and σ represent the length of the measured segment, arterial cross-sectional area, and blood conductivity. In (2) is based on three assumptions: the arterial pulsation is uniform, blood conductivity is consistent during measurement, and the electrical current pass through the arterial in parallel [10].

$$Z(f)=\frac{V(f)}{I(f)} \tag{1}$$

$$A=\frac{L}{\sigma Z} \tag{2}$$

The arterial impedance response can be characterized by the cross-sectional area changes [11], [12], according to (3). Where L, Z_0, σ, dA, and dZ represent the length of the measured segment, the original impedance of the segment, blood conductivity, changes in arterial cross-sectional area, and impedance.

$$dA=-L\frac{dZ}{\sigma Z_0^2} \tag{3}$$

The impedance of the total segment (Z) can be regarded as the parallel model of the artery, including original impedance (Z_0) and the impedance induced by blood volume change (Z_b). The effective parallel impedance model can be expressed as **Fig. 4(b)** and (4), where Z_0 and Z_b were attributed to the original arterial cross-sectional area (A_0) and change in the cross-sectional arterial area (dA).

$$1/Z(t)=1/Z_0+1/Z_b \tag{4}$$

Equation (5) can be acquired from (3) and (4) by assuming $1/Z_b$ is much smaller than $1/Z_0$.

$$dA=-L\frac{dZ}{\sigma Z^2} \tag{5}$$

The BP has a high correlation with the pulse transition time (PTT) and cross-sectional arterial area, according to the Bramwell-Hill equation (6). Where dP, ρ, D, A, and dA represent the change in arterial pressure, blood density, the distance between two measurement sites of the artery, arterial cross-sectional area, and change in arterial cross-sectional area.

$$dP=\rho\left(\frac{D}{PTT}\right)^2\frac{dA}{A} \tag{6}$$

To further explore the relationship between the arterial impedance and BP, (7) can be obtained from (2), (5), and (6).

$$dP=-\rho\left(\frac{D}{PTT}\right)^2\cdot\frac{dZ}{Z} \tag{7}$$

In this study, the blood density ρ and PTT were represented by an arterial coefficient of K_1, whose magnitude depended on the physiological conditions of the individual participant. Performing integrating dP and dZ in (7), the beat-to-beat SBP and DBP can be expressed in terms of arterial impedance as (8). Where K_2 is a constant of integration.

$$\begin{aligned} SBP(t)&=K_1\cdot\ln|Z_{SBP}(t)|+K_2\\ DBP(t)&=K_1\cdot\ln|Z_{DBP}(t)|+K_2 \end{aligned} \tag{8}$$

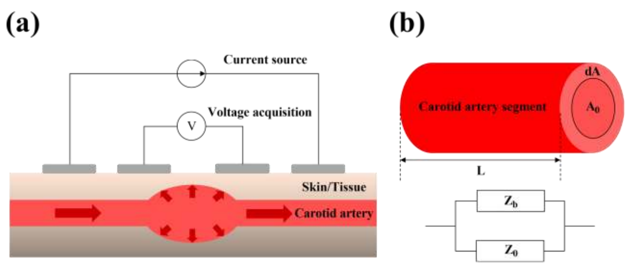

FIGURE 4. IPG electrodes were placed above the carotid artery and continuously measure electrical signals under continuous alternating current excitation.

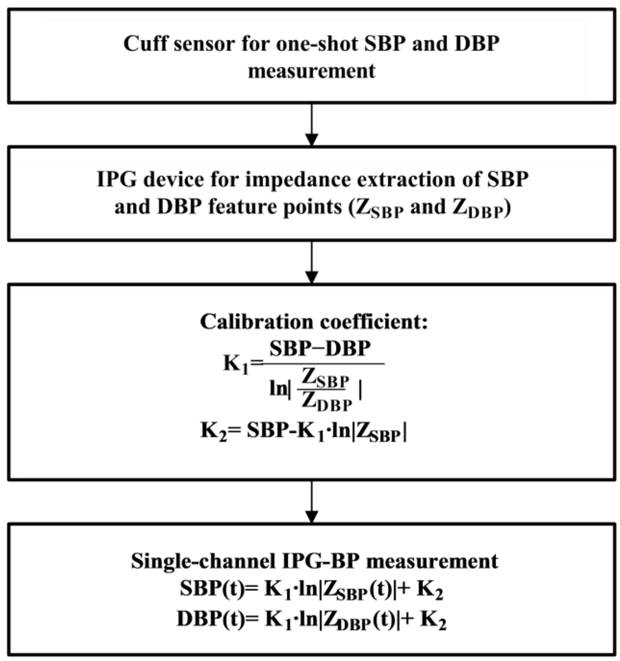

FIGURE 5. Personal IPG-BP model establishment by one-step calibration between the cuff sensor and proposed device for the calibration coefficient of K_1 and K_2.

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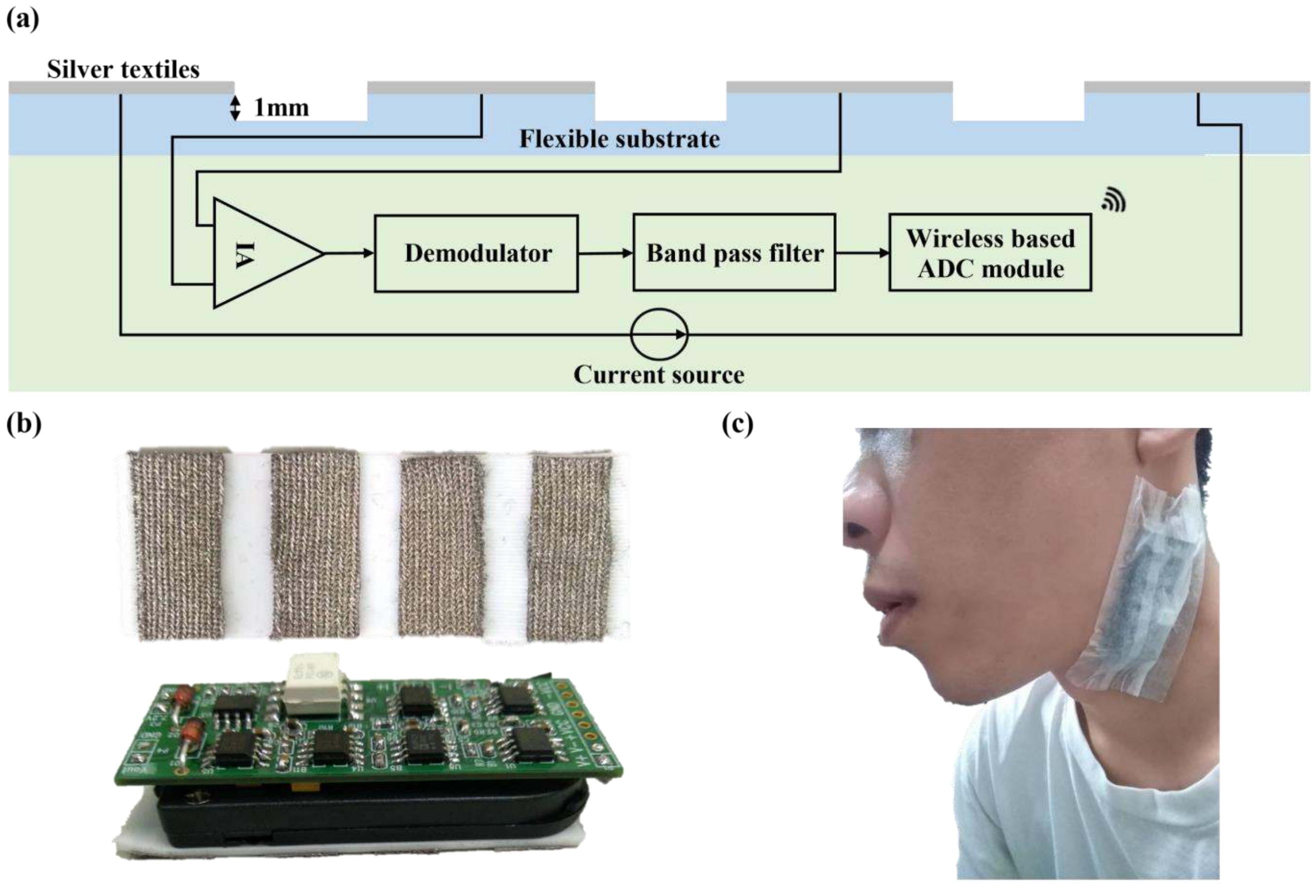

FIGURE 6. **(a) The proposed neck patch device consists of silver textile electrodes, flexible substrate, instrumentation amplifier (IA), demodulation circuit, band pass filter, and wireless-based ADC module. (b) The graphical representation of the IPG neck patch device in top-view and side-view. (c) The proposed device was mounted on the subject's neck by a tape.**

The K_1 and K_2 can be considered as calibration coefficients, which depended on each subject. The calibration coefficients can be obtained by one-step calibration between the proposed device and digital electronic sphygmomanometer, as shown in **Fig. 5**. The synchronous measurement for IPG device and cuff sensor was conducted for one-pair cuff BP (SBP, DBP) and corresponding impedance (Z_{SBP}, Z_{DBP}) extraction. The calibration coefficients in terms of K_1 and K_2 can be calculated, according to (8). Thus, the individual BP formula can be obtained by one-step calibration.

B. SENSING DEVICE

The proposed neck IPG system consists of flexible electrodes, a flexible substrate, current source, instrumentation amplifier, demodulation circuit, band pass filter, and wireless analog-to-digital converter (ADC) acquisition system (**Fig. 6**.) The proposed device is powered with $+6V_{DC}$ by one-pair button battery in combination with a DC/DC converter of ICL7660 (RENESAS Electronics Inc., Koto-ku, Tokyo, Japan). The power consumption of the device is 0.51W.

Two pairs of dry contact silver-plated polyester textile with low surface resistivity (< 0.05 Ω/inch^2) were used for current excitation and voltage sensing electrodes. In this research, each electrode dimension is 20 mm × 9 mm with a thickness of 0.3 mm. The arrangement of electrodes was isometric distribution with an interval of 5 mm. The electrodes were mounted on a flexible thin substrate. The substrate made of silicone could be flexible and bendable in both curvatures and directions. Moreover, the substrate with the step structure height of 1 mm was designed for eliminating the air gap between the skin and electrode sensing surface during the measurement and obtaining better measurement stability.

The combination of the Wien bridge oscillator and improved Howland current source was implemented as a current source. The Wien-bridge oscillator was used to produce sine waves with 50 kHz. The high-frequency sine wave was as an input of the improved Howland current pump that generated a consistent current with an amplitude of 140 μA (< 1 mA), which allows safety guidelines in the human body [13]. A low-noise and high-speed instrumentation amplifier IC of AD8421 (Analog Devices Inc., Norwood, MA, USA) with a high common-mode rejection ratio (CMRR) of 110 dB and a gain of 1000 at 50 kHz was implemented to amplify the small impedance change of the carotid artery. To

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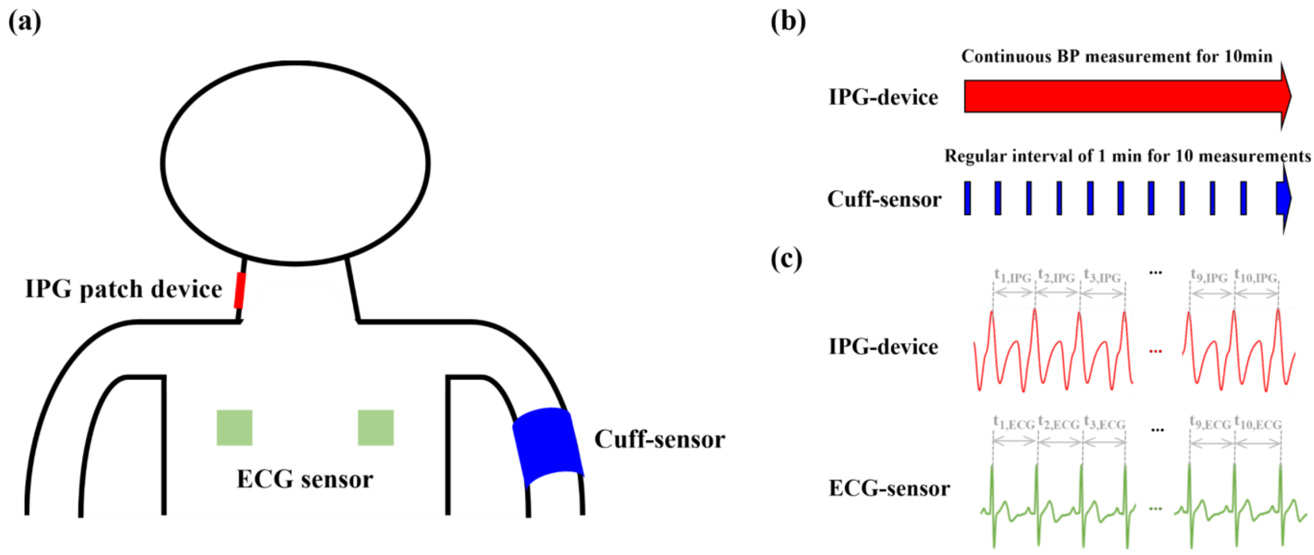

FIGURE 7. **Measurement locations arrangement for reference sensors (cuff-sensor and ECG sensor) and proposed device to perform synchronous BP and HR monitoring. (b) BP accuracy evaluation was performed by the synchronous measurement for IPG device and cuff-based sensor, obtaining 10 pairs of BP data from both devices for each subject. (c) HR accuracy calculation between IPG device and ECG sensor from an average 10 pulse interval.**

remove the 50 kHz carrier signal and interfering noise, the demodulator of AD8310 (Analog Devices Inc., Norwood, MA, USA) was utilized for envelope waveform extraction. The envelope signals variation was induced by the pulsatile blood volume during the systolic and diastolic phases. To satisfy the pulse-rate range (0.67 to 3.33 Hz) and suppress the DC components, the second-order Butterworth band pass filter was implemented with bandwidth from 0.3 Hz to 5 Hz. The filtered analog IPG signal was transmitted to a wireless ADC acquisition system based on the wireless module of HC-05. A customer-based software of LabVIEW was performed for further signal conditioning.

Figure 6(a) shows the designed hardware for the IPG patch device. The device was implemented on printed circuit boards (PCB) with geometric dimensions of 2 cm × 5.5 cm, as shown in **Fig. 6(b)**. The patch device was installed above the subject's carotid artery by tape, as shown in **Fig. 6(c)**.

C. EXPERIMENT PROTOCOL AND VALIDATION

The experiment was permitted by the Institutional Review Board of National Chiao Tung University (NCTU-REC-109-012E). A total of 20 young healthy subjects (12 males and 8 females) participated in the experiment, with the age of 22.20 ± 1.61 years, the height of 170.85 ± 7.45 cm, the weight of 65.55 ± 16.93 kg. During the experiment, all subjects agreed to engage were instructed to remain in a sitting position.

To evaluate the BP and HR accuracy for the proposed patch device, the reference devices were installed for synchronous measurement, including the cuff-based sensor and ECG system, as shown in **Fig 7(a)**. We evaluated the accuracy of BP and HR between the proposed device and reference sensors by statistical results in terms of the mean error (ME), mean percentage error (MPE), mean absolute error (MAE), and mean absolute percentage error (MAPE) as the evaluation metrics.

(1) BP ACCURACY EVALUATION

The digital electronic sphygmomanometer (HEM-1000, OMRON) was used as the golden reference for BP measurement. By performing a one-step calibration, the calibration coefficients and individual IPG-BP estimation model was obtained. The BP accuracy evaluation for each subject was performed by the synchronous measurement for IPG device and cuff-based sensor, as shown in **Fig 7(b)**. Each measurement was conducted for 30 s and then rest for 30 s to allow the arteries to recover after the cuff sensor measurements. The measurement trial was performed by 10 times, obtaining 400 measurement data for SBP and DBP within 20 subjects.

(2) HR ACCURACY EVALUATION

ECG commercial module AD8323 (Analog Devices Inc., Norwood, MA, USA) and proposed IPG device conducted synchronous measurement to assess the HR accuracy, as shown in **Fig. 7(c)**. The 10 intervals within 11 beats were measured from the IPG patch device and commercial ECG sensor (reference method) to calculate the average beat per minute (bpm), according to (9). The beat rhythm of ECG and IPG signals were detected by R-peaks in ECG and maximum points.

$$\text{Average HR}=\frac{1}{10}\sum_{i=1}^{10}\frac{60}{t_i} \tag{9}$$

III. RESULTS

A. SBP AND DBP FEATURE POINTS EXTRACTION

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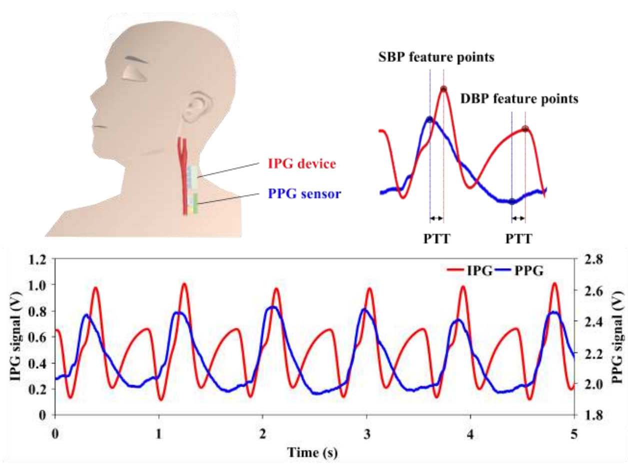

FIGURE 8. **Synchronous physiological sensing between PPG sensor (reference) and IPG device for SBP and DBP feature points definition.**

To extract SBP and DBP features points in measured IPG signals from the patch device, the synchronous IPG and PPG measurement was performed due to well-known SBP and DBP feature points at the maximum and minimum value of PPG waveform (**Fig. 8**). A commercial PPG sensor (DFEROBOT, Shanghai) was installed below the IPG patch device with a distance of 3.7 cm. The IPG signal lags behind the PPG signals due to different measurement locations of the sensor in the artery of the subject's neck. Since the same reference of heart, the IPG device took the more distant path through the carotid artery than the PPG sensor. Both of physiological signals obtained PTT of 8 ms, resulting in a reasonable PWV of 4.6 m/s, according to (10). The SBP and DBP feature points in IPG signals can be defined by eliminating the PTT effect within both of signals.

$$\mathrm{PWV} = \frac{\mathrm{Distance}}{\mathrm{PTT}} \tag{10}$$

B. BP ACCURACY EVALUATION

The calibration coefficients of K_1 and K_2 in (8) were acquired by one-step calibration between digital electronic sphygmomanometer and IPG patch device. The accuracy of the individual BP formula was examined by synchronous BP measurement between the cuff sensor (gold standard) and the IPG device. The box plots analysis presents the distribution of the measured BP (the maximum, 75th percentile, median, 25th percentile, and minimum values) by the cuff and IPG sensors, as shown in **Fig. 9(a),(b)**. The mean SBP from cuff and IPG sensors were respectively 118.76 ± 6.98 mmHg (range: 103 – 139 mmHg) and 118.60 ± 7.93 mmHg (range: 100.79 – 142.66 mmHg); 60.52 ± 5.37 mmHg (range: 45 – 75 mmHg) and 60.60 ± 6.58 (range: 42.78 – 79.25 mmHg) for DBP. The scatter plot shows that BP measurement using the cuff sensor and IPG device has a high correlation, as shown in **Fig. 9(c),(d)**. Pearson's correlation coefficients of SBP and DBP were 0.93 and 0.87 for 20 subjects.

The difference in measured BP between digital electronic sphygmomanometer and IPG devices was evaluated by Bland-Altman plots, as shown in **Fig. 10**. The limits of agreement of ±1.96SD represent the 95% confidence interval. The SBP estimation error indicated that the ME was -0.16 ± 2.97 mmHg with MPE of -0.15 ± 2.52 %; the MAE was 2.43 ± 1.71 mmHg with MAPE of 2.05 ± 1.46 %. The DBP estimation error in terms of ME, MPE, MAE, and MAPE were 0.09 ± 3.30 mmHg, 0.09 ± 5.52 %, 2.83 ± 1.68 mmHg, 4.71 ± 2.85 %, respectively. The BP accuracy was satisfied with the Association for the Advancement of Medical Instrumentation (AAMI) standard criteria of MAE less than 5 ± 8 mmHg.

C. HR ACCURACY EVALUATION

The synchronous measurement of IPG and ECG recording was conducted to evaluate the HR accuracy, as shown in **Fig. 11(a).** The 10 intervals within 11 beats were measured from the IPG patch device and commercial ECG sensor (reference method) to calculate the average beat per minute (bpm), according to (9). The box plots analysis shows that the mean heartbeat from ECG and IPG sensors were respectively 73.00 ± 8.05 bpm (range: 59.61 – 85.36 bpm) and 73.02 ± 7.96 bpm (range: 59.66 – 85.24 bpm), as shown in **Fig. 11(b)**. The scatter plot demonstrates the strong correlation between HR monitoring using IPG patch device and ECG sensors with Pearson's correlation coefficients of 0.99 for 20 subjects, as shown in **Fig. 11(c)**.

The Bland-Altman plots were analyzed to compare the measured HR difference between ECG sensor and IPG devices, as shown in **Fig. 12**. The HR accuracy by the proposed device against reference measurement by ECG sensor performed the low estimation error with 0.02 ± 0.17 bpm for ME, 0.04 ± 0.23 % for MPE, 0.14 ± 0.08 bpm for MAE, and 0.19 ± 0.12 % for MAPE. The HR performance agreed with the American National Standards Institute (ANSI)/AAMI EC13:200 standards with an estimation error of ± 5 bpm or ±10%, whichever is greater [14].

IV. DISCUSSIONS

A. INNOVATION FOR CARDIOVASCULAR NECK PATCH

The novelty of this study is to implement a neck patch IPG device with a single physiological measurement to realize cardiovascular monitoring, including continuous BP and HR. Compared to previous studies of PTT-based and IPG sensors, our proposed device provided two important cardiovascular monitoring functions (BP and HR) using a single-channel physiological measurement. The combination of patch form and single-channel IPG measurement is beneficial for unobtrusive measurement and wearable application.

The physiological measurement location of the carotid artery was selected due to strong arterial pulsation and site near the heart. The carotid artery with palpable arterial pulsation is the most adjacent to the arch of the aorta that provides clear pulse waveforms [15]. The strong arterial

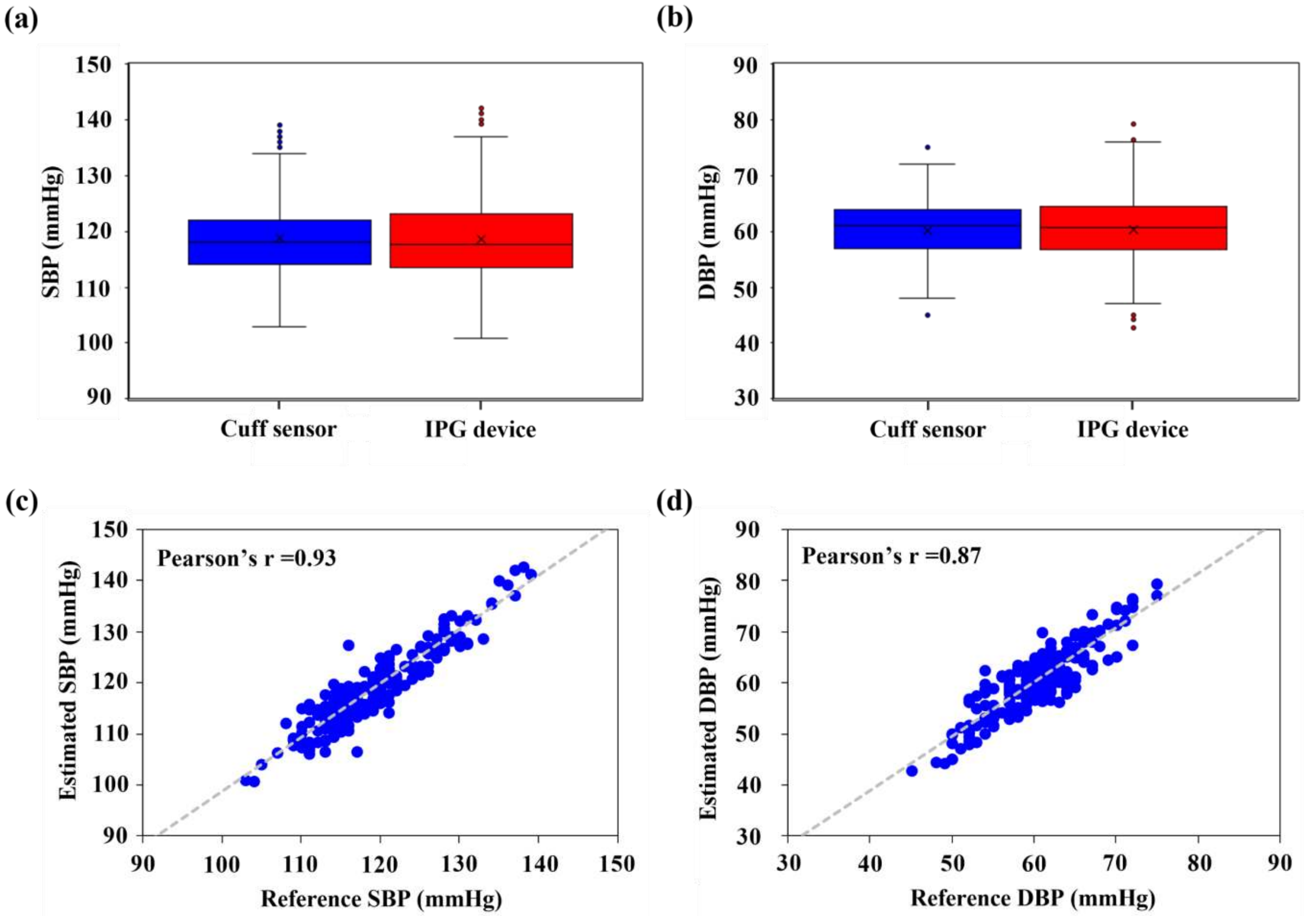

FIGURE 9. Boxplots for (a) SBP and (b) DBP distribution from cuff-sensor (reference) and proposed sensor. Scatter plots between reference BP by cuff-sensor and estimated BP by the proposed device in (c) and (d) for SBP and DBP.

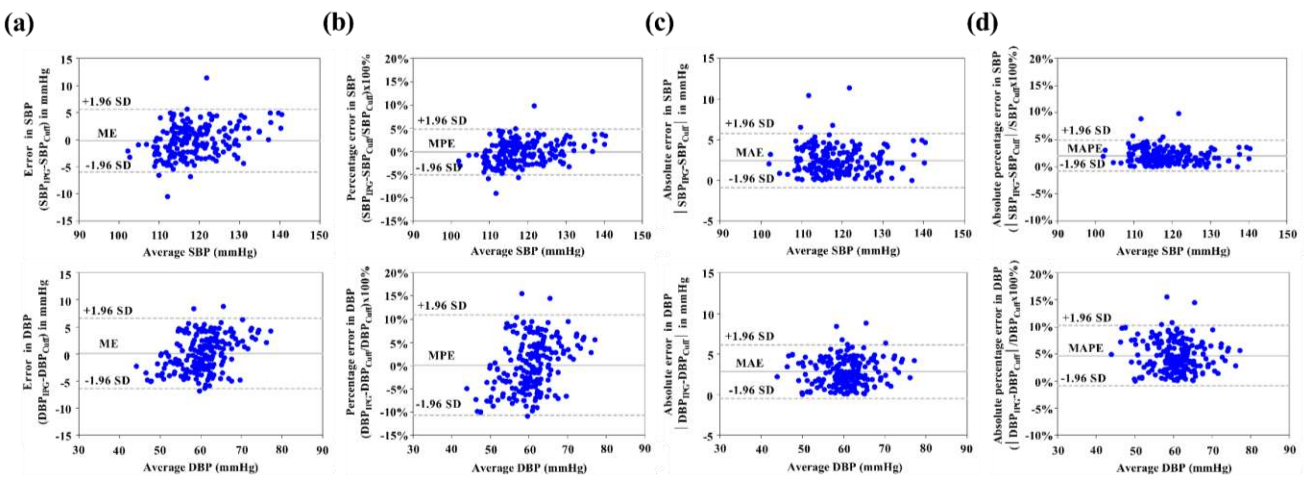

FIGURE 10. Bland-Altman plots analysis for BP measurement difference between the reference sensor and proposed device in terms of (a) ME, (b) MPE, (c) MAE, and (d) MAPE for SBP and DBP estimation error. The solid and dash lines represent the mean and 95% limits of agreement (±1.96 SD).

pulsation induced large changes in arterial blood volume tends to easily extract the obvious impedance characteristics by IPG device during the systolic and diastolic phases. Also, the carotid measurement site can reflect the truer load imposed on the artery than branchial and radial arteries as a longer path with much arterial branch could induce higher SBP and lower DBP, resulting in the serious BP distortion [16]. Based on the above two significant considerations, a neck patch device was

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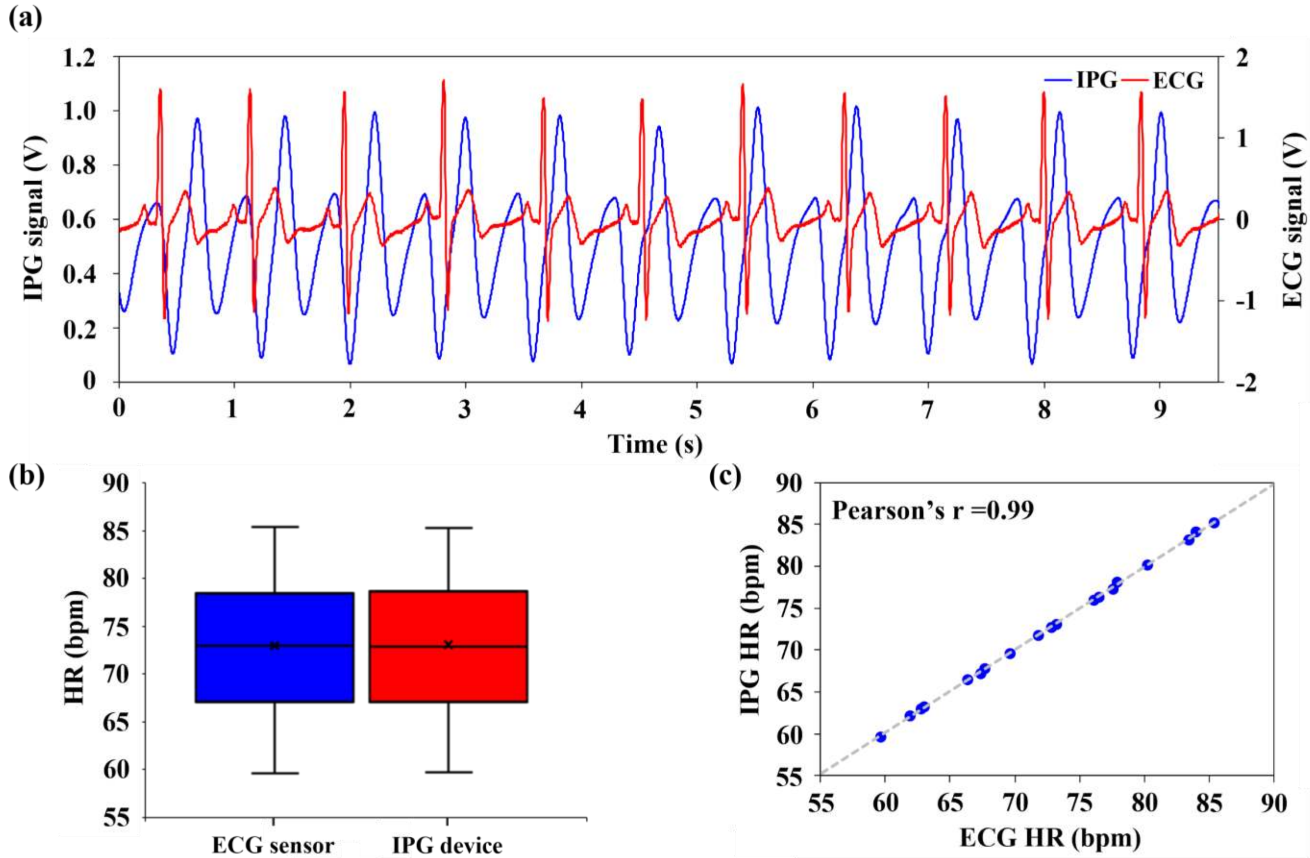

FIGURE 11. (a) ECG and IPG devices conducted synchronous physiological measurements for 11 beats. (b) Boxplot analysis for demonstrating HR distribution from ECG sensor and IPG device within 20 subjects. (c) Scatter plots show that the measured HR correlation between the reference sensor and the proposed device.

designed for high-fidelity cardiovascular monitoring. Furthermore, the configuration design of the neck patch can make users comfort and unobtrusive measurement.

To reduce the device complexity for wearable application and low-cost manufacturing in the cardiovascular sensor, the single-channel IPG function was established for continuous BP and HR monitoring. An IPG-based BP estimation model was provided in this study based on the Bramwell-Hill BP equation and impedance characteristic in the artery. Furthermore, the one-step calibration algorithm was applied in continuous BP monitoring that could reduce measurement procedure from laborious inflation and deflation of cuff sensor. Compared to PTT-based methods for cuffless BP estimation [2], [7], [17], this study relies on a single-channel physiological measurement without bulky system and measurement preparation. Most of all, the proposed device provided two significant cardiovascular monitoring functions (BP and HR) using a single sensor. Therefore, this study provided a neck patch with a single-channel IPG sensing function that is suitable for wearable, long-term, and low-cost cardiovascular monitoring.

B. IMPLEMENTATION AND VALIDATION

The cardiovascular patch device was implemented with a dimension of 2 cm × 5.5 cm, including electrodes, the flexible substrate, current source, and analog frond-end. The device with wireless function is flat battery powered. The dry contact-based electrode of silver-plated polyester was used for IPG excitation and sensing electrodes. Moreover, the conductive textile with a soft characteristic can make the users comfortable to prolong the measurement time. The stretched substrate below the electrode made of silicone could be bendable in both directions during the measurement. The substrate surface with the step structure was designed for improving the electrical interface between electrodes and skin.

To validate the performance of our cardiovascular patch device, the golden benchmark of a digital electronic sphygmomanometer and ECG sensor were used as the references for BP and HR accuracy assessment. Twenty healthy subjects (12 males and 8 females) with a mean age of 22.20 ± 1.61 were recruited in the experiment. The performance of our device was evaluated in terms of ME, MAE, MPE, and MAPE as metrics.

In BP measurement, the beat-to-beat BP values can be obtained by conversion from impedance signal to arterial pressure, according to the proposed IPG-BP model as (8). To validate the BP accuracy, the cuff sensor (golden benchmark)

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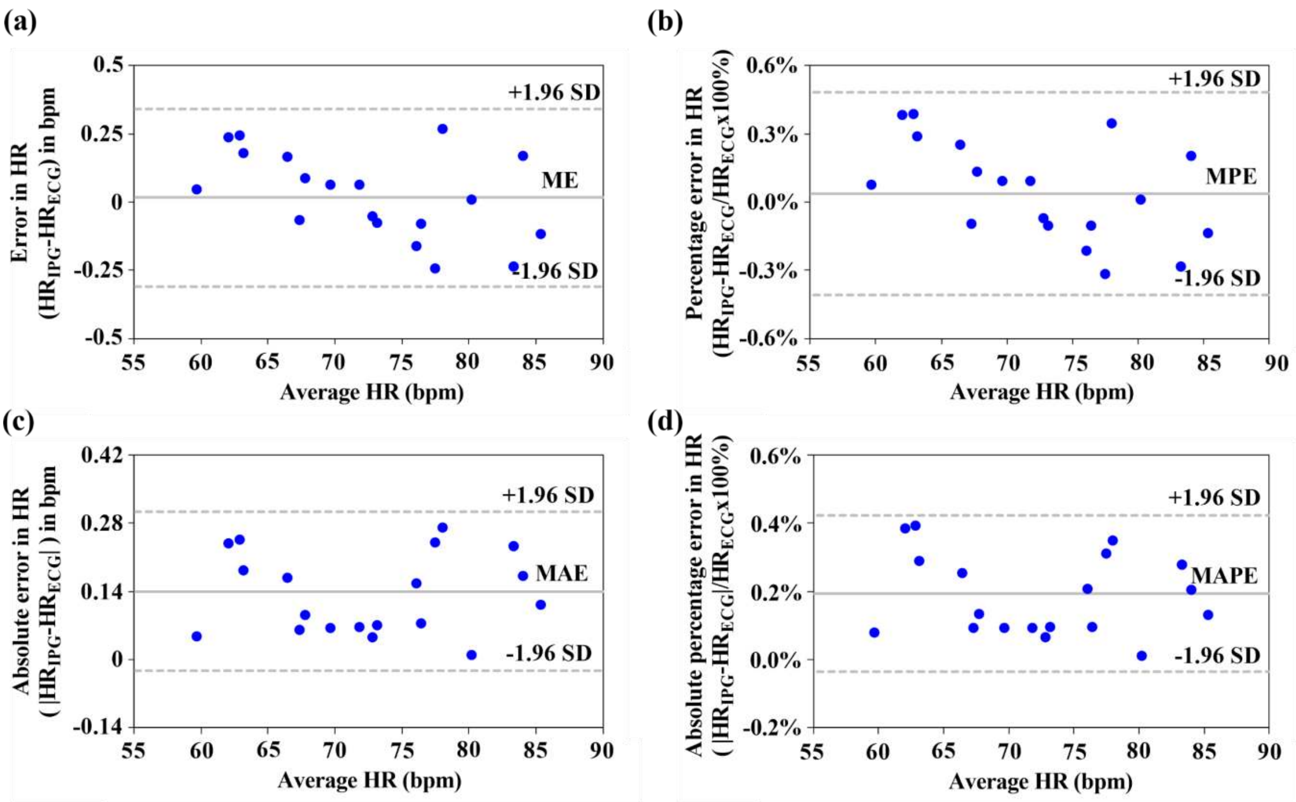

FIGURE 12. Bland-Altman plots indicating the agreement between HR measurement from the reference sensor and proposed device in terms of (a) ME, (b) MPE, (c) MAE, and (d) MAPE.

TABLE 1.
CARDIOVASCULAR MONITORING PERFORMANCE COMPARISON WITH PREVIOUS WORKS

Work	Participants	Bio-signals	SBP (mmHg)		DBP (mmHg)		HR (bpm)	
			ME±SD	MAE±SD	ME±SD	MAE±SD	ME±SD	MAE±SD
Our work	20 healthy subjects	IPG	-0.16 ± 2.97	2.43 ± 1.71	0.09 ± 3.30	2.83 ± 1.68	0.02 ± 0.17	0.14 ± 0.08
Marzorati *et al*. [2], 2020	20 healthy subjects	PPG, PCG	1.47 ± 3.76	1.83	0.01 ± 7.55	3.06	-	-
Tabei *et al*. [7], 2020	6 healthy subjects	2-channel PPGs	-	2.07 ± 2.06	-	2.12 ± 1.85	-	-
Yousefian *et al*. [17], 2020	23 healthy subjects	ECG, BCG, PPG	-	7.2 ± 0.9	-	4.7 ± 0.5	-	-
Miao *et al*. [18], 2020	85 subjects (17 hypertensive and 12 hypotensive patients)	ECG, 2-channel PPWs	1.62 ± 7.76	-	1.49 ± 5.52	-	-	-
Khalid *et al*. [19], 2020	Queensland and MIMIC II datasets	PPG	0.07 ± 7.1	-	-0.08 ± 6.0	-	-	-
Poh *et al*. [20], 2017	40 healthy subjects	PPG	-	-	-	-	0.30 ± 1.57	1.30 ± 0.91
Zhang *et al*. [21], 2017	10 healthy subjects	ECG, PPG	1.63 ± 4.44	3.68	-	-	-	0.21

and proposed IPG patch device conducted synchronous measurement to evaluate the correlation both of devices by scatter plots and Bland-Altman plots. The BP scatter plots have a high correlation between the cuff sensor and the proposed device. Pearson's correlation coefficients of SBP and DBP were 0.93 and 0.87 for 20 subjects. Based on the analysis of the Bland-Altman plot, our device for BP estimation error indicates that the ME and MAE were within -0.2 ± 3.4 mmHg and 2.9 ± 1.8 mmHg. The BP percentage estimation of MPE and MAPE were within -0.2 ± 5.6 % and 4.8 ± 2.9 %. The BP statistical results validated the performance of our proposed device agreed with the criteria of AAMI of MAE ± SD below 5 ± 8 mmHg.

In HR monitoring, the beat-to-beat heart rhythm can be detected by consecutive SBP feature points in IPG signals. The synchronous physiological measurement of the proposed IPG device and commercial ECG (gold standard) sensor was conducted to evaluate HR accuracy. The correlation plot between the proposed device and the ECG sensor demonstrates a highly significant correlation with Pearson's correlation coefficients value of 0.99 for 20 subjects. Moreover, the HR estimation by IPG device has a ME and MAE of 0.02 ± 0.17 bpm and 0.14 ± 0.08 bpm. The percentage error in terms of MPE and MAPE were 0.04 ± 0.23 % and 0.19 ± 0.12 %. Based on our HR performance, our device agreed with ANSI/AAMI EC13:200 criteria for HR measurement with an accuracy requirement of ± 5 bpm or ± 10%, whichever is greater.

C.COMPARISON WITH PREVIOUS STUDIES

We compared the proposed cardiovascular device with recent works, as shown in **Table 1** [2], [7], [17]-[21]. The number of recruited subjects was comparable with most works to prove the concept for cardiovascular monitoring. Based on **Table 1**, most studies utilized PTT-based method for cuffless BP estimation [2], [7], [17], [18], [21]. Despite these technologies present the high reliable BP performance, the PTT-based method required at least two sensors that could make them unfeasible for wearable applications. Khalid *et al.* [19] provided the single-channel PPG for cuffless BP estimation based on the Queensland and MIMC datasets. Although the technique is calibration-free for BP estimation, it required manual PPG signal pre-processing from datasets during the algorithm training that is not suitable for realistic application. Compared to Poh *et al.* [20] work, this study provided two significant cardiovascular monitoring items (BP and HR) using single-channel IPG measurement.

D. LIMITATION AND FUTURE WORKS

Although this paper validated the cardiovascular monitoring function of continuous BP and HR recording, some limitations require to improve in the future. First, participants need to keep sitting position to avoid movement artifact during cardiovascular monitoring. Second, the IPG patch device installation above the carotid artery using tape could not suitable for long-term cardiovascular monitoring. The electronic tattoo and optimized analog frontend design will be implemented to address the important limitation of ambulatory long-term monitoring. Third, the device scaling down using micro or nanotechnology is necessary to make the device smaller and lower power consumption for practical application and long-term monitoring. Fourth, the humidity effect from sweating could alter impedance characteristic during BP measurement, calibration frequency was further evaluated was required to remain qualified BP monitoring. Fifth, this study validated the cardiovascular function of the proposed IPG device within young healthy participants. The old-aged people group and patients with hypertension and arrhythmia will be recruited to make BP and HR functions of our device more reliable for clinical applications.

V. CONCLUSION

This study designed a neck patch device for cardiovascular monitoring. The technique is to combine a patch form device and single-channel IPG measurement for carotid artery sensing that bring some potential advantages such as unobtrusive measurement and wearable application for cardiovascular monitoring. Compared to previous works, the new device provided two cardiovascular monitoring items of continuous BP and HR using a single-channel physiological measurement. The experimental results validated that the BP and HR performance satisfied with the AAMI/ANSI standard. Overall, this paper implemented a neck patch device with multi-cardio functions monitoring by a single-channel IPG measurement that is suitable for wearable applications and low-cost manufacturing.

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