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Wearable Acceleration Plethysmography for Carotid Pulse Pressure Monitoring: A Feasibility Study

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Abstract—**Central blood pressure (CBP), which is the pressure at the aorta and other central arterial sites such as the carotid, is more predictive of target organ damage and future adverse events, as opposed to conventional blood pressure assessed at more peripheral sites. However, methods to estimate CBP are complex, require frequent calibration and are not suitable for continuous tracking purposes. Here, we introduce a wearable accelerometer based pressure sensing system to track carotid pulse pressure (PP). The wearable system detects the transcutaneous pressure (P_T) on the skin surface over the carotid artery and identifies the key fiducial points (g_1, g_2). In-vivo study on 11 subjects showed that the peak-to-peak value, ΔP_T and maximum value, g_2 of P_T have a statistically significant and strong correlation with carotid PP ($r = 0.75$, $p < 0.05$) and SBP ($r = 0.78$, $p < 0.05$) respectively. The magnitude response (percentage mean difference between pre and post-exercise intervention) of P_T parameters (ΔP_T and g_2) were 78 % and 89 % as compared to 33 % and 19 % in carotid PP and systolic blood pressure (SBP), respectively. Reliability (SNR > 38 dB) and repeatability (CoV < 10%) were seen in the obtained transcutaneous pressure signals. The study limitation is identifying an appropriate calibration or model for carotid BP estimation. This study reveals the feasibility of using an acceleration plethysmogram (APG) based wearable pressure-sensing system for tracking changes in carotid PP and SBP which could pave the way for wearable systems for ambulatory assessment of central BP for clinical and home use.**

Keywords—wearable, carotid pulse pressure, transcutaneous pressure, accelerometer, acceleration plethysmogram

I. INTRODUCTION

More and more studies identify increased pulse pressure—the pulsatile component of blood pressure as a risk factor for cardiovascular diseases, particularly coronary heart disease [1]. Studies have shown a significant correlation of pulse pressure (PP) with the degree of atherosclerosis and vascular hypertrophy than with systolic blood pressure (SBP). In this regard, pulse pressure measured from the central artery has a stronger association with the signs of cardiovascular disease than its brachial counterpart [2]. Since the central (i.e. aortic) pressure waveform is rarely available, carotid blood pressure is frequently utilised in cardiovascular monitoring as a surrogate of central blood pressure [3] and thus necessitates the need for continuous carotid BP measurement. Over the years, ambulatory blood pressure monitoring is gaining more importance in hypertension care than one-time BP measurement which stresses the need for a wearable central BP measurement [4].

Applanation tonometry at the carotid artery and calibration using brachial BP parameters is the accepted technique for determining carotid BP parameters, with all measurements conducted with the subject in supine posture [5]. The use of accelerometers to estimate BP has been extensively explored in recent years [6]. One is based on measuring local PTT [7], which is measured by the time difference between acceleration signals from two accelerometer sensors placed at the skin surface near to carotid artery site. Another method using an accelerometer for carotid PP estimation is based on measuring displacement at the skin surface and then calibrating to brachial BP parameters [8]. Both these methods measure a pressure-dependent variable from the skin surface and then use mathematical models relating arterial diameter or PTT, with blood pressure, whose assumptions of a linear-pressure diameter relation is not strictly true. Hence, we propose the assessment of pressure at the skin surface, which is the effect of transmural pressure of the carotid artery wall transferred to skin. However, to measure this transcutaneous pressure using an accelerometer, there should be negligible hold-down pressure at the skin surface. It is thus essential to have a lightweight wearable accelerometer device for reliable assessment of transcutaneous pressure at the neck.

Hence, we are proposing a wearable pressure-sensing system based on an accelerometer that can track the carotid PP and SBP. Section II discusses the measurement principle and wearable system; Section III addresses the reliability and response of transcutaneous pressure.

II. MATERIALS AND METHODS

A. *Principle of Transcutaneous Pressure Measurement*

The transcutaneous pressure (P_T) is the pressure felt at the skin surface, radially outwards with a significant component in the z-direction, which is the direction perpendicular to the skin surface. The origin of transcutaneous pressure at the neck is the transmural force (F) at the near wall of the common

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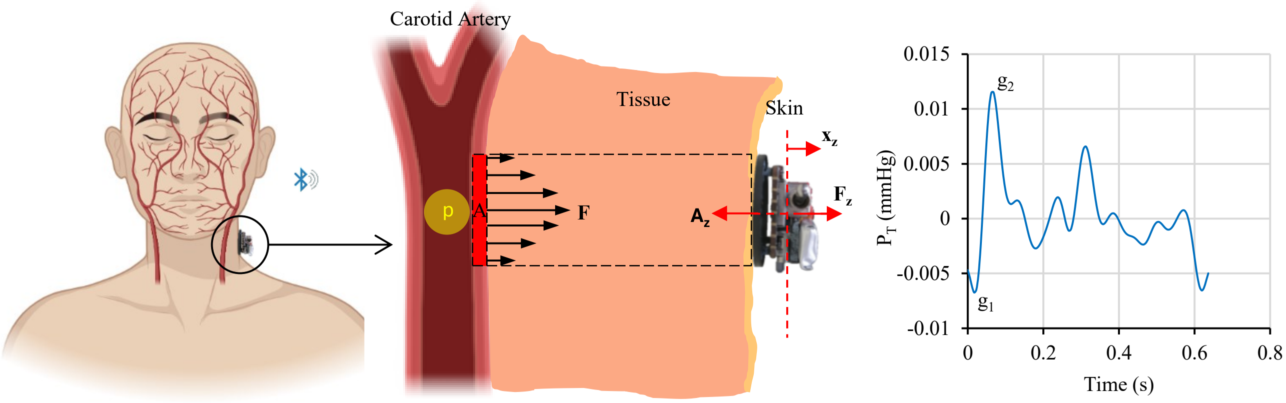


(a) (b)

Fig.1 Transcutaneous pressure measurement principle demonstrating the (a) method and (b) transcutaneous pressure cycle

carotid artery. However, this P_T will be an attenuated form of transmural pressure (p) at the common carotid artery due to the presence of tissues between the artery wall and the skin under the assumption of homogeneous elastic property of tissue. We measure P_T using a wearable accelerometer attached to the neck, having a circular contact area, A_z oriented towards the artery wall (Fig.1(a)). The transcutaneous force, F_z is related to P_T as follows,

$$F_z = -P_T A_z \tag{1}$$

The convention that the force is regarded as directed towards the surface element and the area normal vector points outward is the source of the minus sign. The wearable accelerometer measures F_z as follows,

$$F_z = m_d a_z \tag{2}$$

$$a_z = \frac{d^2 x_z}{d^2 t} \tag{3}$$

where m_d is the mass of the wearable device and a_z is the z-axis acceleration measured by the accelerometer which represents the acceleration plethysmogram (APG) at the skin surface. Thus, our wearable accelerometer measures transcutaneous pressure, P_T by the following relation,

$$P_T = -\frac{m_d a_z}{A_z} \tag{4}$$

B. *Wearable Transcutaneous Pressure-sensing System*

To perform continuous transcutaneous pressure measurement, we developed a Bluetooth-based wearable system that includes a transmitter (m_d = 5.2 g, and A_z = 570 mm^2), with a digital accelerometer sensor (LSM6DS3TR-C) interfaced with nRF52840 Bluetooth Low Energy (BLE) microcontroller. Using the equation given in (4), and the mechanical characteristics (sensitivity, RMS noise) of the accelerometer, our wearable system can measure transcutaneous pressure with a resolution of 0.001 mmHg. A uniform contact of the wearable transmitter with the skin surface is ensured by providing a circular acrylic sheet (diameter = 27 mm, thickness = 1.5 mm) in the transmitter. A double-sided biocompatible adhesive is used to attach the transmitter to the skin surface at the carotid artery site. More information about the hardware is mentioned in [9], [10].

An Android smartphone receives timestamped samples of z-axis acceleration signals at 175 Hz. The data acquisition was done using Serial Bluetooth Terminal application and the resulting .txt files were saved to the phone's local storage.

C. *Signal Processing of Transcutaneous Pressure*

Identification of minimum (g_1) and maximum (g_2) values of P_T (as depicted in Fig.1(b)) is important for finding ΔP_T since it is related to the pulse pressure that gets transferred from the artery wall to the skin through the tissues. The z-axis acceleration signal is first bandlimited to 0.5 Hz to 15 Hz to remove artifacts from respiration and other motions. The filtered signal is then segmented into individual cycles using an automatic cycle segmentation algorithm developed in LabVIEW®. An average of 10 consecutive acceleration cycles is then converted to pressure using the equation (4). The g_1 and g_2 are then identified from this average transcutaneous pressure cycle.

D. *Study Objectives and Measurement Protocol*

An in-vivo study on 11 subjects aged 22 to 30 years was conducted in supine posture for the following objectives.:

(a) to determine the ability to measure transcutaneous pressure (P_T) using a wearable accelerometer device,
(b) to find the association between transcutaneous pressure parameters and carotid pressure parameters measured from carotid applanation tonometry
(c) to compare the response of transcutaneous pressure parameters towards change in carotid pressure parameters.

Each participant completed an exercise intervention consisting of 10 minutes of graded-intensity treadmill running to induce hemodynamic disturbances. The ten minutes were divided into four parts: two minutes at 3 km/h, three minutes at 5 km/h, three minutes at 7 km/h, and two minutes at 9 km/h. To verify the study objectives, we need reference pressure measurements from the carotid artery during pre- and post-exercise intervention. BP from the brachial artery was measured using an automated oscillometric BP (SunTech® 247™, SunTech Medical). Tonometer (SPT-301, Miller Instruments) measurement was then performed by maintaining a hold-down pressure of 100 mmHg with a tolerance of ± 10 mmHg for all subjects. Then, using the well-established theory that DBP and MAP can be regarded as constant throughout the arterial tree [11], the tonometer measurement was calibrated. Subsequently, transcutaneous pressure measurement was performed by attaching the wearable accelerometer device to the skin surface in the same location where the tonometer measurement was performed. Every participant received information regarding the goals of the study and the procedures of measurement. Before any data was collected, each of them provided written, informed consent. The work complies with the ethical norms of the Helsinki Declaration as revised in 2013, and the in-vivo measurement protocols were approved by the Institutional Ethical Committee, IIT Madras.

III. RESULTS AND DISCUSSIONS

A. *Reliability of Transcutaneous Pressure Signals*

A sample of filtered transcutaneous pressure signal obtained from a participant (age = 24) at the skin surface of the carotid artery site is shown in Fig.2. P_T signals were found to be reliable for all the subjects with an SNR > 35 dB. The characteristics of the study population are summarised in Table I. The design of the wearable device was very light (m_d = 5.2 g) to give negligible hold-down pressure on the neck in supine posture. The hold-down pressure at supine posture due to gravity is calculated to be 0.67 mmHg, which is negligible to have any effect on interfering with the actual transmural pressure at the walls of the carotid artery. The P_T signal is not disturbed since the hold-down pressure is constant when in the supine position and because the bandpass filter removes the transcutaneous pressure's DC level. It was found that the desired fiducial points of the P_T (g_1 and g_2) were repeatable with a coefficient of variation (CoV) < 10%.

TABLE I. STUDY POPULATION CHARACTERISTICS (N = 11)

Parameter	Value (*Mean ± SD*)	Range
Gender (male/female)	9/2	-
Age (years)	25 ± 2	22 - 30
Height (cm)	170 ± 6	157-178
Weight (kg)	60 ± 8	50-73
Brachial Systolic BP (mmHg)	110 ± 6	102 -119
Brachial Diastolic BP (mmHg)	64 ± 6	55 - 72

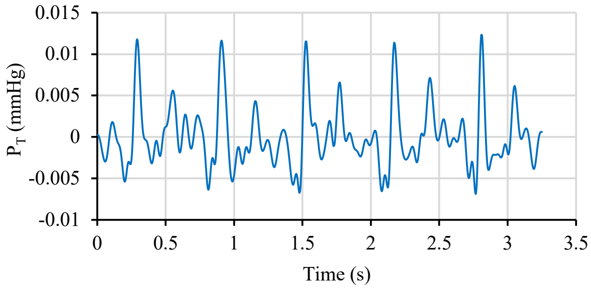


Fig.2. Transcutaneous pressure signal

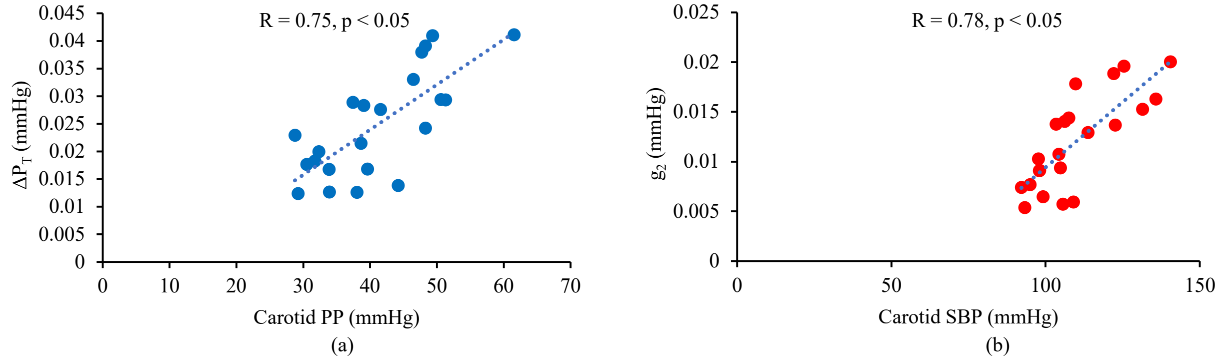
B. *Association between Transcutaneous Pressure and Carotid Pressure*

Before proceeding to the response of P_T to exercise intervention, it is important to understand the relation between P_T parameters and carotid BP parameters. As seen in Fig.3, it is observed that there are statistically significant and strong associations between ΔP_T and carotid PP (r = 0.75) and between g_2 and carotid SBP (r = 0.78). This observation is in line with the origin of transcutaneous pressure, as mentioned in section II.A. An increase in ΔP will cause an increase in the pressure difference felt at the skin surface level, which we are measuring and representing as ΔP_T. Both pre- and post-intervention data points were considered for the association depicted in Fig.3. By doing this, a large pressure range for the association is achieved.

C. *Response of Transcutaneous Pressure and Carotid Pressure*

As seen in Fig. 4(a) and (c), respectively, measurements made with the reference device revealed a statistically significant difference ($p < 0.05$) between pre and post-measurements of carotid PP and carotid SBP. Thus, a pressure-induced hemodynamic disturbance has been brought on by the exercise of running on a treadmill. A comparable pattern can be seen in the transcutaneous pressure parameters during pre- and post-exercise, with P_T and g_2 displaying a statistically significant change ($p < 0.05$) in Figs. 4(b) and (d), respectively.

The magnitude response of transcutaneous pressure parameters, P_T and g_2, was compared with that of carotid PP and SBP, respectively. This is done by evaluating the percentage mean difference between pre- and post-exercise from the box-whisker plots in Fig.4. It was found that the magnitude response in P_T was 78.3%, but the carotid PP response was only 33.5%. In a similar manner, g_2 displayed an 87.2% magnitude response as opposed to 19.1% in carotid SBP. The sequential measurement of wearable and tonometer devices, which may cause the blood pressure to drop



(a) (b)

Fig.3. Regression plots illustrating the correlation between (a) ΔP_T versus carotid PP (b) g_2 versus carotid SBP

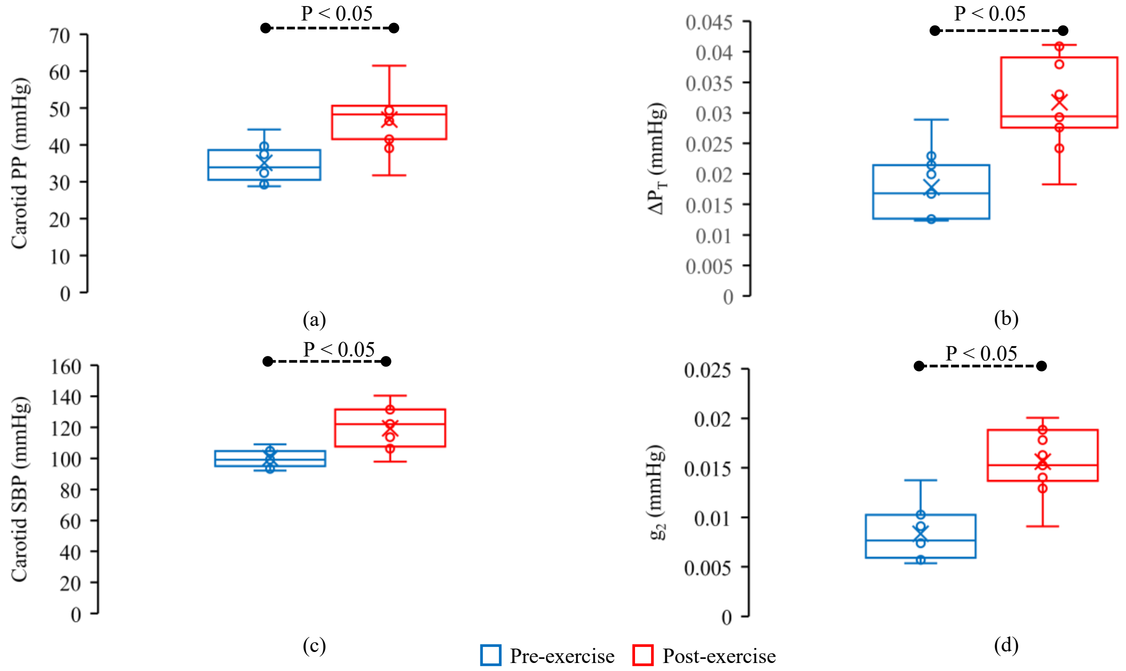


Fig.4. Box-whisker plots illustrating changes in (a) carotid PP (b) ΔP_T (c) carotid SBP (d) g_2 pre- and post-exercise

significantly at the time of tonometer measurement, is responsible for the large magnitude response in transcutaneous pressure parameters.

D. *Limitations and Future Scope*

The P_T signals were acquired only in a limited cohort of young and healthy participants. A suitable calibration of P_T is required for estimating carotid PP and SBP. This is important for continuous and long-term central (carotid) BP measurement. Therefore, further research is planned to overcome these limitations and to verify the usability of the wearable device for ambulatory purpose. Modelling the tissue between the artery wall and skin as a second-order system [12] could be a more effective way of estimating carotid pressure parameters from transcutaneous pressure.

IV. CONCLUSION

This work demonstrates the ability of our wearable accelerometer device for acquiring transcutaneous pressure from the skin surface near to carotid artery and thereby capture changes in carotid PP and SBP. The transcutaneous pressure parameters (ΔP_T and g_2) have shown a strong correlation of $r > 0.75$ with carotid PP and carotid SBP, respectively. Analysis of pre- and post-exercise intervention shows a statistically significant difference ($p < 0.05$) in ΔP_T and g_2, following the trend with carotid PP and SBP, respectively. Also, the parameters, ΔP_T and g_2 showed a magnitude response greater than 75 % between pre- and post-measurements. Further studies are required to establish the performance of the wearable system in continuous and long-term carotid BP measurement.

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