Control Method for Continuous Non-Invasive Arterial Pressure Monitoring using the Non-Pulsatile Component of the PPG Signal

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Abstract

We propose a new technique enabling continuous control of transmural pressure using the non-pulsatile (DC) component in the PPG signal as feedback. Photoplethysmograph (PPG) contact pressure has a noticeable effect on blood pressure (BP) tracking, pulse wave analysis and pulse propagation measurements. BP changes alter the difference between intra-arterial and contact pressure, called transmural pressure. Our method is based on keeping the PPG DC component constant by altering the external pressure applied. This way the pressure read from the pressure sensor equals intra-arterial BP. The technology was verified by comparing: (i) measured pressure variation induced by hydrostatic changes with theoretical values, (ii) pulse morphology with and without feedback control during hydrostatic changes, and (iii) continuous MAP readings measured with the reference device (CNSystems CNAP 500) and our device. The proposed technology performed well compared to traditional volume clamp technique while requiring significantly less complex control logic and no fast-switching pneumatics.

1. Introduction

For decades, the art of measuring continuous blood pressure non-invasively has been a subject of both academic and industrial interest[1]. Studies suggest that a continuous or semi-continuous BP profile is a better marker for cardiovascular disease than traditional office spot BP measurements[2]. Nocturnal or night-time BP tracing is considered to be an accurate diagnostic tool for assessing hypertension[3]. Various attempts to measure continuous non-invasive arterial pressure (CNAP) have been made. Two methods stand out for being in relatively widespread investigational use: pulse propagation methods and vascular unloading technique (VUT) [4–6]. Pulse propagation methods, such as pulse transit time (PTT) and pulse wave velocity (PWV) rely on the correlation between BP and blood velocity. Devices using these technologies include Biobeat (Biobeat, Israel) and SOMNOtouch (SOMNOmedics GmbH, Germany).

VUT or volume clamp method was invented by the Czech physiologist Jan Penaz in 1973[6]. A typical VUT system consists of a main unit similar to hospital patient monitors and a finger cuff device connected via communication cable and pneumatic tubing. The main unit houses the pump and valves that are responsible for controlling cuff pressure. The finger cuff unit consists of a wrist mounted control unit and miniature air cuffs that are placed around the fingers. The cuff has a photoplethysmographic sensor consisting of both a light emitting diode (LED) and a photodiode. Such a PPG system probes the pulsatile blood volume in the artery by measuring the amount of light passing through it. The device has a feedback control loop system that applies pressure to the cuff in order to keep the optical blood flow signal constant during each cardiac cycle. [6–8]

A PPG signal consists of two components: alternating current (AC) and direct current (DC) component[9]. The former corresponds to the pulsatile blood flow in the artery and the latter is considered to be a composite of the steady venous and arterial blood volume in the underlying tissue[9]. A study comparing intra-arterial BP to a PPG signal showed clear correlation between BP the PPG DC component[9]. This suggests that there is BP information in the DC component of the PPG signal. PPG contact pressure has been found to have a noticeable effect on PPG waveform morphology as well as pulse propagation measurements [10, 11]. Additionally, contact pressure is directly proportional to the DC component. In case the PPG probe is attached with a simple clip or a strap, BP changes alter the difference between intra-arterial and contact pressure, called transmural pressure (P_t). We propose a new control method that uses the DC component as a reference to control external contact pressure in order to minimize transmural pressure, enabling continuous BP measurement.

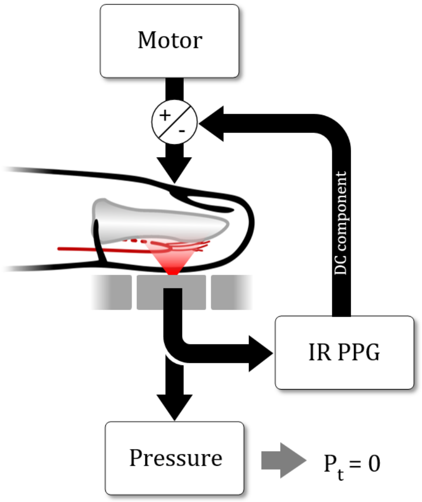

Figure 1. A system diagram showing the proposed control method. A stepper motor controlled press is used to apply pressure to the finger. The DC component acquired from unfiltered infrared PPG signal is used to control the pressure applied. The control logic ensures that transmural pressure (P_t) is kept at near zero mmHg and the pressure read from the pressure sensor equals mean arterial pressure.

2. Methods

We have prepared an instrument with a combined pressure and infrared (880 nm) PPG sensor. A stepper motor controlled press construction is used to apply pressure to the finger [12]. A custom sensor is used to record blood flow from the fingertip optically and measure the pressure applied to it. An initial BP calibration is performed using an arm cuff device (Omron Intellisense M6). An increasing pressure ramp is induced to obtain a bell shaped oscillometric waveform envelope from the pressure sensor signal. The oscillogram is used to find the point of maximum pressure transfer to the sensor. This corresponds to mean arterial pressure (MAP) on the corresponding pressure ramp. Diastolic BP (DBP) is found at the level of 70% of oscillogram maximum, at the side of negative transmural pressure. The device converts the raw pressure value y_n to a calibrated BP value x_n using

$$x = \frac{y - b}{k} \tag{1}$$

Constants k and b are calculated as follows:

$$k = \frac{y_{MAP} - y_{DBP}}{x_{MAP} - x_{DBP}},\ b = y_{MAP} - k \cdot x_{MAP}, \tag{2}$$

where y's represent the DBP and MAP values computed from the oscillogram and x's are the initial arm cuff values. External pressure is lowered until it reaches a level corresponding to MAP. At this point, transmural pressure equals zero and the DC component of the raw PPG signal is marked as a setpoint for the feedback loop.

The DC level of a reflective type PPG signal is inversely proportional to intra-arterial pressure. By adjusting the contact pressure, the DC level of the PPG signal is ”clamped” to the setpoint in order to compensate for variations in BP. As the DC level shifts from the setpoint, the applied pressure is adjusted in order to maintain zero transmural pressure. The pressure reading from the sensor then equals intra-arterial pressure. A proportional-integral-derivative (PID) controller was used to adjust external pressure. Pressure values obtained during larger deviations from the setpoint were discarded in real-time.

3. Results

The technology was verified by comparing: (i) measured pressure variation induced by hydrostatic changes with theoretical values, (ii) pulse morphology with and without feedback control during hydrostatic changes, and (iii) continuous MAP readings measured with a reference device (CNAP 500, CNSystems, Austria) and our device.

(i) The arm was resting on height adjustable table at the heart level with the device worn in the finger and hydrostatic change was induced by raising the desk. After recording the baseline measured for 30 s at heart level, the desk was raised and the corresponding pressure was recorded respectively. Theoretical pressure change can be calculated using $p = \rho g \Delta h$, where ρ is the density of blood, g is acceleration due to gravity and Δh is the change of height from heart level. A 10 cm shift equals a pressure change of 7.4 mmHg. In our tests, the level shift resulted in pressure changes of 4.3 mmHg, 5.4 mmHg and 8.4 mmHg. Comparably, without DC component feedback control the change in pressure was unmeasurable, with the change getting lost in the natural variation of blood pressure.

(ii) In order to study the effect of contact pressure on pulse wave morphology, we raised and lowered the desk 10 cm and compared the corresponding waveforms to the initial one at zero transmural pressure. The procedure was repeated with and without feedback control. With the feedback loop on, the waveform remained very similar to the original indicating that transmural pressure had not changed. Correspondingly with the feedback loop switched off the level shift resulted in a significant change in pulse morphology. When the arm was lowered from heart level, transmural pressure turned positive resulting in a sharp and pointy pulse. When raised, transmural pressure

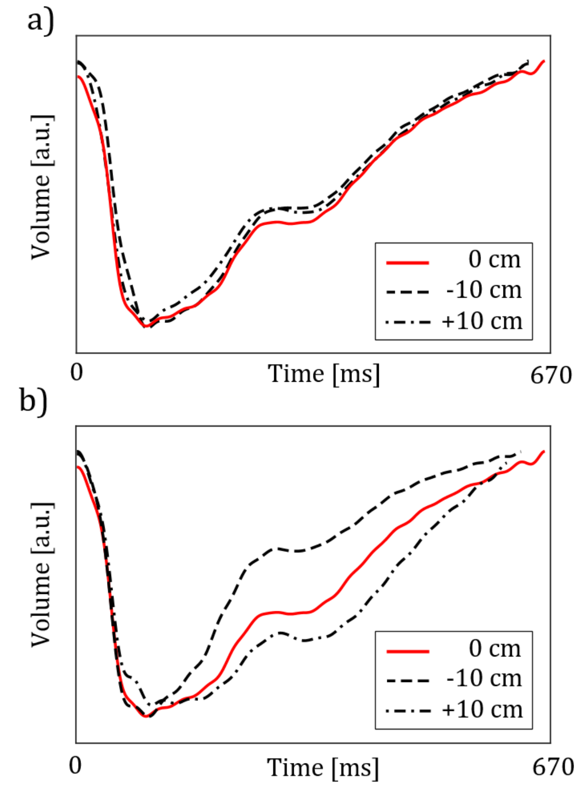

Figure 2. Pulse morphology analysis during pressure changes (a) with and (b) without feedback control. Each plot represents an averaged pulse waveform at different heights from heart level. Note that the pulse is inverted since we are using reflective instead of transmissive PPG.

turned negative and the pulse had a more smooth and wide and appearance. In both cases the amplitude of the pulse decreased when applied pressure diverged from MAP.

(iii) The ability to maintain zero transmural pressure as expected and track MAP continuously was assessed by simultaneously recording with the reference device our device. The reference device (CNAP 500) utilizes VUT to measure beat-by-beat BP [13]. It outputs SBP, DBP and MAP for each heartbeat. A 6 min measurement was made with CNAP 500 worn on the middle finger and our device on the index finger ipsilaterally. Figure 3 shows good correlation between the two instruments. At approximately 100 s into the measurement, the desk is raised 20 cm and at approx. 250 s it is lowered back to the original level. The measurement shows that the device can recover from high BP changes. However, fast changes from the setpoint take unreasonably long time to settle at the moment. This can be improved by adjusting control logic.

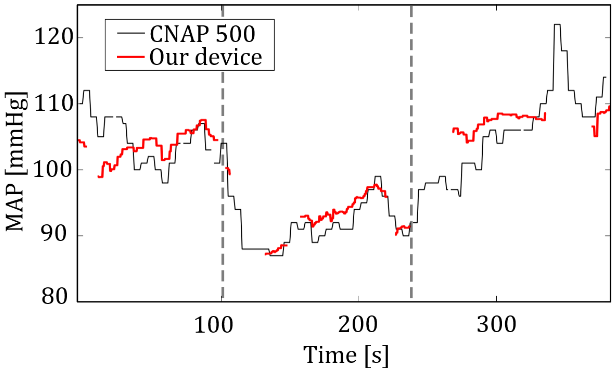

Figure 3. A Measurement comparing our method to the reference (CNSystems CNAP 500). Both devices were calibrated using the same arm cuff device. The desk was lowered and raised respectively at the points marked by dashed lines.

4. Discussion

The proposed technology performed well compared to traditional volume clamp method while requiring significantly less complex control logic and no fast-switching pneumatics. The technology could be used for continuous BP monitoring or improving the accuracy of PPG based pulse wave analysis (PWA) and pulse transit time (PTT) devices. Currently our device only measures MAP continuously. However, the initial oscillogram can be used to fix both systolic and diastolic levels and use the PPG or pressure pulse amplitude to continuously reassess SBP and DBP. Along with pulse pressure information, pulse morphology analysis can be used to estimate e.g. cardiac output.

In 2021, CNSystems introduced a new control method for readjusting transmural pressure[14]. In the study they presented a modified CNAP 500 device called CNAP2GO, which monitored the pulse morphology in order to modify cuff pressure on a beat-to-beat level. Since this technology relies heavily on high quality pulse wave acquisition, we believe that the DC component method might have an advantage in case of cold fingers and individuals with poor peripheral circulation.

Further studies should be conducted to investigate the accuracy of the proposed technique. Since the technique is used for continuous rather than spot BP measurements, the traditional ISO standard for automated BP instruments will not be relevant[15]. Instead, a custom protocol or a more comprehensive standard such as the IEEE Standard for Wearable, Cuffless Blood Pressure Measuring Devices should be used[16]. Additionally, the effect of vasomotoric activity on the feedback method should be studied. The original VUT method proposed by Penaz suffered from deviation caused by long term vasomotoric activity. Commercial devices implement additional control logic to compensate for this phenomenon[17, 18].

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