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SENSOR FUSED BLOOD PRESSURE MEASURING DEVICE CAPABLE OF RECORDING KOROTKOFF SOUNDS IN INFLATIONARY CURVES

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ABSTRACT

This study describes a non-invasive medical device capable of measuring arterial blood pressure (BP) with a combination of inflationary and deflationary procedures. The device uses the pressure cuff pressure signal, arterial skin-surface acoustics, and photoplethysmography (PPG) to make a sensor-fusion estimation of blood pressure readings. We developed an apparatus composed of 1) a modified off-the-shelf oscillometric blood pressure system, 2) a contact microphone with an amplifier, 3) and high-sensitivity pulse oximeter, and its control electronics.

Keywords: blood pressure, artery, cardio, photoplethysmography, bio-signal, Korotkoff

NOMENCLATURE

BP	blood pressure
DBP	diastolic blood pressure
MAP	mean arterial pressure
mmHg	millimeters of mercury
OMW	oscillometric waveform
OMWE	oscillometric waveform envelope
PPG	photoplethysmography
PVDF	polyvinylidene Fluoride
SBP	systolic blood pressure

1. INTRODUCTION

Accurate blood pressure measurements are crucial to diagnose and understand cardiovascular health. High blood pressure is a risk factor for a multitude of diseases, including ischemic heart disease and stroke [1]. There are a multitude of forms to measure blood pressure, and we can classify these procedures as invasive or non-invasive. Invasive BP meters require the use of a catheter and may present several risks: bleeding, infection, etc. Non-invasive BP meters are less risky but may be compromised in accuracy and precision [2].

The gold standard in non-invasive BP is the auscultatory method, where a highly-trained medical provider uses a stethoscope with a combination of manually-controlled blood pressure cuff and a mercury sphygmomanometer [3]. The medical provider controls the inflation of an arm cuff, he/she pumps the cuff until a certain level (usually over 120 mmHg), and then he/she deflates the cuff slowly and listens to the Korotkoff sounds [4]. On the first Korotkoff sound the provider determines the systolic value. After further deflation, the health provider determines the diastolic value when he/she cannot hear any more Korotkoff sounds. This method is manual, takes practice and specialized training, and requires well-calibrated instrumentation. Health providers get accuracy through continuous training and adherence to recognized protocols.

Non-invasive accurate and repeatable blood pressure measurements are more challenging. There is a trend towards automation since it provides so many benefits: home care, easy to use, a higher number of reading samples, etc. The most common automated BP protocols are based on a) plethysmography, b) tonometry, c) vascular unloading, d) automated auscultatory, e) doppler ultrasound sphygmomanometry and f) oscillometry [5].

One of the most common and simple methods used in over-the-counter BP meters is oscillometry. This method measures and analyzes small pressure oscillations within the pressurized inflatable cuff. An algorithm correlates the oscillometric pulses to the SBP and DBP readings using the OMWE. The maximum of the OMWE establishes the MAP point, after that, the system calculates the SBP and DBP by applying empirically-calculated coefficients to the left and right ramps to the MAP value in the OMWE. Pulse pressure and arterial compliance play a key role in the oscillometry's accuracy, and some studies suggest that the measurement may benefit by using patient-specific coefficients [6]. Oscillometric methods readings can significantly differ from the ones obtained by the auscultatory method, especially in non-standard populations like the elderly [7].

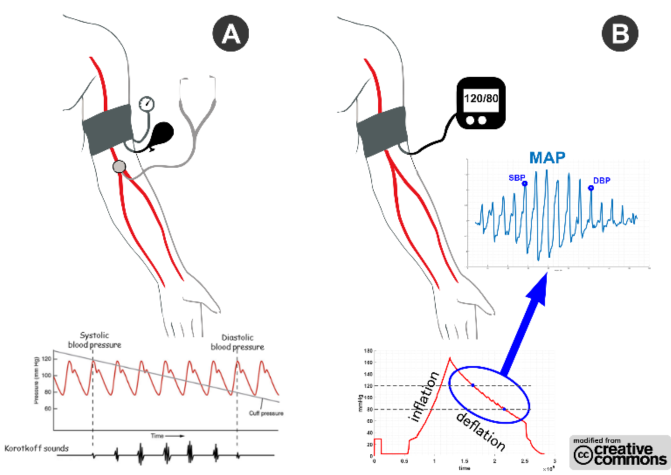

FIGURE 1: THE TRADITIONAL AUSCULTATORY METHODS ILLUSTRATED IN FIGURE 1A CONSISTS OF LISTENING TO KOROTKOFF SOUNDS BY A TRAINED MEDICAL PROVIDER WHILE DEFLATING THE ARM CUFF. MOST AUTOMATIC BP METERS USED THE OSCILLOMETRIC ENVELOPE (FIGURE 1B), WHERE A PRESSURE SENSOR RECORDS ARTERY PULSATIONS TRANSMITTED TO THE ARM CUFF USUALLY WHILE DEFLATING THE ARM CUFF.

The most common procedure for oscillometric techniques is to obtain the OMWE in the deflation curve (deflationary devices). However, devices that measure while inflating are also available (inflationary devices). The benefits of inflationary oscillometric devices are lower cuff pressure to detect SBP and DBP and faster measurements [8], [9]. A problem with inflationary devices is that they have to deal with inflationary pumping noise due to pressurizing the cuff when conducting a reading [10].

The oscillometric estimations may differ from the gold standard (auscultatory) [7]. A similar technique to the standard healthcare-conducted auscultatory method is the machine-driven automatic auscultatory method. This technique uses a microphone near the brachial artery, in contact with the skin, that records vibrations caused by blood flow. This audio is then processed by a machine that calculates SBP and DBP based on Korotkoff sound detection. This method doesn't need highly-trained healthcare personnel and is highly effective in quiet environments, however it lacks robustness when noise is introduced.

In addition to measuring pressure oscillations near the arm cuff, we wanted to monitor blood flow behavior when the arm was being pressurized/depressurized by the cuff. The PPG signal has been shown to provide information about arterial and venous flow [11] and valuable insights on blood pressure estimation and cardiac output [12]. PPG allows us to log arterial blood flow, venous system behavior, and blood oxygen saturation while the arm cuff inflates and deflates. Some drawbacks of PPG are that it is affected by contact pressure, usually needs calibration, and that it can carry a significant BP error (over 10 mmHg) [13].

Our research team has developed a system that simultaneously combines some of the most popular methods to measure BP readings: auscultatory, oscillometric, and plethysmography. We selected these techniques because of availability, simplicity, cost, and commonality within the non-invasive techniques. Our apparatus allows us to combine the strengths and characteristics of each of the techniques. With this device we can further understand the relationship between Korotkoff sounds, OMWE and PPG.

We intend this device to be a step towards a more accurate, cost-effective, comfortable and precise procedure to get BP readings automatically by studying how to combine the strengths of these readily-available technologies. We aim to develop hardware to study the strengths of three common techniques to improve blood pressure measurements.

2. MATERIALS AND METHODS

We have developed a prototypical system based on the combination of three off-the-shelf devices in addition to custom-designed hardware and self-implemented software. We based the system on the following three main subsystems: 1) Omron BP meter model# BP710, 2) a Maxim MAX30101 Pulse Oximetry and Heart Rate Module and 3) a PVDF piezoelectric thin film vibration sensor CM-01B,

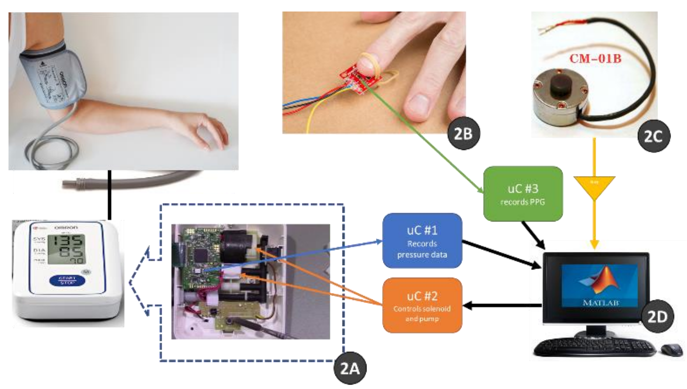

FIGURE 2: GENERAL DEVICE DIAGRAM. THE DEVICE HAS THREE MAIN INPUT COMPONENTS: A PRESSURE SENSOR (2A), AN OXIMETER (2B), AND A CONTACT MICROPHONE (2C). ALL THE INPUTS ARE COMBINED AND THEN ANALYZED USING MATLAB (2D).

We used one microcontroller to manage the inflation/deflation parameters of the Omron meter. In addition, we had two microcontrollers tasked to sample the pressure sensor signal and the pulse oximeter. The sampling was synchronized with the help of a timestamp signal that was received by all the microcontrollers from a bus.

2.1 Pressure meter

The altered BP meter allows us to control the pumping rate, to open/close the solenoid valve (which is a valve that, in the OFF/open position allows the system to exhaust all the air in the cuff chamber, or in the ON/close position makes the chamber airtight), and to read the MEMS gauge pressure sensor. This device captures the pressure signal transmitted from the arm cuff and then channels it to a 16-bit ADC (ADS1115) with a programmable gain amplifier. The ADS1115 samples the signal at 55 Hz, amplifies it, and then sends it to a microcontroller using the I2C protocol. Then, the microcontroller transmits the samples to the PC and into Matlab™ for further analysis.

2.2 Contact Microphone

Korotkoff sounds are detected by using a contact microphone. Our research group selected the model CM-01B because it is widely used in digital stethoscopes and has been documented in previous research [14]. An LM741 amplifier conditions the microphone signal from the CM-01B and connects to the PC audio line-in input. Afterward, the computer samples the audio signal at 8 kHz and the signal is then transmitted to a Matlab program. The Matlab procedure amplifies the audio digitally and applies a one-dimensional 100th order median filter. This process enhances the local maxima present in the signal originated from wall turbulence in the brachial artery.

2.3 Pulse Oximeter

To obtain a PPG signal, our team selected a readily available pulse oximeter MAX3010. This chip is a well-used high-sensitivity pulse oximeter and a heart-rate sensor for wearable health. We placed the sensor on the tip of the finger. The sensor emits two wavelengths (red and green) and captures the reflection of the blood flow in the fingertip. The receiving part of the sensor then processes the signal and sends it to the microcontroller. The microcontroller samples the signal at 55Hz, inverts it and sends it to the PC using I2C.

2.4 Software analysis

The research team developed specific communication procedures to get the signals simultaneously. The PC uses a series of callback functions to store the received samples from the two microcontrollers and the audio line-in.

After storing the signals, Matlab is used to plot them. We can create custom BP measuring procedures since we can control the pumping rate and the solenoid valve on the system. **FIGURE 3** shows an example of cuff inflation or deflation at different rates (pressure signal shown in red signal).

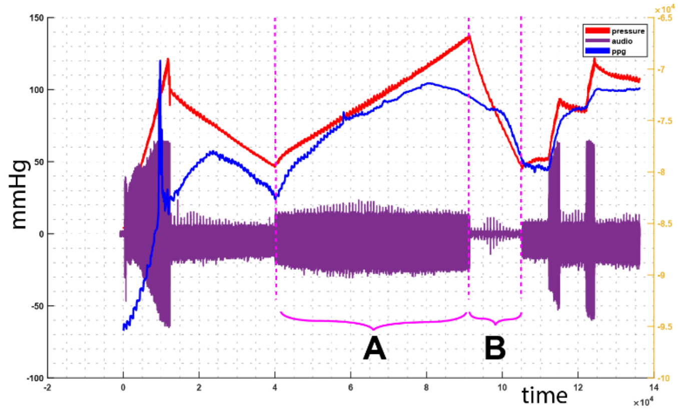

FIGURE 3: RAW SIGNALS PLOTTED IN REAL-TIME BY THE MATLAB PROCEDURE. SECTION 'A' ILLUSTRATES AN INFLATIONARY CURVE AND SECTION 'B' A DEFLATIONARY CURVE (MOST COMMONLY USED IN BP METERS).

Two sections: 'A' and 'B' are used as an example to show how the system processes different signals.

Section 'A' includes an inflationary curve. The pressure signal (shown in red) increases with time due to a volume increase of air in the arm cuff.

FIGURE 4 illustrates the audio envelope in 'A1'. We plotted the Korotkoff sounds by applying a threshold algorithm. In this case, the threshold is fixed and established based on signal variance and energy calculated in the Korotkoff sounds envelope. To extract the Korotkoff sounds the signal is first filtered using a one-dimensional 100th order median filter. After that, a series of the local maxima are detected in the audio signal. Next, the audio envelope is defined while inflating the arm cuff. This does not require any hardware alteration.

Next, we section the pressure signal by removing the best straight-fit line from the curve and then high-pass filtering it. This results in the small pressure oscillations that characterize the oscillometric behavior of the BP signal. Next, a wavelet signal de-noising procedure improves the pulse detection. The result of this process is shown graphically in section 'A2' under **FIGURE 4**. We can get the OMWE from the pulses and predict an empirical estimation of BP using fixed coefficients.

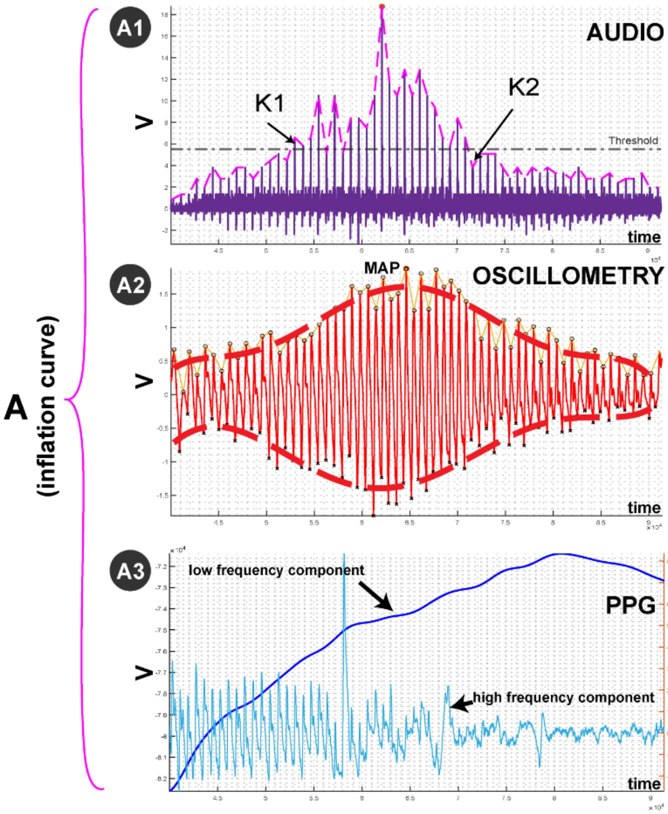

FIGURE 4: FIGURE 4A SHOWS THE KOROTKOFF SOUNDS, FIGURE 4A2 DEPICTS OSCILLOMETRY, AND FIGURE 4A3 SHOWS PPG SIGNALS OUT OF THE INFLATIONARY CURVE FROM SECTION 'A' IN **FIGURE 3**.

The PPG signal was inverted and divided into a low-frequency component and a high-frequency component. **'Figure 4 A3'** shows how the behavior of both components change in time while we inflate the arm cuff.

Similar to the ramp-up, we can apply the same algorithm to the ramp down. We sectioned the ramp down curve in **FIGURE 3** and we named it 'B'.

Section 'B' includes the pressure signal in red, the audio signal in purple, and the PPG signal in dark blue. We applied the same analysis described in section 'A' to section 'B', and we plotted the graphs shown in **FIGURE 5**. We gathered the Korotkoff sounds using again a threshold algorithm; we calculated the OMWE and MAP on the pressure signal and we decomposed the PPG signal in low and high-frequency components. Please note that the 'B' section is shorter. However, this section requires inflating the arm cuff pressure to a high level of mmHg in order to be effective and to produce valid BP readings.

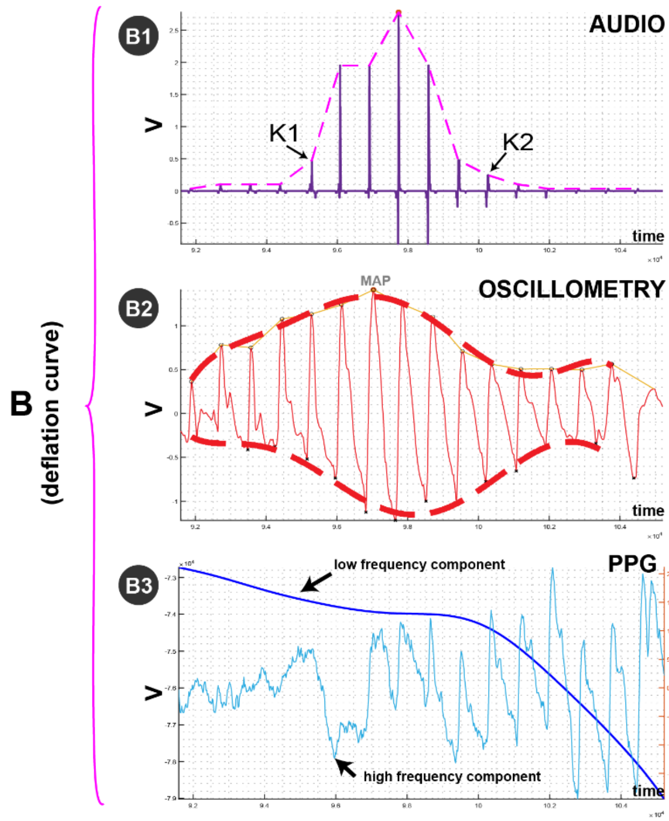

FIGURE 5: SECTION 'B' DESCRIBES THE BEHAVIOR OF OUR ALGORITHM IN THE DEFLATIONARY CURVE. SECTION B1 SHOWS THE DEFLATIONARY KOROTKOFF SOUNDS. B2 DISPLAYS THE OMWE WHILE DEFLATING THE CUFF AND B3 DISPLAYS THE TWO FREQUENCY COMPONENTS OF THE PPG SIGNAL.

3. RESULTS AND DISCUSSION

Estimations of BP using the inflationary curve are more challenging. The pump noise makes it difficult to get a reliable automatic auscultatory reading. However, Korotkoff sounds were obtained by adapting the pumping rate of the arm cuff and by applying specific digital signal analysis to the data. We have made minimal hardware modifications to keep the cost of future developments low as well as to maintain simplicity in the reading methods.

3.1 Possibilities with custom procedures

This work shows pressure signals, PPG, and vessel acoustics can be detected and applied to different procedures and in different environmental conditions. With the help of our custom device, we can control the cuff's air volume, inflation, and deflation rates. Our team will be able to develop custom procedures using various inflationary and deflationary curves. With the use of these protocols, we will be able to compare Korotkoff sounds on both types of curves and analyze our three sensors in a variety of self-made procedures.

We intend to further understand how the three signals can be combined and how we can generate a more accurate BP measurement.

3.2 Future work

Our research group has acquired bio-signals from a few participants as a measure of feasibility. With feasibility established, we will test this on a larger number of diverse subjects to better investigate the possibilities brought by this equipment to create a patient-specific model of BP. Within this dataset of subjects, we intend to include atypical conditions such as participants with high or low values of BP, obesity, and the elderly. We will specifically study how these bio-signals can be optimally-fused to produce a more accurate BP estimation.

With proper fusion, the investigation team hopes to focus on obtaining patient-specific coefficients using automatic auscultatory procedures that we could then apply to patient-specific OMWE.

We also seek a more comfortable BP measurement experience. If we can acquire BP readings by sensor-fusion while keeping a lower arm cuff pressure, we could create a more pleasant and reliable experience for patients while taking BP measurements.

Further research is needed to develop a robust model that integrates all the signals and creates a strong sensor fused model.

4 CONCLUSION

Our team has designed and implemented a low-cost BP device capable of recording PPG, Korotkoff sounds, and pressure signals at the same time. The signals are processed and stored in Matlab files for further analysis. Our group has detected Korotkoff sounds in the inflationary curve with the use of digital signal analysis and with no major hardware changes applied to an off-the-shelf BP meter.

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