DEVELOPMENT OF A NEW DEVICE TO MEASURE FINGER'S MEAN ARTERIAL PRESSURE

BUMARAN A/L CHELLATHURAI

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For my beloved mother and wife

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ABSTRACT

Measuring the blood pressure is a vital process in order to diagnose the health problem particularly to avoid the heart attack or stroke. Currently, there are two common procedures to test the blood pressure namely via the automated oscillometric device and the manual auscultatory device. Both oscillometric and auscultatory methods are performed on the human arm by using a blood pressure cuff. The above measurement methods are discomfort and time consuming since the cuff is placed on the human arm that involves inflation and deflation process. Hence, a new development of the Finger Mean Arterial Pressure (Finger M.A.P) device is proposed as an alternative measurement device. Instead of placing the cuff on the human arm, a new Finger M.A.P device allows us to measure the blood pressure on the finger. This type of measurement is derived from the photoplethysmography (PPG) signal which conventionally used to estimate the oxygen saturation level. A series of tests based on 10 subjects have been conducted in order to validate the Finger M.A.P device. From statistical analysis using Pearson correlation coefficient, the R value of 0.982 and 0.9416 are obtained when the data of finger's mean arterial pressure and brachial mean arterial pressure (oscillometric based and korotkoff based respectively) are compared. These results show that the Finger M.A.P device produced sufficient signal characteristic close to the signal produced by the automated oscillometric and the manual auscultatory device. Certainly, these preliminary results show that there is a correlation between a conventional technique (i.e. via automated oscillometric device and the manual auscultatory device) and a newly proposed measurement technique (via Finger M.A.P device).

ABSTRAK

Pengukuran tekanan darah adalah satu proses yang penting untuk mendiagnosis masalah kesihatan terutamanya untuk mengelakkan serangan sakit jantung di peringkat awal. Pada masa ini, terdapat dua kaedah untuk mengukur tekanan darah iaitu melalui peranti *oscillometric* yang beroperasi secara automatik dan peranti *auscultatory* yang beroperasi secara manual.. Kedua-dua kaedah *oscillometric* dan *auscultatory* dilakukan pada lengan manusia dengan menggunakan *cuff*. Walaubagaimanapun, kaedah pengukuran-pengukuran tersebut akan mengakibatkan ketidakselesaan dan mengambil masa kerana *cuff* perlu diletakkan pada lengan danperlu melalui proses pengembangan dan penguncupan. Oleh itu, satu peranti baru (jari M.A.P) bagi mengukur Tekanan *Mean Arterial* Jari dicadangkan sebagai peranti alternatif. Tanpa menggunakan *cuff* pada lengan manusia, peranti alternatif ini dapat menunjukkan bahawa pengukuran tekanan darah melalui jari boleh dilakukan. Secara asasnya, kaedah ini menggunakan isyarat photoplethysmography (PPG) yang mana secara konvesionalnya digunakan untuk menyukat tahap tepu oksigen dalam darah . Ujian telah dijalankan terhadap 10 subjek untuk mengesahkan peranti jari M.A.P. Melalui analisa secara statistik, nilaian R bersamaan 0.982 dan 0.9416 diperolehi apabila membandingkan data diantara tekanan *mean arterial* jari dan tekanan *mean aterial* brachial (berdasarkan kaedah oscillometric dan korotkoff). Keputusan ini mengesahkan bahawa peranti jari M.A.P menunjukkan ciri isyarat yang berkait rapat dengan isyarat yang dihasilkan oleh peranti automatik oscillometric dan peranti manual auskultori. Keputusan awal ini menunjukkan bahawa terdapat hubungan yang rapat antara teknik konvensional (iaitu melalui peranti automatik oscillometric dan peranti manual auskultori) dan kaedah baru pengukuran yang dicadangkan (melalui peranti jari M.A.P).

CONTENT

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LIST OF SYMBOLS AND ABBREVIATIONS

M.A.P	-	Mean Arterial Pressure
PPG	-	Photophylethysmogram
IR	-	Infrared
UTHM	-	Universiti Tun Hussein Onn Malaysia
BP	-	Blood Pressure
NIBP	-	Non-Invasive Blood Pressure
GS	-	Gold Standard
SaO_2	-	Oxygen Saturation
mmHg	-	Millimetre mercury
SBP	-	Systolic blood pressure
DBP	-	Diastolic blood pressure
OMWE	-	Oscillometric waveform envelope
MAA	-	Maximum amplitude algorithm
OMW	-	Oscillometric waveform
HbO_2	-	Oxidised haemoglobin
Hb	-	Reduced haemoglobin
S_pO_2	-	Oxygen saturation estimation

CHAPTER 1

INTRODUCTION

1.1 Research motivation

The contraction and expansion of the heart chamber pumps blood through blood vessels to all major organs in the human body. The pressure of the blood pushing against the blood vessels is known as blood pressure (BP). Blood pressure is stated in two values: systolic pressure and diastolic pressure. BP fluctuates between systolic and diastolic pressures during each contraction and expansion of the heart. Systolic BP refers to pressure in the blood vessels during a heartbeat, whereas diastolic pressure refers to pressure in the blood vessels during heart rest. These two terms are commonly used to summarize the BP profile.

BP can be measured either by using invasive methods or non-invasive methods. Non-invasive blood pressure (NIBP) is widely used in many situations since it involves reduced patient discomfort and ease of use, as compared to invasive methods. In fact, the use of automated electronic BP measurement devices among the general population is increasing [1,2]. Auscultatory (manual method) and oscillometric (automated method) [3] are regularly applied for NIBP [4].

The auscultatory method relies on the generation and measurement of Korotkoff sounds to non-invasively approximate the systolic and diastolic BPs. This method was introduced in 1905 and has become widely accepted as a golden standard (GS) for NIBP [5, 6, 7-12]. Korotkoff sounds rise during the gradual release of occlusive arm cuff pressure over the brachial artery. The brachial artery is completely blocked when cuff pressure is above the systolic value. When the cuff pressure is gradually released, blood starts to flow and blood pressure reaches systolic pressure during the onset of Korotkoff sounds. The sounds continue until the cuff pressure drops below the diastolic pressure.

The oscillometric method for estimating BP is established on the oscillation of pressure in the cuff during its gradual deflation from above the systolic to below the diastolic pressure. This small amplitude pressure oscillation is modulated onto the transduced deflating cuff pressure. The oscillation amplitude reaches its maximum peak when the cuff pressure reaches the mean arterial BP. The systolic and diastolic pressures are determined by reading the value of the cuff pressure when the oscillation amplitude is at some fraction of its maximum amplitude. This method is employed in most automated NIBP devices [13].

Transmural pressure is generally known as the pressure inside relative to the outside of a compartment. However, in physiological terms, it is defined as the difference between mean arterial pressure (MAP) and external pressure against the blood vessel wall [14]. The MAP originates from the contraction and expansion of heart chambers, which causes the blood to be pressurized and flow in the blood vessel. When the transmural pressure is at equilibrium, the MAP of a blood vessel is at its maximum. The physiological concept of maximum MAP (generally known simply as MAP) is commonly used in the study of auscultatory and oscillometric methods of NIBP measurement. This concept is based on the principle that the MAP will first increase and then decrease when an external pressure is continuously applied on the blood vessel. The generation of pulsatile photoplethysmography (PPG) signal (the signal used to estimate oxygen saturation (SaO_2) levels through a pulse oximeter) also originates from MAP. Therefore, with continuous external pressure applied on a finger, the finger's MAP can also be practically measured through the pulsatile PPG signal.

As such, since the concept of MAP is deployed in measuring blood pressure (either through auscultatory or oscillometric methods) as well as generating the PPG signal, the correlation between measuring blood pressure and the PPG signal might be achieved by analyzing the brachial's MAP (known as brachial MAP) and finger's MAP. This study could thus serve as a preliminary study to measure blood pressure using PPG signal.

1.2 Problem statement

The conventional blood pressure measurement method causes discomfort to patients due to the inflation and deflation of the cuff, long measurement time, and the need for a physician to properly wrap the pressure cuff on patients and listen to Korotkoff phases in order to determine the systolic and diastolic pressures during blood pressure measurement. Furthermore, improper placement of the cuff pressure will lead to wrong measurement. Therefore, this study proposed a possible technique that may avoid the use of cuff and reduce the measurement time during blood pressure measurement

1.3 Research Objectives

The current work aims to achieve the following objectives:

1. To build an apparatus to measure finger's MAP.
2. To investigate the relationship between finger's MAP and finger's transmural pressure through the PPG signal.
3. To validate the relationship between finger's MAP (finger maximum transmural pressure) and brachial's MAP using correlation analysis.

1.4 Research Scope

The main focus of this research is to develop a new device to measure finger's MAP and. This new device will provide more comfort to the user, save time, and reduces the possibility of false readings. The developed new hardware is validated by proving the correlation between the finger's MAP and brachial's MAP. The Pearson correlation method is used to calculate and demonstrate the correlation.

1.5 Thesis contribution

The contribution of this thesis includes:

- The development of a novel apparatus to measure finger's MAP.
- Identification of the characteristics of finger's MAP from pulse oximetry signal.
- Provision of preliminary results to the study measuring blood pressure using finger's MAP.

1.6 Thesis layout

Chapter 2 provides background information related to the research work presented in this thesis, including blood pressure signals, transmural pressure, and pulse oximetry genesis. Since this thesis aims at developing algorithms for assessing BP and pulse oximetry signals, a brief literature review of previously designed techniques associated with artefact detection is presented. In this thesis, PPG signals were used to assess the performance of developed algorithms, for BP and pulse oximetry signals. As such, the background information on PPG signals and their correlation with BP signals are also presented.

In chapter 3, the hardware and algorithms to record pulse oximetry and contact/transmural pressure are presented. The modified hardware designed to record Korotkoff sounds and blood pressure signals is also described.

Chapter 4 discusses the results obtained from comparing the output from the algorithm, in addition to results discussions and a conclusion.

Chapter 5 summarises the work presented in this thesis and discusses some future directions that can be pursued to advance signal quality and transmural pressure research.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Good health condition implies absence of disease. Health is a state of normal function that could be disrupted from time to time by disease. The state of health or the presence of disease (if any) could be diagnosed from some physiological measurements. Physiological measurements are the measurements made to assess how well the body functions. Physiological measurements may be very simple, such as body temperature measurement using thermometer, or may be more complicated, such as ECG measurements to examine heart function.

Two vital physiological measurements that could diagnose the presence of some critical diseases are blood pressure and pulse oximetry (known as PPG signal). These two parameters play significant roles in determining one's cardiovascular health and blood oxygenation.

The conventional method of measuring blood pressure is performed using cuff pressure. The measurement is normally taken from the patient's arm. However, to the best of our knowledge, there is no alternative device that has been publicly made available to measure blood pressure from any other part of the human body, such as the fingers. As such, this study will validate the reliability of measuring blood pressure using PPG signal through the finger.

2.2 Blood pressure

Blood pressure is the pressure of blood in the arteries as it is pumped around the body by the heart to supply oxygen. Determining the blood pressure is essential to protect and prevent humans from health diseases. High blood pressure usually does not have any symptoms and can lead to major health problems. It is a major risk factor in heart attacks, strokes, and cardiovascular diseases. For the prevention and early detection of hypertension, it is necessary to frequently measure blood pressure. Hypertension Society recommends effective BP monitoring at least three times per week [15]. Both physical stress and mental stress influence blood pressure. Normal ranges are only valid for relaxed persons. Occlusion of the arteries by a cuff changes the parameter to be measured. The most commonly used oscillometric method measures the MAP and only calculates the diastolic and systolic values [16]. For instance, blood pressure in the human body is measured using the units of millimetre mercury (mm Hg). Blood pressure is stated in two numbers, which are systolic pressure and diastolic pressure. Systolic pressure is a measure of blood pressure in blood vessels when the heart beats, whereas diastolic pressure is a measure of blood pressure in blood vessels when the heart rests.

2.2.1 Non-invasive and invasive blood pressures

Blood pressure can be measured using two methods: invasive method or non-invasive method. The non-invasive method, which measures blood velocity, does not provide a volumetric flow reading, unless the vessel cross section can be measured, such as in the case of ultrasound [17]. Conversely, the invasive method involves the use of a catheter. Alternatively, venous occlusion plethysmography is only capable of measuring average blood flow [17]. NIBP measurement requires a proper occluding and deflating mechanism and a well-trained observer [18]. The gold standard of NIBP measurement is based on the auscultation method [18]. The observer should decide whether the Korotkoff sound has appeared and disappeared so as to indicate systolic and diastolic pressures. The NIBP measuring methods can be further divided into two types, namely electronic methods and auscultatory methods. Electronic methods are further divided into two types, namely auscultatory and oscillometric methods. The auscultatory method is based on Korotkoff sound detection. The

Korotkoff and the oscillometric techniques for the indirect measurement of brachial artery BP were developed empirically [19]. They both show a reasonable correlation with the mean arterial BP, although it has been noted with either of these methods that individual measurements may, on occasion, differ substantially from the direct recordings and it is not known whether one method is better than the other in this regard [19]. Figure 2.1 illustrates the methods used to measure blood pressure.

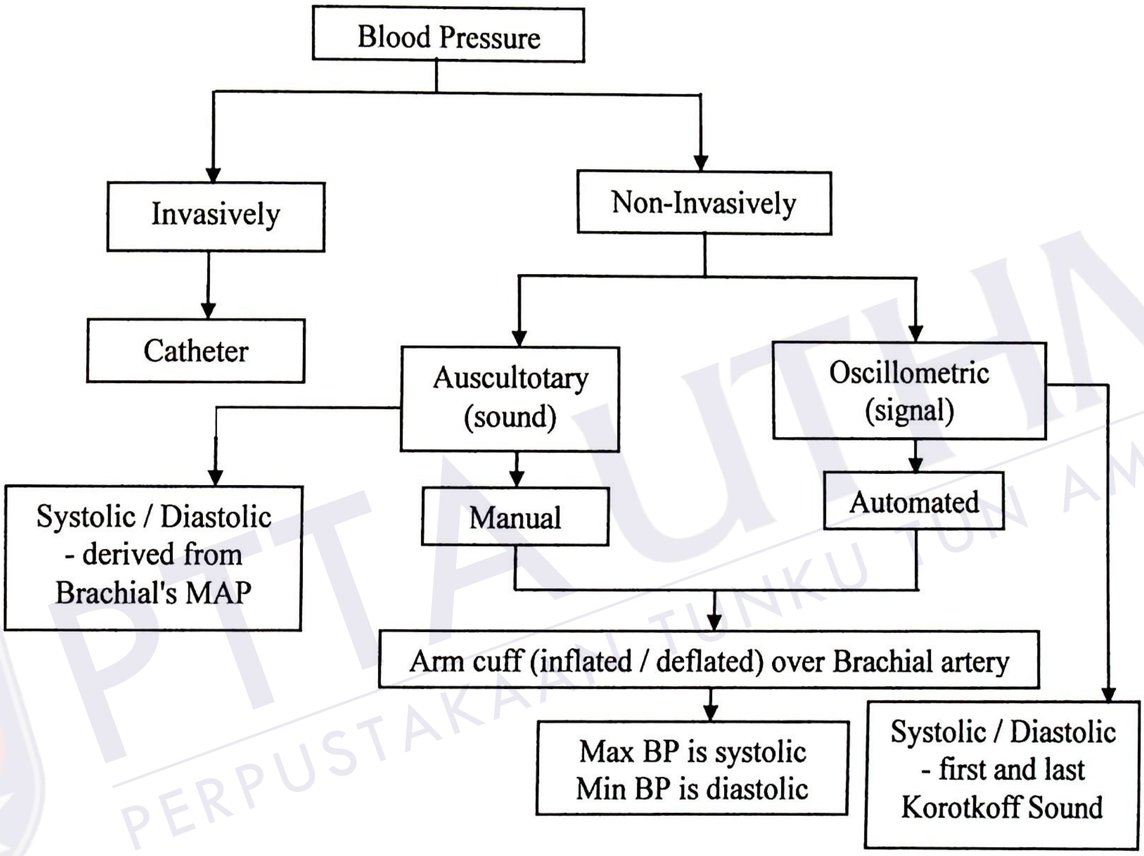

Figure 2.1: Blood pressure measuring methods

2.2.2 Auscultatory method

Auscultotary blood pressure measurement is a popular common non-invasive method frequently used in healthcare centres. In this method, an air bladder occlusion cuff and pressure gauge (sphygmomanometer) are used to occlude and then gradually release a patient's brachial artery. The presence or absence of a sound distal is used to identify the pressure at which the blood initially begins to flow through the brachial artery (systolic pressure) and at which normal blood flow returns (diastolic pressure) [20]. Auscultatory blood pressure measurement uses the presence and absence of acoustic pulses generated by an artery, which are detected with a stethoscope or a sensitive microphone, to non-invasively estimate the systolic and diastolic pressures [20]. Non-invasive methods are divided into two types: auscultatory method and electronic method. During the auscultatory method, Korotkoff sounds are detected through a stethoscope after the cuff is inflated and then deflated. Cuff-based blood pressure measurement devices provide no information on continuous blood pressure values [21].

2.2.2.1 Korotkoff sounds

Theories on the origin of the Korotkoff sounds have been divided into two categories: flow origin and pressure origin. The flow origin theory from Waterhammer stated that a high velocity stream of blood is released upon the opening of the lumen of the artery [22]. This stream then impacts upon the downstream stationary pool of blood. The resulting sudden deceleration of blood is assumed to produce the Korotkoff sound. The Korotkoff sounds have been shown to arise from the dynamic behaviour of brachial artery collapse under an occlusive arm cuff. The collapse results in increased nonlinearity of the segmental pressure–flow and pressure–volume relationships. As cuff pressure is allowed to fall, during blood pressure determination, the onset of Korotkoff sound is identified with systolic pressure and is referred to as S1 in Figure 2.2. Meanwhile, diastolic pressure is referred to as phase S4 or S5 sounds that characterise muffling and disappearance of sound, respectively. There are total of five phases in Korotkoff sounds, as presented in Table 1.

Table 2.1 : Five stages of Korotkoff sounds and their characteristics [23].

Phases	Characteristics of the phases
Phase 1 (S1)	Initial "taping" sound
Phase 2 (S2)	The taping sound increases in intensity is less precise in time
Phase 3 (S3)	The loudest phase, more similar to a thump than a tap
Phase 4 (S4)	A much more muffled sound
Phase 5 (S5)	Silence – no Korotkoff sound

During blood pressure measurement, the cuff is inflated above the systolic pressure. The cuff is then deflated and the audio signal from the stethoscope is analysed to determine what phase of Korotkoff sounds are being listened. The first phase (S1) of sound is recorded as systolic pressure and the fourth phase (S4) is recorded as diastolic pressure.

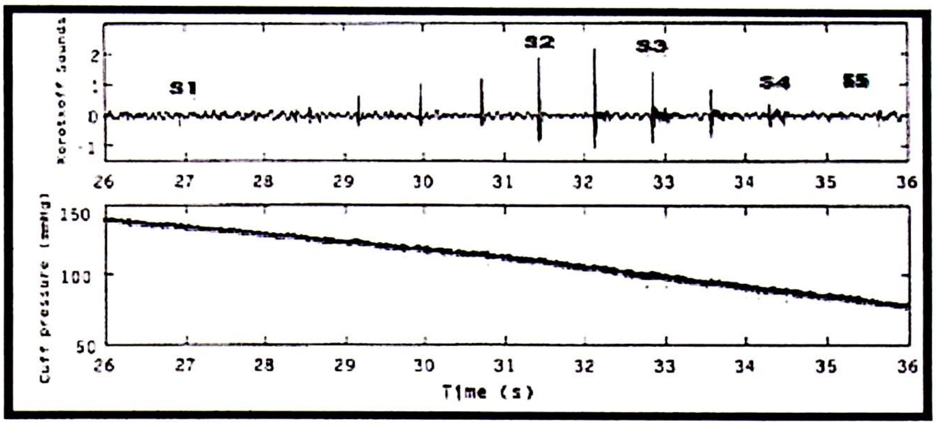

Figure 2.2: Korotkoff signals [23]

The five sound phases of Korotkoff sounds are shown in Figure 2.2, where S1 represents a very short duration 'tap' with frequencies concentrated below 300 Hz (dominant frequency 100 Hz), S2 is a larger amplitude signal with 3 frequency components about 10 ms apart with frequencies concentrated below 200 Hz (dominant frequency 60 Hz), S3 is a large amplitude signal with frequencies concentrated below 200 Hz (dominant frequency 110 Hz), and S4 is a lower level signal with frequencies concentrated below 300 Hz (dominant frequency 150 Hz). The last (fifth, s5) phase represents the complete disappearance of the sound [24].

During cuff pressure deflation from 160 to 40 mmHg, the signal value that produces the highest peak in Korotkoff waveform is the MAP, which is also known as the brachial MAP [25] as depicted in Figure 2.2.

2.2.3 Oscillometric

Non-invasive blood pressure measurement is an indisputable technique for assessing and treating patients in healthcare centres. This technique has been implemented using equipment based on the oscillometric method, as illustrated in Figure 2.3.

In the last few years, the oscillometric method has become widely popular for BP measurement. This is because the oscillometric system has strong resistance to noise from external environment interference since it does not employ a sound sensor. It only obtains accurate MAP rather than directly accessing the systolic blood pressure (SBP) and diastolic blood pressure (DBP) [26]. Most automated clinical NIBP monitors use the oscillometric technique. A cuff pressure is wrapped around the subject's bicep in an oscillometry system, which is based on sensing the pressure pulsations. During the oscillometry blood pressure measurement method, a pressure sensor used to record the pressure oscillations within the cuff pressure, instead of listening to distal sound (Korotkoff sounds) with a stethoscope, as in the case of the auscultatory method. An inflatable cuff pressure is wrapped around the patient's upper arm and is inflated, similar to the one used in the auscultatory method.

The automatic blood pressure monitoring system filters the microphone signal using a band pass filter whose pass band corresponds to the known frequency range of blood pressure sounds. This eliminates much of the noise from the microphone signal. A conventional electronic oscillometric measurement method uses only one pressure sensor instead of two sensors, as in the case of an advanced electronic oscillometric method. In both conventional and advanced electronic oscillometric methods, a pressure sensor is used to detect variations in pressure. The pressure sensor is also known as a pressure transducer, since it takes in mechanical air pressure and outputs an electronic voltage carrying the information from the pressure wave.

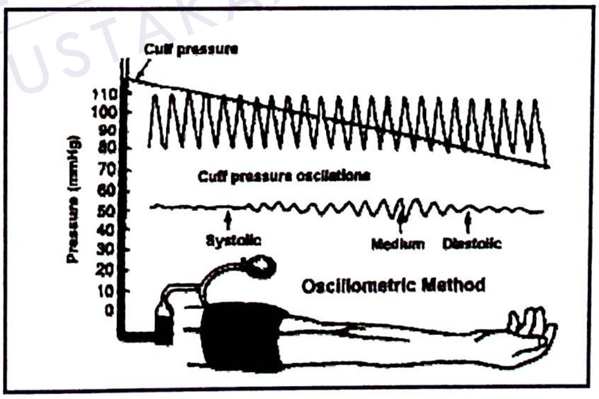

Figure 2.3: Oscillometric method [27]

The pressure cuff should be placed at the centre on the front arm during BP measurement. During oscillometric measurement, the data is obtained due to the flexing of the brachial artery after constriction. After fixing the pressure cuff on the arm, the pressure sensor should sit/be placed at the centre front of the arm. Hence, the manufacturer designs the cuff pressure with some marking/indication to be followed.

This will in turn change the profile of the air pressure wave being sensed by the pressure sensor. The pressure sensor (pressure transducer) detects pressure vibrations although the pressure cuff is inflated above the systolic pressure. This is because pressure changes (air oscillation) can still be found in the cuff. However, this minor oscillation is usually neglected.

When the cuff is inflated, the arm tissues are compressed until the blood vessel (artery) is reached, as shown in Figure 2.3. With the oscillometric method, it is assumed that the cuff membrane in contact with the patient's skin virtually becomes one, and they are assumed to share the same surface pressure. Any temporary changes in the skin's pressure due to the arterial walls flexing from the blood flow will cause pulses in the skin. As the skin is viewed as being one with the cuff, any pulses in the skin will cause air oscillations in the cuff. The cuff is then slowly deflated while the pressure sensor measures the pressure oscillations within the cuff. The pressure sensor measures the pressure vibration. The cuff deflation signal is filtered into the oscillometric waveform. The form and amplitude of the pulse waves are influenced by numerous factors, such as the heart rate, MAP, pulse pressure, arterial elasticity, cross section of the artery, thickness of the muscular tissues, and cuff compliance [28]. When a cuff placed around a bicep is deflated from above the systolic to below the diastolic pressure low amplitude (1 to 2 mmHg) pressure oscillations, arterial pulsations are induced in the cuff. The oscillations reach maximum amplitude when the cuff pressure equals the MAP [29]. This indicates that the highest oscillometric waveform envelope (OMWE) indicates MAP. The systolic and diastolic pressures can be determined empirically from the relationship between the envelope of the oscillations and the cuff pressure.

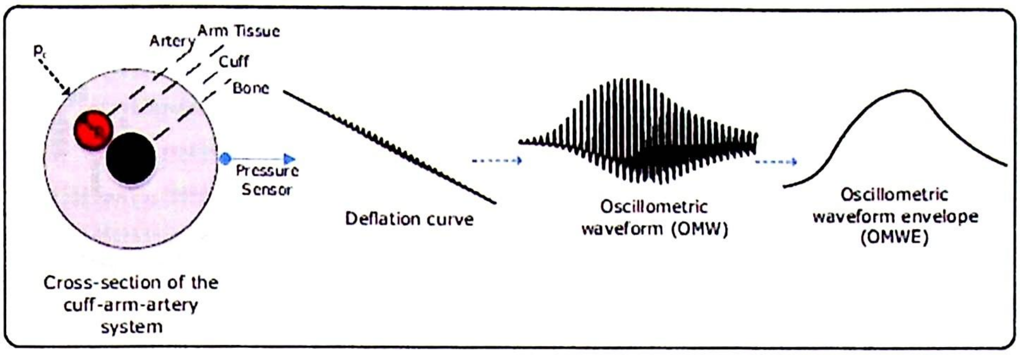

Figure 2.4: Oscillometry system physical setup [30]

Figure 2.4 illustrates the physical setup of the oscillometry system, which consists of three main components, namely the artery, cuff, and arm. The input of the system is the applied cuff pressure and mean arterial BP. As the cuff is inflated, the cuff pressure is transmitted through the arm soft tissue to the arterial wall. During inflation, the arterial vessel area decreases until it becomes flat and occluded. During the cuff gradual deflation period, the arterial vessel area increases until it becomes completely open at very low cuff pressures.

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