Non-invasive measurement of arterial pressure

I. Background

A. Circulatory systems

Human circulation takes place in a closed system that consists of two subsystems, *pulmonary circulation* and *systemic circulation*, connected in series. The blood in the circulatory system is kept in motion by the periodic contractions of the heart. In a cardiac cycle, the following steps take place:

- oxygen-depleted blood in the systemic vessels is collected by venae, which empty into the right atrium (RA);
- from the right atrium, blood flows into the right ventricle (RV);
- the contraction of the right ventricle pumps blood through the lungs;
- in the lungs, the blood releases carbon dioxide and picks up oxygen;
- pulmonary veins return the oxygenated blood to the left atrium (LA);
- from the left atrium, blood flows to the left ventricle (LV);
- the contraction of the left ventricle pumps oxygenated blood into systemic vessels.

Blood is prevented from flowing backwards by valves.
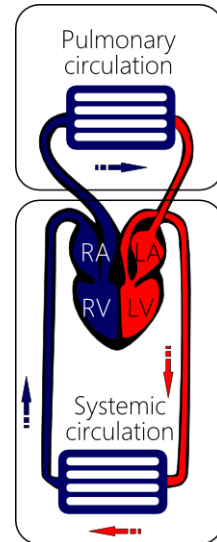
B. The fundamentals of haemodynamics

1. Equation of continuity

Since blood is an incompressible fluid, we can apply the *equation of continuity* to describe its flow and find the relationship between the average blood flow speed v and the cross-section area A of the vessel:

$$A \cdot v = \text{constant.}$$

This equation explains why blood flows much slower in capillaries, whose combined cross-section area is much greater than that of arteries. The product $A \cdot v$ is equal to the *volumetric flow rate I*, which is defined as follows:

$$I := \lim_{\Delta t \to 0} \frac{\Delta V}{\Delta t} = \frac{dV}{dt},$$

where t denotes the time and V denotes the volume flowing through a given cross section of the vessel.

2. Parabolic velocity profile

Due to its viscosity, blood does not flow with uniform speed throughout the cross section of the vessel. Flow speed is the greatest in the axis and the least near the walls of a vessel. Considering the propelling force due to a pressure difference Δp and the frictional forces exerted by neighbouring fluid layers, we can find the flow speed $v(r)$ at a distance r from the axis of the vessel:
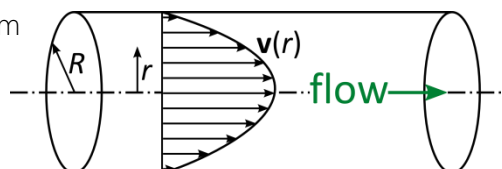
$$v(r) = \frac{\Delta p}{4\eta L}(R^2 - r^2),$$

where η denotes the viscosity of blood, R is the radius and L is the length of the vessel segment. This speed distribution over the cross section of the vessel is called the *parabolic velocity profile*.

3. The Hagen–Poiseuille equation

Using the parabolic velocity profile, we can obtain a relationship between the pressure difference Δp between two ends of a vessel and the volumetric flow rate I of the resulting flow:

$$I = \frac{\pi R^4}{8\eta L}\Delta p,$$

where R an L denote the radius and the length of the vessel, respectively, and η stands for the viscosity of the fluid. This is called the *Hagen–Poiseuille equation*, one of the very few physical equations in which a physical quantity scales with the fourth power of another quantity. The Hagen–Poiseuille equation shows us why vasoconstriction and vasodilatation (the narrowing and the widening of blood vessels) represent the most effective mechanism of blood flow regulation: since the volumetric flow rate I depends on the fourth power of the radius R, a slight alteration of the radius of the vessel will lead to huge changes in the volumetric flow rate.

Note that the Hagen–Poiseuille equation is the hydrodynamical analogue to Ohm's law in electricity. If we define the total peripheral resistance (TPR) as

$$\mathrm{TPR} := \frac{8\eta L}{\pi R^4},$$

the relationship between pressure difference and volumetric flow rate is of the form

$$\mathrm{TPR} = \frac{\Delta p}{I},$$

which follows the same pattern as that of the **resistance = voltage/current** relationship stated by Ohm's law.

4. Laminar and turbulent flow

The equations above assumed *laminar flow:* regular, orderly flow in which fluid layers slide upon each other without disruption. Observations show that in certain conditions (above a speed threshold, for example), fluid flow can become *turbulent:* noisy, ineffective flow in which eddies appear. Such transitions from laminar to turbulent flow can be predicted using the so-called *Reynolds number:*

$$\mathrm{Re} := \frac{\varrho v D}{\eta},$$

where ϱ and η denote the density and viscosity of the fluid, respectively, v is the flow speed and D is the diameter of the tube. If the Reynolds number calculated for the flow is below the critical value, the flow is expected to be laminar; otherwise, turbulence will set in.
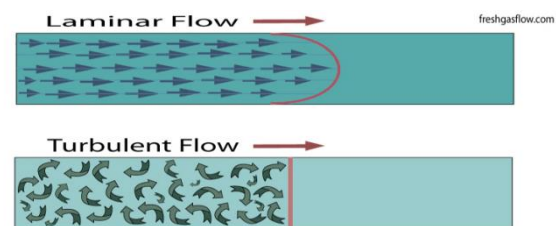
5. Blood pressure values

Heart contractions, vascular dynamics and pulse waves reflected from peripheral veins result in a characteristic time dependence of arterial blood pressure depicted in Figure 1.
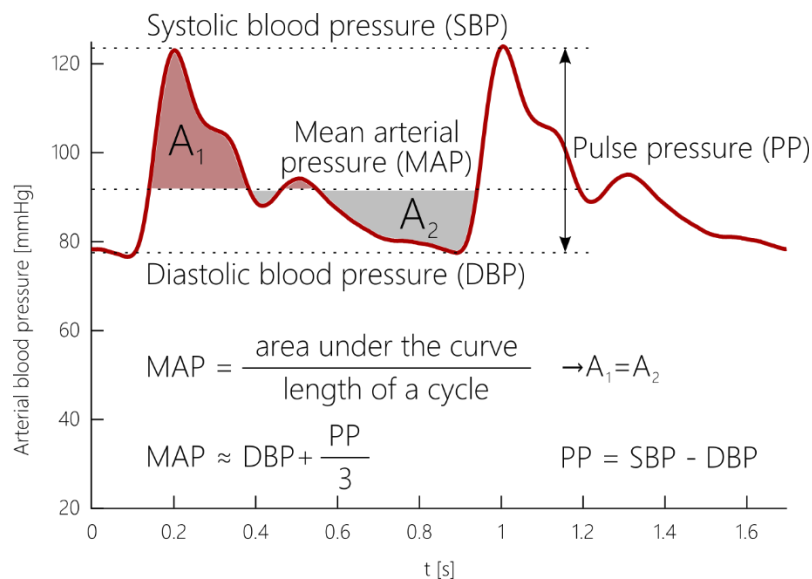
Figure 1. Characteristic blood pressure values

As you can see, arterial blood pressure varies in a cyclic manner between a maximum value called the *systolic pressure* (SBP; this corresponds to ventricular contractions) and a minimum value called the *diastolic pressure* (DBP). Reference values for healthy adults are 90–120 mmHg for systolic pressure and 60–80 mmHg for diastolic pressure. The difference between systolic and diastolic values is called the *pulse pressure* (PP). The *mean arterial pressure* (MAP) is defined as the mean value of the arterial blood pressure for a cardiac cycle, and it is often approximated with the following formula:

$$\text{MAP} \approx \text{DBP} + \frac{\text{SBP} - \text{DBP}}{3} = \text{DBP} + \frac{\text{PP}}{3}.$$

6. Hydrostatic pressure

Apart from heart action and vascular effects, hydrostatic pressure (the pressure resulting from the weight of a fluid column) also influences the blood pressure at a given location of the body. If at a certain point in a fluid the pressure is p_0, at another point which is located deeper by an amount h the pressure will be

$$p(h) = p_0 + \varrho g h,$$

where ϱ is the density of the fluid and g denotes the acceleration due to gravity. This $\varrho g h$ *hydrostatic pressure* allows us to express pressure values in terms of the height of the corresponding liquid column. Whereas the SI unit of pressure is the pascal ($1\,\text{Pa} = 1\,\text{N/m}^2$), in medical practice it is rarely used. The most widely used medical pressure unit is the *millimetre of mercury* (mmHg), which is the hydrostatic pressure of a 1-mm high column of mercury:

$$1\,\text{mmHg} = 13\,600\,\frac{\text{kg}}{\text{m}^3} \cdot 9.81\,\frac{\text{m}}{\text{s}^2} \cdot 0.001\,\text{m} = 133.4\,\text{Pa}.$$
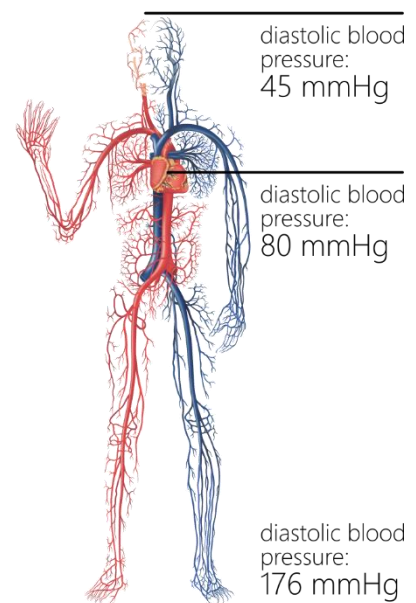
To express central venous pressure or intracranial pressure, a smaller unit, the *centimetre of water* (cmH$_2$O) is commonly used:

$$1\ \mathrm{cmH_2O} = 1000\ \frac{\mathrm{kg}}{\mathrm{m^3}} \cdot 9.81\ \frac{\mathrm{m}}{\mathrm{s^2}} \cdot 0.01\ \mathrm{m} = 98.1\ \mathrm{Pa.}$$

Comparing these, we can see that the conversion formula between mmHg and cmH$_2$O is

$$1\ \mathrm{mmHg} = 1.36\ \mathrm{cmH_2O.}$$

II. Measurement principles

A. Invasive methods

Blood pressure can be measured directly, by inserting a cannula needle in the artery. The needle is connected to a manometer, which can record the intra-arterial pressure continuously. This method is used in intensive care units and operating theatres.

B. The auscultatory method

Invasive methods are not desirable most of the time. The most robust and widely used non-invasive technique was established in 1905 by Nikolai Sergeyevich Korotkoff (also Romanised Korotkov). This method relies on auscultation. A sphygmomanometer cuff is placed on the upper arm of the patient and inflated securely above the expected systolic pressure so that it totally blocks any blood flow. While the cuff is slowly deflated, the examiner places a stethoscope over the artery and waits for sounds to be heard. When cuff pressure just drops below the systolic pressure, arterial blood pressure is just able to open the artery for the duration of the systole, and blood will start to flow. This is when the first sound (a so-called *Korotkoff sound*) is heard. This is followed by a series of Korotkoff sounds at each systole. When cuff pressure falls below the diastolic value, even the lowest blood pressure will suffice to keep the artery open, so blood will flow unblocked and without sound. The protocol can thus be summed up as monitoring the cuff pressure continuously (with a manometer), and reading the systolic value at the instant when the first Korotkoff sound is heard then the diastolic value when the last sound is heard.
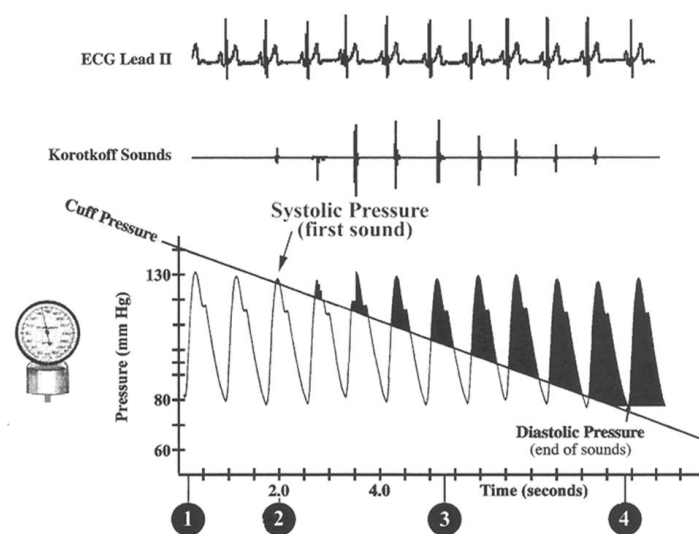

Figure 2. The auscultatory principle

The mechanism of the Korotkoff sounds is rather complex. Turbulence due to an increased flow speed (see the equation of continuity), the detachment of artery walls and cavitation (formation of bubbles) due to sudden pressure drops might all play a part.

C. The oscillometric method

Modern digital blood pressure meters do not apply auscultation. They rely on the observation that the variations of blood pressure will cause oscillations in the pressure in a cuff inflated over an artery. Modern electronic pressure sensors can record cuff pressure continuously and microcomputers can perform additional signal processing tasks on the recorded signal. Empirical data indicate that oscillations in the cuff pressure have the highest amplitude when cuff pressure is equal to the mean arterial pressure. Systolic and diastolic values are estimated using numerical techniques: most often, systolic pressure is identified as a cuff pressure above the mean arterial pressure at which oscillation amplitude is 50% of the maximum and the diastolic pressure is found as the pressure below the mean arterial pressure at which oscillation amplitude is 80% of the maximum (percentage values may depend on the method and the manufacturer).

D. Plethysmographic methods

The non-invasive methods described above have the disadvantage that they only record systolic and diastolic values and are not capable of monitoring blood pressure continuously. *Plethysmographic methods,* on the other hand, do not have this shortcoming. They are based on the observation that transmission of infrared light through a fingertip, for instance, will depend on the current blood volume there (since the main light absorbent in this range is haemoglobin). The so-called *Peňaz principle* utilises the fact that blood volume oscillations are greatest when there is no difference in pressure between the external and internal sides of the wall of a vessel (there is zero *transmural pressure*); if a feedback mechanism that regulates the cuff pressure ensures a constant plethysmographic signal (and therefore zero transmural pressure), we just have to record the pressure in the cuff, knowing that it follows the arterial pressure. A continuous waveform recorded using this principle can be seen in Figure 1.

III. Measurement objectives

- to estimate the values of systolic blood pressure (SBP) and the diastolic blood pressure (DBP) by the auscultatory identification of the first and last Korotkov sound, respectively, during automatic deflation of the upper arm cuff;
- to compare these measurements to the SBP, DBP and the heart rate (HR) displayed by the semi-automatic upper arm meter and the wrist blood pressure meter placed on the opposite arm;
- to assess the variability of the readings by repeating the measurements at least 3 times;
- to make measurements with the wrist blood pressure meter at the level of the heart and a different known level (eg, with raised arm) and explain the differences.

IV. Measurement protocol

1. Start BSL Lessons and open Lesson 16: Blood pressure. The name of the file should be the electronic student code of the patient.
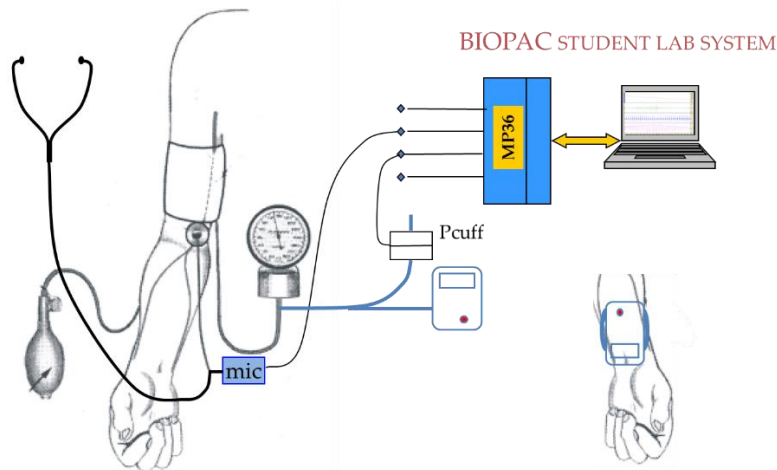2. Leave the cuff on the desk completely deflated. Pick up the stethoscope.

Figure 3. The measurement set-up (ECG electrodes are not indicated)

3. Follow the calibration steps shown in the Journal of BSL Lessons: tap (or blow) twice on the diaphragm gently. The calibration ends automatically after 8 s.

4. Put the cuff of the upper-arm blood pressure meter (the one connected to the Biopac device) on the upper left arm and insert the stethoscope head under the cuff before you tighten it. Place the wrist pressure meter on the wrist of the right arm.

5. Perform the following steps:

a) Turn on the upper-arm blood pressure meter. Wait for the zero and the heart symbol to appear.
b) Start the recording in BSL Lessons *(Record)*.
c) Pump the cuff up to about 160 mmHg. The pressure in the cuff will start decreasing automatically when the pumping is stopped.
d) While continuously looking at the pressure gauge on the screen, read the pressure values when you start hearing the Korotkoff sounds, and when you stop hearing them.
e) Suspend recording *(Suspend)*.

Perform 3 or 4 manoeuvres repeating the steps above. In each manoeuvre, a different student should be the listener.

6. Using the wrist pressure meter, record the systolic and diastolic pressure values as well as the pulse with your hand in an elevated position then in a lowered position.

V. Data analysis

A. Determining blood pressure values using the auscultatory method and the oscillometric method

1. Open the regular laboratory report file located at C:\Temp\Measure\4-BloodPressure.xlsm.

2. Start BSL Pro and open the recording to be analysed (eg, BP-J.acq).

3. Zoom in on the Korotkoff sound interval in the Stethoscope channel – use the *Vertical Autoscale* and *Horizontal Autoscale* buttons (see below) if zooming goes wrong.
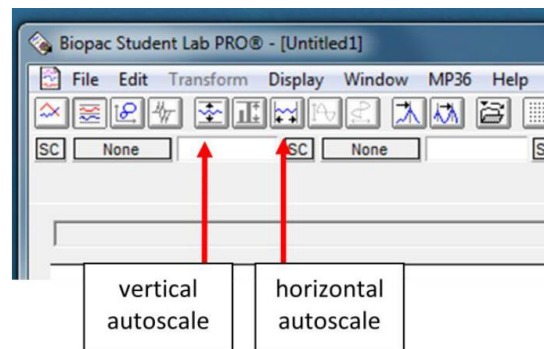
Figure 4. Autoscaling in Biopac

4. Find the first and last Korotkoff sounds and read the systolic and diastolic pressure, respectively (channel 1 – *Value*), and type SBP and DBP in the corresponding Excel report cells.

5. Select (I-beam) the interval between the first and last Korotkoff sounds and calculate the *Mean* of the *Rate* channel; type the value in the corresponding cell in the report.

6. Find the maximum oscillation amplitude in channel *Oscillometric signal* by I-beam selection of each large pulse (from maximum to minimum) and reading the peak-to-peak *(P-P)* value. The oscillometric estimate of MAP is the mean cuff pressure value of the selection when the oscillation amplitude in the cuff pressure has a maximum; type this value in the report cell.
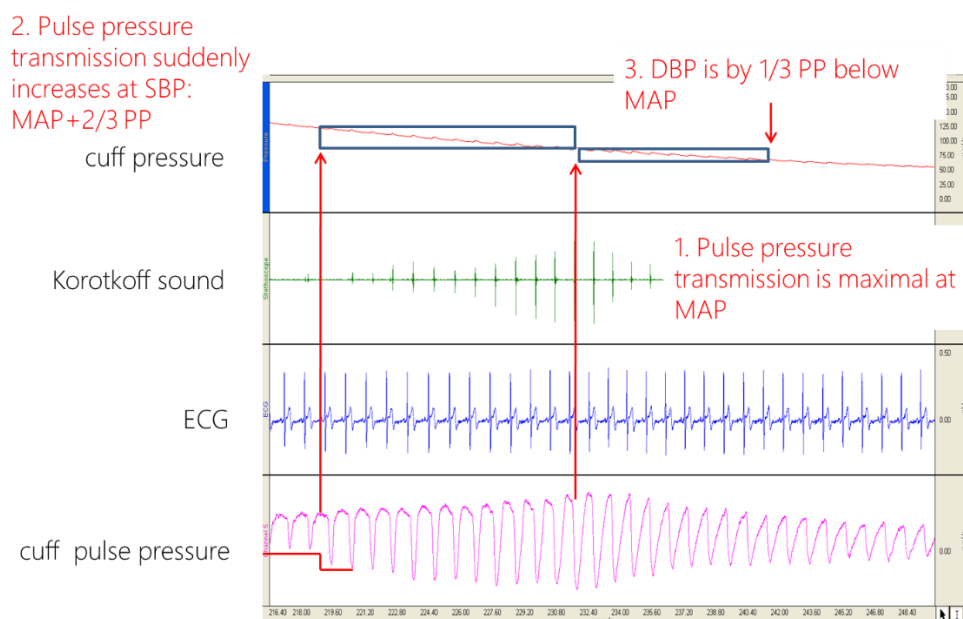

Figure 5. Finding the mean arterial pressure using the oscillometric principle

7. Scroll and search for the next **valid** deflation manoeuvre and repeat the steps 3–6.

8. Using the appropriate formula, calculate MAP from each pair of SBP and DBP just read.

9. Look at the column means and standard deviations and summarise your observations in the green text cell.

B. The effects of hydrostatic pressure

1. Calculate the hydrostatic pressure difference between the elevated and lowered positions of the arm using the height difference previously measured (see I.B.6 – Hydrostatic pressure).

2. Convert the hydrostatic pressure obtained in pascals to millimetres of mercury (see I.B.6 – Hydrostatic pressure).

3. Compare the predicted pressure difference between lowered and raised positions to the pressure difference actually measured and decide whether the difference can be caused by the hydrostatic pressure.

4. Submit your report.