Non-invasive Blood Pressure Measurement

Introduction

The determination of an individual's blood pressure is a standard clinical measurement, whether taken in a GP's office or in hospital during a surgical procedure. As we have already seen, the function of the blood circulation is to transport oxygen and other nutrients to the tissues and to carry metabolic waste products away from the cells. The resistance to blood flow is regulated by the arterioles, which are under local, neural and endocrine control. The exchange of the nutrient material takes place at the capillary level. Mechanical contraction of the ventricular muscle generates ventricular pressures that force the blood through the pulmonary circulation (right ventricle) and the systemic circulation (left ventricle), causing pressures in each. Blood is pumped from the left ventricle through the *vascular* system which consists of (broadly) three sub-systems:

1. The high pressure arterial tubes which carry the blood away from the heart. These tubes are relatively thick-walled and stiff.
2. A microscopic capillary network in which the blood is brought into close proximity with cells allowing transfer of oxygen, nutrients and enzymes into the cell and the removal of waste products and enzymes from the cell. The precise nature of this transfer depends on the nature of the cell.
3. The low pressure venous tubes which return the blood to the heart. These tubes are relatively elastic and thin (but of greater cross-sectional area than the arterial tubes).

By this means, blood can be brought to within a cell or two of every cell in the human body. However, not every cell receives blood all the time;

the regulation of where the blood goes at any point in time is a complex subject and beyond the scope of this course.

Blood pressure is generally expressed using two numbers: the *systolic* and *diastolic* arterial blood pressures. A common misconception is that they are the pressure in the arterial and venous systems respectively. In fact:

- Systolic pressure is the arterial pressure when the heart is beating (i.e. during systole). To a first approximation, it is the highest pressure present in the arterial (and indeed the whole vascular) system and is a reflection of how hard the heart is pumping.
- Diastolic pressure is the arterial pressure when the heart is not beating (i.e. during diastole) and, to a first approximation, is the lowest pressure present in the arterial (but not vascular) system when the heart is resting between beats. It is a reflection of how difficult it is to pump blood into the body (as represented by the capillary system).

Both pressures are usually measured in millimetres of mercury (mmHg). When blood pressure is quoted, it is given in the form "systolic over diastolic": e.g. 120/70 is a systolic pressure of 120 mmHg and a diastolic pressure of 70 mmHg. Doctors are interested in both the absolute values and the difference between the two (known as the *pulse pressure*) as these three factors help them diagnose conditions.

A fourth measure of blood pressure is sometimes used: *mean arterial pressure* or MAP. In cases where the systolic and diastolic pressures are known, MAP provides a single value summary of arterial pressure according to the following formula:

$$\text{MAP} = \text{Diastolic Pressure} + (1/3)\,(\text{Systolic Pressure} - \text{Diastolic Pressure})$$

Direct blood pressure measurement

Invasive blood-pressure sensor systems can be divided into two categories according to the location of the sensor element. The first method for direct measurement of pressure is to couple the vascular pressure to an external sensor element via a liquid-filled catheter. In the second category, the liquid coupling is eliminated by incorporating the sensor into the tip of a catheter that is placed in the vascular system. Such a device is known as an *intravascular pressure sensor* and blood pressure in the Intensive Care Unit is usually monitored beat-by-beat using this type of device.

The focus of this course, however, is on non-invasive measurements and so we will now consider two methods by which systolic and diastolic blood pressure may be measured non-invasively but intermittently. These methods both involve the use of an occlusive cuff (usually applied to the arm) which is inflated to a pressure above the systolic level and then slowly released.

Indirect blood pressure measurement -vascular unloading

Figure 30 shows a representation of the limb to which the occlusive pressure, P_o, is applied. This pressure is transmitted through the tissues to the arteries and the pressure applied to the wall of an artery is also P_o. This means that the pressure difference between the inside of the blood vessel and the surrounding tissue, the *transmural pressure*, is lowered. When the applied pressure is raised sufficiently for it to be equal to the arterial pressure, then there is no radial stress in the arterial wall. It is assumed that there is also no hoop stress in the wall at this point and the blood vessel is said to be unloaded (known as *vascular unloading)*. If the applied pressure is further increased such that $P_o > P_a$, where P_a is the arterial pressure, the blood vessel will collapse and flow will be completely occluded.

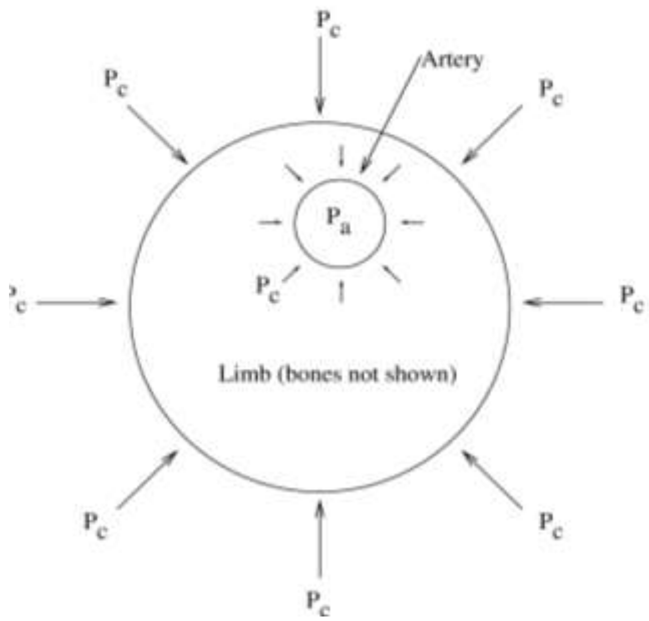

Figure 30: Occlusive pressure applied to the outside of a limb is transmitted to the arteries in the limb.

The cuff is usually a flat bladder which can be wrapped around the arm and inflated, thereby applying the internal pressure of the air in the bladder uniformly around the limb as in Figure 30 in which we can now take P_o to refer to the cuff pressure, P_c.

Hence if P_o is greater than the pressure P_a in the artery, blood flow will be blocked beyond the point of occlusion. Using medical terminology, it can be said that the flow *distal* to the occluding cuff is stopped. (The opposite of distal is *proximal*.)

Korotkoff sounds

Also known as the *auscultatory* method, the method of Korotkoff was introduced by the Russian army physician Korotkoff in 1905. The occlusive cuff is inflated until the pressure is above systolic pressure and then is slowly bled off at a rate of around 2 to 3 mmHg/s. When the systolic peaks are higher than the (decreasing) cuff pressure, the blood spurts under the cuff and the audible sounds generated by the flow of blood and the vibrations of the vessel under the cuff are known as *Korotkoff sounds.* As the pressure in the cuff is decreased further, the audible Korotkoff sounds pass through five phases:

I Initial "tapping" sounds.
II The tapping sounds increase in intensity but are less well defined in time.
III The loudest phase, more akin to a thump than a tap.
IV A much more muffled sound.
V Silence - no Korotkoff sounds

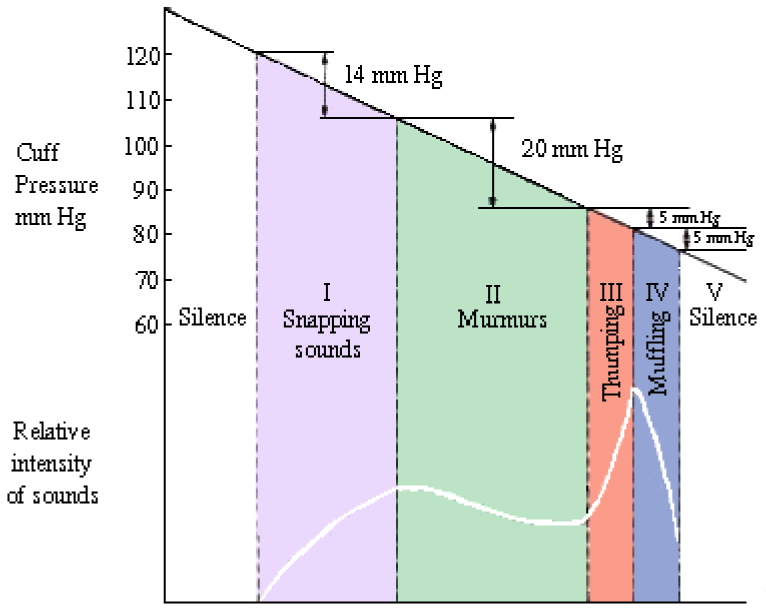

Figure 31: A summary of the five Korotkoff sounds for a healthy patient. Source: Guydon

It is important to note that these are very empirical descriptions (for example, Phase III is sometimes described as being followed by a brief murmur due to turbulence). However, the vast majority of clinicians use the Korotkoff sounds to take accurate blood pressure measurements because the systolic and diastolic pressures are relatively well defined by this method. They are the pressures at which the Korotkoff sounds start and at which the sounds become muffled (Phase IV) respectively. Figure 31 presents a summary of Korotkoff sounds.

Automating the method of Korotkoff

Figure 32 shows the overview of a system for automating the measurement of blood pressure using the method of Korotkoff. A control system receives a request for a reading to be taken and this initiates the following three-phase process:

1. The cuff is inflated to 20-30 mmHg above the systolic pressure. If a valid reading has already been taken, the previous value can be used to determine the initial cuff inflation pressure.
2. The cuff is deflated slowly (2-3 mmHg per second) and the audio signal from the microphone is analysed to extract the different phases of Korotkoff sounds. The system records the pressure at which sounds start (the systolic pressure) and the pressure at which phase IV sounds are present (the diastolic pressure).
3. Once Phase IV has been identified, both the systolic and diastolic pressures will have been determined. The cuff is then deflated rapidly and the values of systolic and diastolic pressures are displayed.

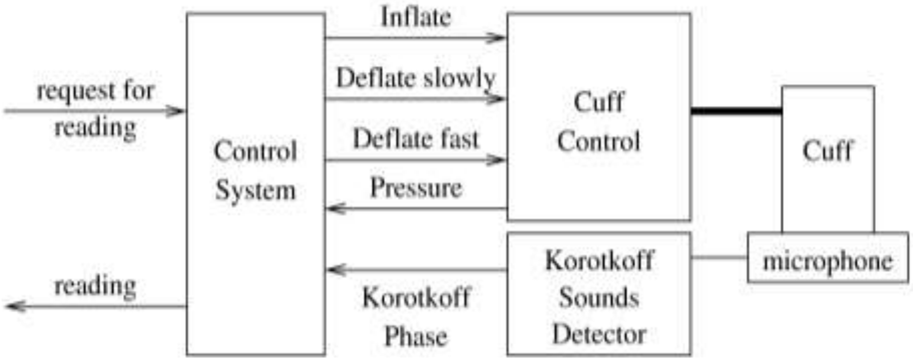

Figure 32: An overview of a system for automated blood pressure readings using the method of Korotkoff. Note that thick lines represent piping.

The automated analysis of Korotkoff sounds is not a trivial task. First, it is necessary to separate the Korotkoff sounds from the background noise (including the noise of the heart beating). Second, the identification of the different phases requires the implementation of a non-linear pattern matching system or the use of a rule-based system. These are beyond the scope of this course. However, it is worth considering the cuff control system in more detail.

Cuff control

Figure 33 shows a cuff control system. The cuff is inflated (pressurised) by using a pump to blow air into it. When cuff inflation is requested, the pump is turned on and Valve 1 is opened. When the cuff is sufficiently inflated, the control signal will be changed to "deflate slowly" and Valve 1 will be shut to present unwanted air leakage. Valve 2 will be opened which allows a controlled slow leakage of air from the cuff. Finally, once the readings have been made, the cuff can be emptied of air and Valve 3 is opened to achieve this.

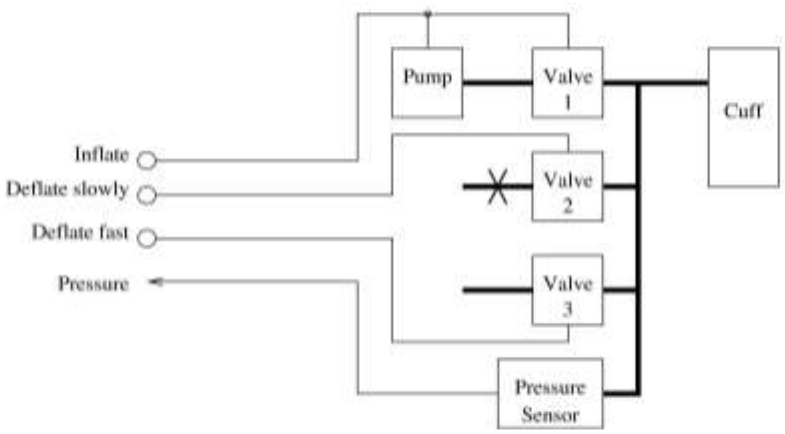

Figure 33: A control system for an occlusive cuff. Note that the safety cut-out devices which would be present in a real system are not shown. Thick lines represent tubing and the valves are "open or shut".

Safety aspects of cuffs

It is important that cuffs are not inflated to too high a pressure, or even held at moderately high pressure for too long. There are two reasons for this: firstly, given that the purpose of the pressure is to occlude blood flow, it is necessary to ensure that oxygen depletion does not occur for too long in the occluded sections of the limb. Secondly, over-inflation of the cuff can result in bruising of the arm as shown in Figure 34.

Figure 34: Bruising on an arm caused by over-inflation of the cuff

Oscillometry

Oscillometry is now the standard method for automated blood pressure measurement. It measures the amplitude of oscillations in the cuff pressure signal which are created by expansion of the arterial wall each time blood is forced through the artery. This phenomenon has been recognized since 1885 when the French physiologist Marey observed that, if he placed a patient's arm in a pressure chamber, the pressure of the chamber would fluctuate with the pulse and the magnitude of the fluctuation would vary with the pressure of the chamber.

Oscillometry is performed using a standard arm cuff, with a pressure transducer in line with the cuff tubing to record the cuff pressure. When the cuff pressure is raised quickly to pressures higher than systolic pressure, the radial arterial pulse disappears as the artery is completely occluded. With a slow reduction in cuff pressure, blood spurts through the main artery at the point when the cuff pressure is close to systolic pressure and the cuff-pressure oscillations become larger as shown in Figure 35.

As the cuff continues to deflate, the amplitude of the oscillations increases reaching a maximum, and then decreases as the cuff pressure is reduced to zero. The maximum is reached at the true mean arterial pressure (MAP).

Intuitively, one might expect that the onset of the oscillations would occur at systolic pressure and that the disappearance of the oscillations would occur at diastolic pressure.

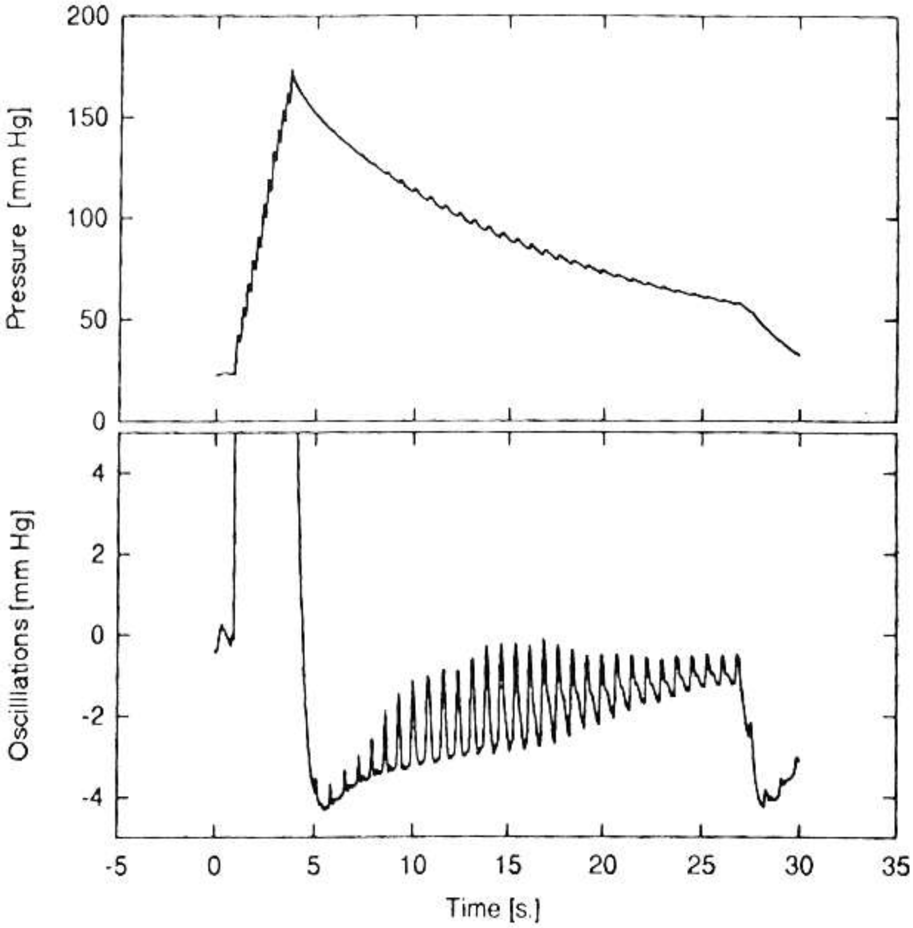

Figure 35: A recording of cuff pressure. The pressure is initially raised rapidly and then lowered slowly. The lower trace shows the oscillations in cuff pressure obtained by high-pass filtering above 0.5 Hz.

In fact, the onset of oscillations occurs well above systolic pressure and the oscillations do not disappear until well below diastolic pressure. At cuff pressures above systolic, small-amplitude pressure oscillations occur in the cuff pressure due to artery pulsations under the upper edge of the cuff, which are communicated to the cuff through the adjacent tissues. Empirical studies have shown that the systolic and diastolic pressures, P_s and P_d respectively, occur when the amplitudes of oscillation, A_s and A_d respectively, are a fixed fraction of A_m, the maximum amplitude of oscillation (which occurs when the pressure is equal to the MAP). Thus:

- P_s is the pressure above MAP at which $A_s/A_m = 0.55$
- P_d is the pressure below MAP at which $A_d/A_m = 0.85$

Using this method, it is therefore possible to design a device for measuring blood pressure non-invasively in which only a cuff needs to be attached to the patient. A block diagram of such a system is given in Figure 36 in which the cuff control system is the same as that discussed for the automated Korotkoff sounds system (see Figure 33).

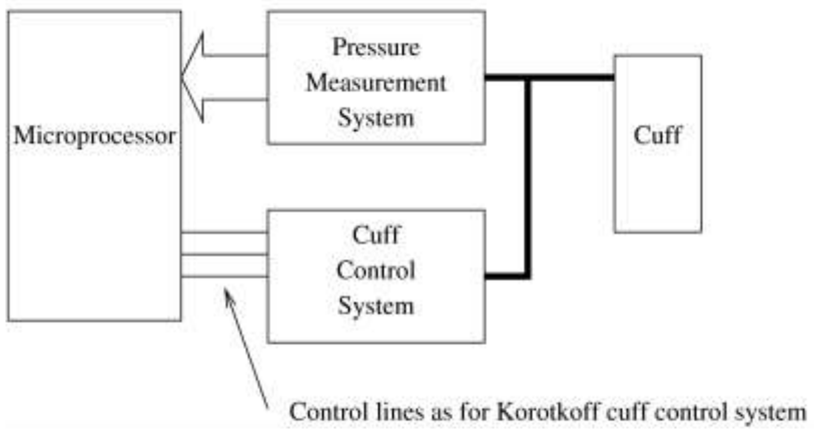

Figure 36: Overview of a system for recording blood pressure using oscillometry

The major components of the pressure measurement system will now be considered block by block.

Pressure sensor

Pressure sensors typically employ the piezo-resistive principle to convert pressure to an electrical signal. A silicon chip is micro-machined to give a diaphragm around which four resistors are diffused in a bridge configuration. Application of pressure to the diaphragm results in a change in the value of these resistors which creates a differential voltage output proportional to the applied pressure.

Pressure has to be measured at values above the highest systolic pressure down to values below the lowest possible diastolic pressure. Systolic pressures above 260 mmHg are rarely seen and so a range of 0 to 300 mmHg should achieve this.

Typical piezo-electric sensors have an output impedance of 5kΩ and generate differential outputs from 0 to 200 mV.

Amplification and filtering

Given the differential nature of the output from the sensor, a differential amplifier is required. It is essential that the circuit used has a near-infinite input impedance because the sensors have a finite output impedance (approximately 5kΩ) which varies with the applied pressure. Hence an instrumentation amplifier such as that considered earlier for ECG amplification would be appropriate.

From Figure 35, it is clear that there are two pressure signals: the underlying pressure to which the cuff is inflated (or deflated) and the cardiac-synchronous fluctuations. The underlying signal is a low frequency signal which can be extracted by passing the original signal through a low-pass filter. The beat-by-beat fluctuations are extracted using a high-pass filter.

Analogue to digital converters

The highest frequency signal we wish to sample is the cardiac-synchronous fluctuation signal. 5 Hz is a reasonable upper limit for the heart rate. Nyquist sampling theory dictates that the minimum sampling rate is therefore 10 Hz. However, in this case it is necessary to characterise the fluctuations in some detail and so it is necessary to take 5 to 10 samples per cardiac-synchronous fluctuation. A sampling rate of 50 to 100 Hz would therefore be appropriate.

The low-pass filtered signal (cuff pressure) must be digitised with sufficient accuracy to quantify the underlying pressure to 1 or 2 mmHg in a range of 300 mmHg. 8 bits give a dynamic range of 2^8 or 256 levels which should be sufficient.

The high-pass filtered signal (cardiac-synchronous fluctuations) should also be digitised with sufficient accuracy for the relative amplitude of each fluctuation to be determined. 8 bits gives a dynamic range of 256 or a step of 1/256 which is less than half a percent, which should be sufficient given a maximum range of ±5 mmHg (see Figure 35).

Microprocessor

The final component of the automated blood pressure measurement system is the microprocessor. This runs the programme which controls the cuff (via the three-phase cuff control circuitry) and interprets the two pressure signals.

The cardiac-synchronous signal is analysed to determine the amplitude of the fluctuations. The maximum amplitude is first detected as this corresponds to the Mean Arterial Pressure (MAP). The systolic pressure can then be determined retrospectively from the data stored in memory and by selecting the cuff pressure (low-pass filtered signal) which corresponds to an amplitude of 0.55 of the maximum amplitude.

The diastolic pressure is the cuff pressure which is measured when the amplitude of the fluctuations decreases to 0.85 of its maximum value. The accuracy of the systolic and diastolic pressure estimates may be increased through the use of interpolation.

Finally, the microprocessor may also compute the pulse rate of the patient. The fluctuations analysed for amplitude information are cardiac synchronous and so the pulse rate can be determined by measuring the interval between successive peaks of the high-pass filtered signal.