Non Invasive Blood Pressure

Alongside heart rate, Blood Pressure is one of the physiological parameters which has been measured by clinicians for the longest period of time: it was known to be important in the 16th century. It remains one of the most important physiological indicators to date and is also one of the more awkward parameters to measure. As has been discussed, blood is pumped round the body by the heart. The blood makes its way around the body through the vascular system which consists of (broadly) three phases:

1. The high pressure arterial tubes which carry the blood away form the heart. These tubes are relatively thick–walled and stiff.

2. A microscopic capillary network is which the blood is brought into close proximity with the cells in organs allowing transfer of oxygen, nutrients, enzymes and so on into the cell and the removal of waste products and enzymes from the cell. The precise nature of what is transferred 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 (of which there are about 1000000000000000, or 20000 times the world population). 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 but a broad approximation is that blood goes to where is its most needed mitigated by doing least long term damage to the body (in terms of future survival).

Blood pressure is generally quoted as 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 (ie during the systole), it is roughly 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 (ie during the diastole) and is roughly the lowest pressure present in the arterial (but not vascular) system when the heart is resting between beats. It is a reflection of how hard the body (as represented by the capillary system) is to pump blood into.

Both pressures are measured in millimetres of mercury (mmHg). When blood pressure is quoted, both values are given in the form "systolic over diastolic": eg 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.

Invasive measures apart, a fourth measure of Blood Pressure is used: mean arterial pressure or MAP. In the case where the systolic and diastolic pressures are known it provides a single value summary of arterial pressure and is determined by the following formula:

\[
MAP = \text{Diastolic Pressure} + \frac{\text{Systolic Pressure} - \text{Diastolic Pressure}}{3}
\]

It is possible to measure MAP non–invasively but clinician prefer to use systolic and diastolic pressures. We will now consider three methods by which systolic and diastolic blood pressure can be measured.

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4 *ie* your brain, heart and lungs are much more important than your toes.
5 See the sections on heart function earlier on in these notes; Figure 8 in particular.
Method of Korotkoff

Also known as the auscultatory method, the method of Korotkoff was introduced by the Russian army physician N. Korotkoff in 1905. Both this method and the next one we will consider rely on blocking, or occluding, the flow of arterial blood for a short period of time.

To achieve this, compressive pressure is applied to a limb such that the pressure is transmitted to the underlying blood vessels. Figure 45 shows a symbolic representation of a limb to which compressive pressure, $P_c$, is applied. This pressure is transmitted through the flesh to the arteries as shown and the pressure applied to the wall of the artery is also $P_c$. This means that the pressure difference between the inside of a blood vessel and the surrounding tissue, the transmural pressure, is lowered.

Consequently, when the applied pressure is equal 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 vessel is said to be unloaded and any method which achieves this is said to achieve vascular unloading. If the applied pressure is further increased such that $P_c > P_a$, the vessel will collapse and flow will be completely occluded.

**Occlusive cuffs**

Vascular Unloading is achieved using an occlusive cuff, 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 45 in which we can now take $P_c$ to refer to the cuff pressure.

So, if $P_c$ is greater than the pressure in an artery then blood flow will be blocked beyond the point of occlusion. In medical terminology, if something is further away from the heart than a reference point, it is said to be distal to that reference point and so we can say that flow is stopped distal to an occluding cuff. (The opposite of distal is proximal.)

**Korotkoff sounds**

What Korotkoff discovered was that if a limb in partially occluded, a cardiac synchronous sound is still present in the limb distal to the occlusion (ie further away from the heart than the occlusion). These sounds are known as the Korotkoff sounds and are what clinicians listen for using a stethoscope when they take Blood Pressure measurements. They are only
present when the artery is partially occluded, if the blood vessel is fully occluded or not occluded at all then they are not present.

To take a Blood Pressure reading, the clinician inflates the cuff to a sufficient pressure to completely occlude the artery. The pressure is then reduced slowly (about 2–3 mmHg a second) and 4 (or 5) different 'phases' of Korotkoff sounds are by the clinician over sequential pressure ranges:

I. Initial "tapping" sounds.
II. The tapping sounds increase in intensity are less precise 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

It is important for us, as engineers, to note that these are very empirical descriptions and although the vast majority of clinicians use them to take very accurate Blood Pressure measurements they describe the phenomenon in an imprecise manner. Searching the literature will reveal a wide variety of slightly varying descriptions, particularly in relation to the "murmurs" which can also be present.

However, the systolic and diastolic pressures are relatively well defined by this method: they are the pressures at which the Korotkoff sounds start and the Phase IV sounds (ie when the sounds become muffled) respectively. Figure 46 presents a summary of Korotkoff sounds.

![Figure 46: A summary of the five Korotkoff sounds for a healthy patient. Source: Guydon](image)

Traditionally, it has been assumed that Korotkoff sounds are caused by turbulence in the artery when the blood is being pumped through an occluded section and many current text books use this explanation. However, there are good arguments that this is not the case (for example, the fact that they still occur when the artery is only marginally occluded near diastolic pressure). The precise cause of Korotkoff sounds is a research area, but a recent plausible suggestion is that they are caused by phase distortion of the pulse resulting from complex pressure/cross sectional area interactions.
Automating the Method of Korotkoff

Figure 47 gives an overview of a system for automating the measuring of Blood Pressure using the method of Korotkoff. A control systems receives a request for a reading to be taken and it then follows a three phase process:

1. The cuff is inflated to slightly (20–30 mmHg) above the systolic pressure. If a 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 determine what phase of Korotkoff sounds are being observed. The system makes a note of 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 the deflated rapidly and the determined pressures are reported.

The automated analysis of Korotkoff sounds is in fact a very complex task. First, it is necessary to separate the Korotkoff sounds from the background noise (including the noise of the heart beating). Second, assessing which phase a particular sound implies is a complex signal processing task which requires a complex combination of hardware and software processing and, probably, the implementation of either a non–linear pattern matching system of the use of rule based systems. These are beyond the scope of this course. However, it is worth considering the cuff control system in more detail.

Cuff control

Figure 48 shows a cuff control system. The cuff is inflated (ie pressurised) by using a pump to blow air into it and so when cuff inflation is requested the pump is turned on and that valve is opened. When the cuff is sufficiently inflated, the control signal will be changed to "deflate slowly" and the valve between the pump and the motor will be shut to present unwanted air leakage. The second valve 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 the final valve is opened to achieve this.
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: first, given that the purpose of the pressure is to occlude blood flow down the limb it is necessary to ensure that the occlusion does not occur for enough time to cause significant oxygen depletion for too long in the occluded sections of the limb.

Secondly, in many people ‘over–aggressive’ measurement of Blood Pressure can result in bruising of the arm as shown in Figure 49. Whilst this may seem a minor side effect, if Blood Pressure readings are being taken every hour, the cumulative effects are quite painful for the patient.

Therefore, it is necessary for the control system to stop the blood pressure reading if the pressure is too high for too long.

Figure 48: A control system for an occlusive cuff. Note that the safety cut–out devices which would be present in a real system are not present. Thick lines represent tubing; the valves are "open–shut" rather than selecting one of two possible flow paths.

Figure 49: Bruising on an arm caused by a single use of an ‘over–zealous’ oscillometric Blood Pressure device.