Blood pressure measurement

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Key points

Blood pressure is one of the minimum standards of patient monitoring required during anaesthesia.

Blood pressure measurement, in combination with pulse oximetry and capnography, will detect 93% of adverse events occurring during anaesthesia.

Unless otherwise indicated, the fifth Korotkoff sound should be used to determine diastolic pressure.

The gold standard method of measuring blood pressure is invasive intra-arterial monitoring. However, this is not without associated risks.

All techniques for the measurement of blood pressure have known limitations.

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Hales first measured blood pressure in 1733 by inserting tubes directly into the arteries of animals. Non-invasive techniques for the measurement of blood pressure have been in existence since the early 1800s, although Riva Rocci, an Italian physician, is credited with developing the first conventional sphygmomanometer in 1896. In 1905, Nicolai Korotkoff described various sounds while auscultating over the brachial artery during deflation of a Riva Rocci cuff.[1]

Blood pressure measurement was first used during anaesthesia by Cushing in 1901. Now it is part of the minimum standard of patient monitoring as recommended by the Association of Anaesthetists of Great Britain and Ireland and should be measured in all patients undergoing, and recovering from, general anaesthesia, regional anaesthesia and sedation.[2] In combination with other monitoring, it will help detect 93% of adverse events occurring under anaesthesia.[3]

Although the System International d'unites (SI) unit of pressure is the Pascal [equivalent to 1 Newton per square metre (N m^{-2})], by convention, blood pressure is measured in millimetres of mercury (mm Hg).

Intermittent, non-invasive blood pressure measurement

Intermittent, non-invasive systems require three key components:

1. an inflatable cuff for occluding the arterial supply to the distal limb;
2. a method for determining the point of systolic and diastolic blood pressures;
3. a method for measuring pressure.

A cuff is placed circumferentially around the limb. Most commonly the upper arm is used although it is possible to use the forearm or leg when the upper arm is inaccessible, for example due to surgical requirements. The cuff should be 20% wider than the diameter of the part of the limb being used (or cover two-third its length).[4] Cuffs that are too small will lead to overestimation of blood pressure and vice versa.
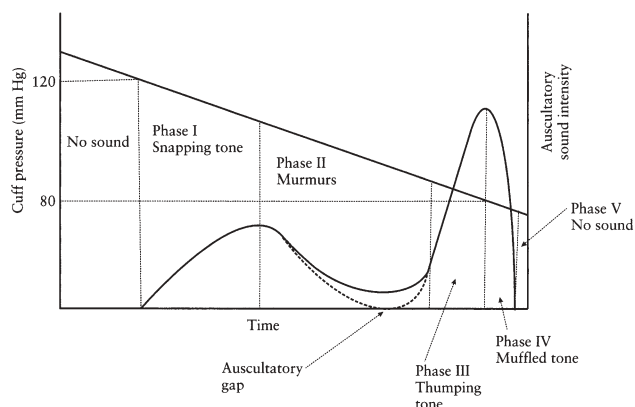
The cuff is inflated to a pressure above that of the arterial systolic pressure. At this point, the walls of the artery are opposed preventing blood flow. The cuff is then deflated below systolic pressure allowing blood flow to resume; this flow can then be detected using various means.

Palpation

While being easy to perform, this technique has been shown to underestimate a systolic pressure of 120 mm Hg by 25%.[5,6] Diastolic and mean pressures cannot be determined.

Doppler

Systolic pressure can also be determined using the Doppler principle. Blood flow towards or away from the Doppler probe, reflects sound waves causing a change in frequency that is detected using the same Doppler probe. As Doppler is so sensitive, this technique is usually reserved for the measurement of low pressures, e.g. vascular insufficiency.

Auscultation

Auscultation over the brachial artery while using a Riva Rocci cuff was first described in 1905 by Nicolai Korotkoff, a Russian army sergeant.[1] He described four sounds, or phases, attributable to the systolic, but also to the diastolic blood pressure. A fifth sound was later described (Fig. 1). The cause of the sounds is uncertain but may be due to formation of bubbles within the blood (cavitation theory), sudden stretching of the vessel wall (arterial wall theory), turbulence within the vessel (turbulence theory), or a most likely a combination of factors. During phase 2, there may be an 'auscultatory gap' when the sounds disappear completely.

In the past, there has been controversy around which Korotkoff sound represents true diastolic pressure. However, the current consensus is to use the fifth sound unless the

Fig. 1 Graphical representation of cuff deflation, intensity of sounds on auscultation. Reproduced from Physics, Clinical measurement and Equipment of Anaesthetic Practice, with kind permission from Oxford University Press.

pulsation continues to be audible on complete deflation of the cuff when the fourth sound should be used.[4] While being simple to perform, operator variability due to differing interpretations of diastolic pressure can be significant.

Oscillotonometry

The Von Recklinghausen Oscillotonometer uses two cuffs and two bellows connected to a measurement gauge.

The two cuffs overlap, one occludes the artery (occluding cuff) and the other senses the arterial signal (sensing cuff). Pressure from both cuffs is transmitted to the two bellows which is in turn displayed via a single gauge, alternating between the two bellows using a lever.

With the lever in the sensing position, the occlusive cuff is inflated above systolic pressure. The cuff is then deflated using a bleed valve until the needle suddenly starts to move vigorously. The lever is then switched to measure the occluding cuff pressure. This is the systolic blood pressure. With the lever back in the 'sensing cuff' position, the occluding cuff is deflated further. The needle will jump further with maximal oscillations occurring at mean arterial pressure (MAP), as measured by moving the lever once more. Diastolic pressure is the point at which these oscillations reduce.

The most accurate measurements taken are those of systolic and mean blood pressures with diastolic measurements being more susceptible to operator variability. However, diastolic pressure can be related to systolic pressure and MAP using the following formula:

$$\text{Mean BP} = \frac{\text{Systolic BP} + (2 \times \text{Diastolic BP})}{3}$$

Therefore:

$$\text{Diastolic BP} = \frac{(3 \times \text{Mean BP}) - \text{Systolic BP}}{2}$$

Liquid manometers

The air in the cuff acts on a liquid forcing it up a manometer. Mercury is used as it has 13.6 times the density of water. (A systolic pressure of 120 mm of mercury equates to 1.62 m of water as 7.5 mm $Hg = 10$ cm H_2O). A sphygmomanometer uses an open manometer and measures gauge pressure, e.g. pressure over atmospheric pressure. Unlike water, the meniscus created by a level of mercury is convex upwards. Measurement is taken from the top of the meniscus.

Closed manometers are used in mercury barometers and measure absolute pressure. A meniscus forms below a Torricellian vacuum. (When the height of a mercury column is above atmospheric pressure, i.e. 760 mm Hg, a space forms above it. It is not a true vacuum as it has a pressure equal to that of the saturated vapour pressure of mercury and hence contains mercury vapour. This vacuum is termed a Torricellian vacuum). Blood pressure could be measured using a closed barometer but this would require a large column of mercury as the measurement would include atmospheric pressure, for example 760 mm $Hg + 120$ mm $Hg = 880$ mm Hg, in order for a meniscus to be created.

Assuming gravity and the density of the mercury remain constant; the height of a column of mercury is only proportional to the force exerted upon that column. Therefore, the width and shape of the manometer has no bearing on the height of the column and therefore no bearing on the measurement.

Aneroid gauge

An aneroid gauge commonly replaces the mercury column as it is more robust and avoids the problems associated with mercury toxicity. An increase in pressure expands a bellows, which then moves a pointer along a scale to indicate pressure. They are susceptible to loss of accuracy over time and hence require regular calibration.

Electronic systems

A change in air pressure causes movement of a diaphragm. That movement is then detected and displayed electronically. This system is utilized by automated, non-invasive blood pressure measuring systems as described below.

Automatic, intermittent, non-invasive blood pressure measurement

This is the technique most familiar to anaesthetists. All systems consist of a pneumatic and electronic component. The original DINAMAP® is basically an automated oscillotonometer utilizing two cuffs and measured mean pressure where oscillations are maximal. Accuracy was increased by minimizing the compressible component of the system.

Modern systems are oscillometers utilizing one cuff that fulfils both occluding and sensing functions. The cuff inflates above
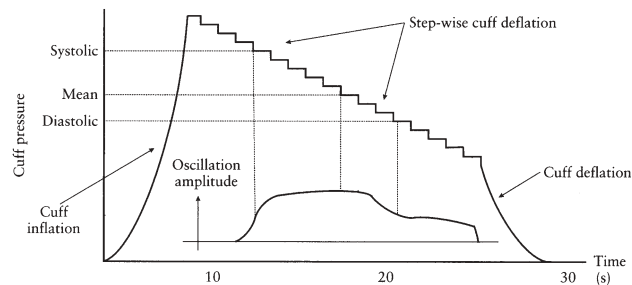
Fig. 2 Diagram of wave amplitude to cuff pressure and BP. Reproduced from Physics, Clinical measurement and Equipment of Anaesthetic Practice, with kind permission from Oxford University Press.

systolic pressure and deflates either continuously or in a step-wise manner (Fig. 2). An electronic transducer detects the pulse pressure wave, as well as the gauge pressure, in the cuff. Systolic pressure is recognized as the point where the rate of increase in the size of oscillation is maximal; diastolic pressure being that of maximal rate of decrease in size of oscillation. The readings are compared with the equation similar to that highlighted above (manufacturers do not give details). Pitfalls of automated non-invasive systems include those of all systems using an inflatable cuff and are given in Table 1.

Continuous non-invasive blood pressure measurement

Equipment such as the Finapres (Finapres Medical Systems) is able to measure blood pressure using the Peñáz principle which

Table 1 Pitfalls of cuff and invasive systems

Pitfalls of cuff systems
1. Relies on a pulse of regular rate and rhythm for accurate measurement.
2. Appropriately sized cuff should be used. The cuff should cover two-third of the upper arm or be 20% larger than the diameter of the extremity being used. Too small a cuff leads to over-estimation of BP.
3. Accidental movement of the limb will impair measurement. Limb should be level with heart.
4. The cuff should not be compressed external, i.e. it should not be placed on the lower limb when the patient is placed in the lateral position.
5. It is not possible to measure very low pressures accurately.
6. Requires an artery to be compressed. Non compliant vessels, e.g. calcified will alter measured BP.
7. Tissues, including nerves, can be damaged due to compression.
8. Often painful for the awake patient. The initial reading requires especially high inflation pressures.

Pitfalls of invasive blood pressure systems
1. System must be zeroed.
2. Transducer must be level with heart.
3. Complication of arterial cannulation:
   Infection
   Damage to local structures, e.g. nerves
   Thrombosis
   Air embolus
   Infarction of distal limb
   Haemorrhage
   Inadvertent arterial injection of drugs

states 'a force exerted by a body can be determined by measuring an opposing force that prevents physical disruption'.

A small cuff is placed around a finger. A light emitting diode within the cuff shines light through the finger and is detected on the other side. The amount of light absorbed by the tissues is proportional to the volume of tissue through which it passes. With each cardiac cycle, the volume of blood within the finger varies and with it, the amount of light absorbed. In order to keep the amount of light absorbed constant, the volume must also be kept constant and so pressure is applied to the finger. The applied pressure waveform correlates to the pressure waveform of the arterial supply to the finger. The information can be displayed as a real-time waveform and as a trend. The system requires calibration using an arm cuff.

There are conflicting data regarding the validity of readings obtained using this technique. While highly accurate in vasodilated patients and those with normal circulation, it is less accurate in hypotensive patients or those with vascular insufficiency. Small changes in positioning and tightness of the finger cuff on the same patient can lead to wide variation in readings. The use of BP monitoring utilizing the Penaz technique is limited in UK clinical practice.[7]

Continuous, invasive blood pressure monitoring

This is the gold standard of blood pressure measurement giving accurate beat-to-beat information. In general, systolic pressure will be slightly higher and diastolic pressure slightly lower (5–10 mm Hg), than non-invasive measurements. It is useful when rapid changes in blood pressure are anticipated (due to cardiovascular instability, large fluid shifts or pharmacological effects) or when non-invasive blood pressure monitoring is not possible or likely to be inaccurate (obesity, arrhythmias such as atrial fibrillation, non-pulsatile blood flow during cardiopulmonary bypass). It is also used when long-term measurement in sick patients is required as it avoids the problem of repeated cuff inflation (causing localized tissue damage) and allows repetitive sampling for blood gases and laboratory analysis.

Continuous invasive BP monitors display the information both numerically and graphically. The basic principle is to provide a solid column of liquid connecting arterial blood to a pressure transducer (hydraulic coupling) and requires the following components:

1. intra-arterial cannula;
2. tubing (incorporating an infusion system);
3. transducer;
4. microprocessor and display screen;
5. mechanism for zeroing and calibration.

Intra-arterial cannula

A short, parallel-sided cannula made of Teflon or polyurethane is inserted into an artery. Normally, a 20G cannula is used although

22G, and 25G are available for children and neonates. Preferably, a non-end artery, such as radial or dorsalis pedis is cannulated. Should thrombosis of the artery occur, arterial sufficiency is maintained via a collateral supply. The collateral supply to the hand can be assessed using Allen's test although this is not 100% reliable. If cannulation of those arteries is not possible, end arteries such as brachial or femoral may be used with due care to distal arterial sufficiency.

Infusion and tubing

The cannula is connected to a disposable tubing system, which delivers a constant infusion of plain or heparinized 0.9% saline, delivered at a rate of $2-4$ mls h^{-1}. This helps prevent occlusion of the cannula by thrombus. The infusion fluid is kept pressurized to ensure a constant flow into the arterial system. The tubing should be stiff and not contain any bubbles in order to minimize resonance and damping (see below).

Transducers

The liquid within the infusion tubing is in contact with a diaphragm that moves in response to the transmitted pressure waveform. The movement is converted to an electrical signal by a transducer. The transducer can do this by acting as part of a capacitor, inductor, or most commonly a strain gauge.

Strain gauges use the principle that resistance of a wire increases with increasing length and visa versa. The diaphragm of the transducer moves a small plate that is connected to four strain gauges. With any one movement, two gauges are compressed and the other two stretched. The material used in the strain gauge is important as different materials have different sensitivity to stress and strain and whose resistances will differ according to temperature. By using four gauges, two of which are compressed and two stretched, the effect of a change of temperature (so long as this remains linear) is cancelled out. All four strain gauges form part of a Wheatstone bridge thus increasing the sensitivity four-fold.

The transducer needs to be kept horizontally level with the patient; traditionally, the right atrium. Raising or lowering the transducer relative to the patient will alter the reading. A 10 cm change in height will alter the pressure reading by 7.5 mm Hg. NB if the cannula is inserted into the radial artery, raising the hand will not affect the measurement so long as the transducer is maintained level with the heart, unlike non-invasive methods.

Microprocessor and display screen

These provide a user-friendly numerical and graphical display allowing beat-to-beat measurement of pressure and also allow analysis of the waveform. Analysis can be clinical (e.g. morphology, determining the position of the dichrotic notch or 'swing' which can give information regarding filling status and cardiac output), or computerized. Systems such as the LiDCO and PICCO rely on such information in order to measure cardiac output.

Zeroing and calibration

While being an important consideration, modern systems do not require calibration. Zeroing is still important and is performed by opening the transducer to atmospheric pressure and electronically zeroing the system.

Damping and resonance

Damping and resonance can affect both physical and electronic systems, but only the effect on the physical system will be discussed here.

Resonance

The arterial pressure waveform is made up of many different sine waves (as determined by Fourier Analysis) with each sine wave having a specific frequency. Every system has its own natural oscillatory frequency, or resonant frequency, and if the resonant frequency of the transduction system coincides with one of the frequencies making up the arterial waveform, resonance, and subsequent distortion of the signal will occur.[8]

The specific cannulae and infusion tubing used in invasive arterial pressure monitoring are designed to keep its natural frequency above 40 Hz, which is above any of the frequencies making up the arterial waveform, thus minimizing resonance.[8]

Damping

Some damping is inherent in any system and acts to slow down the rate of change of signal between the patient and pressure transducer. This can be caused by occlusion of the arterial system, a bubble interrupting the saline column, or using a soft cannula and tubing. Some damping is useful, however, as it reduces the resonant frequency of the pressure transducing system. The amount of damping in a system is indicated by the 'damping factor'.

The system can be:

- *Optimally damped*: The system responds rapidly to a change in signal by allowing a small amount of overshoot (Damping factor 0.7).
- *Critically damped*: No overshooting occurs but the system may be too slow (Damping factor 1.0).
- *Under-damped*: Resonance occurs causing the signal to oscillate and overshoot (Damping factor <0.7).
- *Over-damped*: This may be due to soft tubing, a bubble, or a constriction. The signal takes a long time to reach equilibrium but will not overshoot. It may not reach equilibrium in time for a true reading to be given (Damping factor >1.0).

Other methods

There are many devices available for home and ambulatory measurement of blood pressure. Many employ principles not

discussed in this paper but, as they are not routinely used in anaesthetic practice, they will not be described here. New devices to measure direct blood pressure are available. These include electrical and fibre-optic transducers that are inserted into the artery thus minimizing resonance and damping. However, blood sampling is not always possible and they are expensive and not routinely used.

References

1. Wesseling KH. A century of non-invasive arterial pressure measurement: from Marey to Penaz and Finapres. *Homeostasis* 1995; **36**: 50–66

2. Recommendations for standards of monitoring during anaesthesia and recovery (3rd Edition—revised 2000). Association of Anaesthetists of Great Britain and Ireland

3. Webb RK, Van der Walt JH, Runciman WB et al. The Australian incident monitoring study. Which monitor? An analysis of 2000 incident report. *Anaesth Intensive Care* 1993; **21**: 529–42

4. Pickering TG, Hall JE, Appel LJ et al. Recommendations for blood pressure measurement in humans and experimental animals. *Circulation* 2005; **111**: 697–716

5. Magee P, Tooley M. *The Physics, Clinical Measurement and Equipment of Anaesthetic Practise.* Oxford University Press, 2005; 68–79

6. Ven Bergen FH, Buckely JJ, French LA et al. Comparison of indirect and direct methods of measuring arterial blood pressure. *Circulation* 1954; **10**(4): 481–90

7. Davis PD, Parbrook GD, Kenny GNC. *Basic Physics and Measurement in Anaesthesia*, 4th Edn. Butterworth-Heinemann, 2002

8. Langton JA, Stoker M. Principles of pressure transducers, resonance, damping & frequency response. *Anaesth Intensive Care Med* 2001; **2**:186–90

Please see multiple choice questions 11–13