Patient monitoring techniques

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Abstract

Patient monitoring is now an accepted standard in medical care to ensure that a patient's condition can be evaluated over time and any deterioration identified quickly, enabling appropriate care to be instituted. This article reviews the basic components of any monitoring device, and its importance in relation to improving patient safety. Issues related to increasing complexity of monitoring devices are also discussed. Basic monitoring modalities are described including pulse oximetry, non-invasive blood pressure, electrocardiography, temperature and capnography. Advanced cardiovascular monitoring is also discussed including invasive pressure monitoring, and invasive and non-invasive cardiac output monitoring devices. Neurological monitoring systems which evaluate intracranial pressure, cerebral blood flow and brain electrical activity in the critical care and perioperative environment are also described in relation to acute brain injury. Point-of-care testing (PoCT) modalities are reviewed as all monitoring devices can be regarded as forms of PoCT devices. Common features of PoCT devices together with advantages and disadvantages of PoCT are defined. A range of PoCT devices are discussed.

Keywords Arterial; capnography; cardiac output; intracranial pressure; monitoring techniques; neurological monitoring; patient safety; PoCT; pulse oximetry; thromboelastography

Patient monitoring in its broadest sense is the observation of a disease, medical condition or physiological parameter of a patient over time. Cushing, in 1903, recognized the value of measuring a patient's vital signs routinely and accurately. Since the 1920s, the four vital signs – temperature, respiratory rate, heart rate and arterial blood pressure – have been recorded on patient charts, through observation and simple mechanical devices. The monitoring of these parameters is still standard practice, although the monitoring devices used are far more complex.

The most basic form of monitoring is that of clinical observation, i.e. skin colour (indicating oxygenation and cyanosis), capillary refill time (representing perfusion state, skin turgor, indicating hydration), respiration rate (adequacy of ventilation) and pulse rate (indicating cardiac function). These basic measures of a patient's physiology can be difficult to interpret particularly in the presence of acute illness, so using clinical judgement of a patient's physiological state in isolation is unacceptable in modern practice.

A central tenet in the use of any monitoring device is that the clinician understands how the device works, the limitations of the device and potential sources of error, e.g. signal interference will occur if a pulse oximeter is placed on finger with blue nail varnish. Uncritical acceptance of measurements despite contradictory evidence can result in inappropriate treatment decisions and reduce patient safety and care.

Essential requirements for clinical measurement

All monitoring devices detect a biological signal and then display or record the information. The degree to which a measurement is a true reflection of the physiological data is dependent on the accuracy and precision of the measuring device. An awareness of factors that can affect the accuracy and precision of a measuring device is important in the correct interpretation of the data displayed.

What are the components of a monitoring device?

There are essentially four components to any monitoring device:

- **Sensor**: detects biological signal, e.g. thermal, pressure, mechanical or electrical. The magnitude of the sensor response is proportional to that of the biological signal.
- **Transduction**: signal energy from sensor is converted into another form of energy, usually a continuous electrical signal.
- **Amplification** and signal processing: the relevant signal is magnified and unwanted interference reduced.
- **Display**: output from the instrument is presented to the clinician. Storage: computer memory, printed copy, or paper records.

Modern monitoring devices now rely on microprocessor technology to generate the clinical data. Advantages include:

- continuous real time detection of signal
- processing and recording of measurements
- trend analysis
- automated control of apparatus
- integration of intelligent alarms allowing patient specific settings
- miniaturization of complex equipment (Figure 1a)
- user-friendly visual displays of multiple measurements in colour, customizable display (Figure 1b)
- integration with electronic patient record systems (EPRS).

Does monitoring improve patient safety?

While human observation can be a sensitive and discriminating analyser and integrator of information, continued vigilance over time is often poor. Studies in anaesthesia have shown that up to 30% of incidents are due to lack of vigilance, and momentary distractions can lead to failures to recognize significant physiological changes for 3 minutes or more. This led to the development of minimal monitoring standards to ensure improved safety and detection of abnormal physiological changes during surgery. The Association of Anaesthetists have guidelines on monitoring[1] (Table 1) which set a minimum standard of monitoring which must be observed during any anaesthetic.

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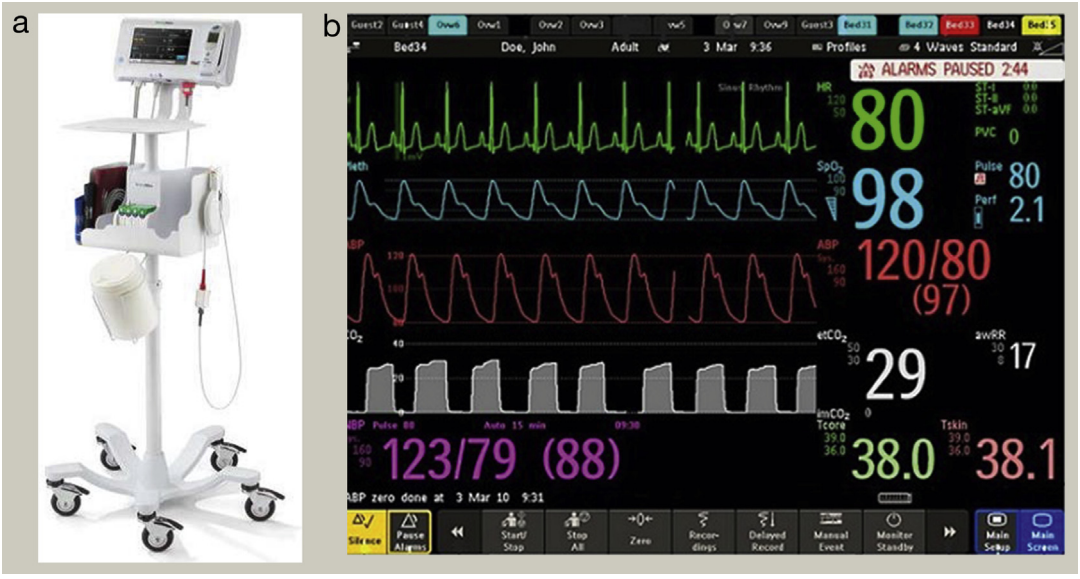


Figure 1 (a) A typical ward-based integrated monitor on stand for ease of use; allows pulse, oxygen saturation, blood pressure and temperature to be recorded. Measurements can be connected to electronic patient records. (b) Display from typical monitor used in critical care environment. Shows multiple parameters, as waveforms and numbers, in different colours for user benefit, can be customizable with different parameters displayed dependent on requirements.

Additional monitoring will then be selected at the discretion of the anaesthetist to ensure not only safety, but optimization of the anaesthetic process, with the aim of provision of the ideal perioperative and postoperative state. The patient's physiology may then be manipulated safely through reference to data observed using monitoring to provide this optimal state, either through pharmacological means or by altering anaesthetic equipment settings.

Adoption of these standards has undoubtedly made anaesthesia safer and reduced anaesthetic-related morbidity and mortality.

Standard monitoring during anaesthesia

Mandatory monitoring	Additional/desirable monitoring
Pulse oximeter (SpO_2)	Invasive blood pressure (IABP)
Non-invasive blood pressure (NIBP)	Central venous pressure
Electrocardiogram (ECG)	Depth of anaesthesia monitors (standard for TIVA)
Inspired and expired oxygen concentration	Cardiac output monitors
End tidal CO_2 concentration (ventilated/sedated)	Point-of-care testing
Inspired and expired nitrous oxide and volatile agent concentration (if used)	Neurological monitors
Airway pressure (if ventilated)	
Peripheral nerve stimulation (if muscle relaxant used)	
Temperature (if procedure >30 minutes duration)	

Table 1

Fundamental to patient safety are device alarms which are designed to generate an alarm signal to indicate an abnormal physiological state or malfunctioning of equipment. Unfortunately it is common practice for alarms to be turned off or ignored due to the perceived high number of false positive alerts. So-called 'alarm fatigue' has been implicated in multiple patient safety incidents. Most devices have pre-set alarm limits which can be reset and individualized for a patient that will reduce false positive alerts but this function is infrequently used. It cannot be stressed enough that failure to response to a device alarm in a critically ill patient can result in serious consequences.

Common themes from the National Confidential Enquiry into Patient Outcome and Death (NCEPOD) indicated that failure to recognize and treat an acutely ill patient was related to failure to monitor the patient adequately. The regular monitoring of certain physiological parameters combined with a score and a structured response to the score (increased frequency of monitoring, medical response, transfer to critical care) has been shown to provide early recognition of an acutely ill patient and reduce morbidity in this high risk group. This 'track and trigger' approach is the basis for the National Early Warning Score,[2] and consists of a monitoring tool to ensure identification of a high-risk patient and a structure to trigger an appropriate response. The physiological parameters that are monitored and scored include: respiratory rate, oxygen saturation, systolic blood pressure, pulse rate, level of consciousness and temperature. A simple bedside monitor combined with regular clinical observation is all that is required to achieve this goal.

Basic monitoring modalities

A characteristic of basic monitoring such as blood pressure, temperature and pulse oximetry is that the training and specialist knowledge required to use them effectively is minimal. The

Basic Monitoring

Clinical observation

- Assessment of a patient's conscious level, skin colour, pulse, respiratory rate, capillary refill time provide an initial evaluation of a patient's clinical condition and response to treatment
- Hourly urine output: Simple measure of organ perfusion and patients volume status (assuming normal renal function)

Pulse oximetry (SpO_2)

- Continuous non-invasive measure of arterial blood saturation based on the difference in absorption spectra of oxygenated and de-oxygenated haemoglobin at red /infrared wavelengths. Changes in light absorption during arterial pulsation is analysed by a microprocessor to record oxygen saturation and a pulse waveform
- Allows detection of desaturation ($SpO_2 < 94\%$)
- Inaccuracy of pulse oximetry reading can occur at $SpO_2 < 80\%$ (algorithm generated on healthy volunteers), hypoperfusion states, hypothermia, movement artefact, cardiac arrhythmias, venous congestion, blue nail vanish, abnormal haemoglobin (Met/Carboxy).

Non-invasive blood pressure

- Automated oscillotonometry is the most common method to measure blood pressure in clinical practice. Uses single cuff for inflation and detection of movement of arterial wall Systolic and MAP are measured and diastolic estimated
- Accuracy ± 15–20 mmHg compared to direct arterial pressure monitoring
- Tendency to over read at high pressures and under-read at low pressures
- Sources of error include: wrong cuff size (cuff width > 20% arm diameter), systolic < 60 mmHg, atrial fibrillation, external pressure

Temperature

- Infrared devices: rely on the principle that infrared radiation emitted by body proportional to temperature of the body
- Electrical devices: include thermocouple, thermistor types rely on change in voltage or resistance which is proportional to change in temperature
- Sites of measurement:
  - Tympanic membrane (infrared) –correlates with hypothalamic temperature
  - Nasopharyngeal* – brain temperature
  - Oesophageal,* bladder* and rectal*(temp > 0.5–1°C higher due to bacterial fermentation) sites all measure core temperature
  - Skin: inaccurate but core skin temperature difference provides some indication of peripheral perfusion
  - Blood: thermistor type incorporated onto end of pulmonary artery catheter

Electrocardiography (ECG)

- Measures the electrical activity of the myocardium. Different lead positions detect electrical activity from different cardiac regions
- Monitors: rate, rhythm and evidence of myocardial ischaemia
- Lead II position most often selected in anaesthesia/ICU to detect rate rhythm. CM5 lead position used in anaesthesia to detect ischaemia in the left ventricle
- 24-hour ambulatory monitoring can be used to assess paroxysmal arrhythmias
- Respiratory rate and waveform generation via thoracic bioimpedance
- Interference can occur due to movement, diathermy, poor lead contact

Capnography: end tidal carbon dioxide ($ETCO_2$)

- Measures the concentration of CO_2 in exhaled air –using infrared absorptiometry to measure CO_2 concentration. Displays value numerically with or without waveform (capnogram)
- Presence of $ETCO_2$ aids in confirmation of endotracheal intubation
- Allows monitoring of respiratory rate in ventilated or spontaneously breathing patents
- $ETCO_2$ monitoring enables allows assessment of adequacy of ventilation during anaesthesia or on critical care. It is elevated occurs in hypoventilation, rebreathing and hypermetabolic states and reduced in hyperventilation, low cardiac perfusion states, pulmonary embolism, hypothermia
- $ETCO_2$ provides non-invasive estimate of cardiac output and organ perfusion during cardiac arrest

Box 1

accuracy and precision of these instruments is acceptable and they are subject to minimal artefact. Integration of the instruments into a single portable device for ward use is now common place. By defining normal physiological ranges for these monitors it allows staff to monitor patient's physiology over a period of time and act on them as required. Fundamental to this system is regular clinical observation and monitoring of hourly urine output (Box 1).

The pulse oximeter probably provides the most information on a patient's physiology as a normal reading is dependent on an intact cardiorespiratory system and adequate peripheral perfusion, abnormalities potentially indicating dysfunction in one or more of these systems.

In anaesthesia and critical care areas additional monitoring devices to those on the ward are commonly used, providing further physiological data to optimize patient safety and outcome.

Electrocardiography allows continuous monitoring of the electrical activity of the heart allowing pulse, cardiac rhythm and myocardial ischaemia to be determined. What it cannot verify is adequacy of cardiac output. Respiratory rate can be obtained by measuring change in thoracic impedance across the ECG electrodes, which is particularly useful in anaesthetic recovery or coronary care units.

$ETCO_2$ monitoring is an essential measurement for any ventilated patient or patient who is heavily sedated for a procedure or recovering from anaesthesia (Box 1).

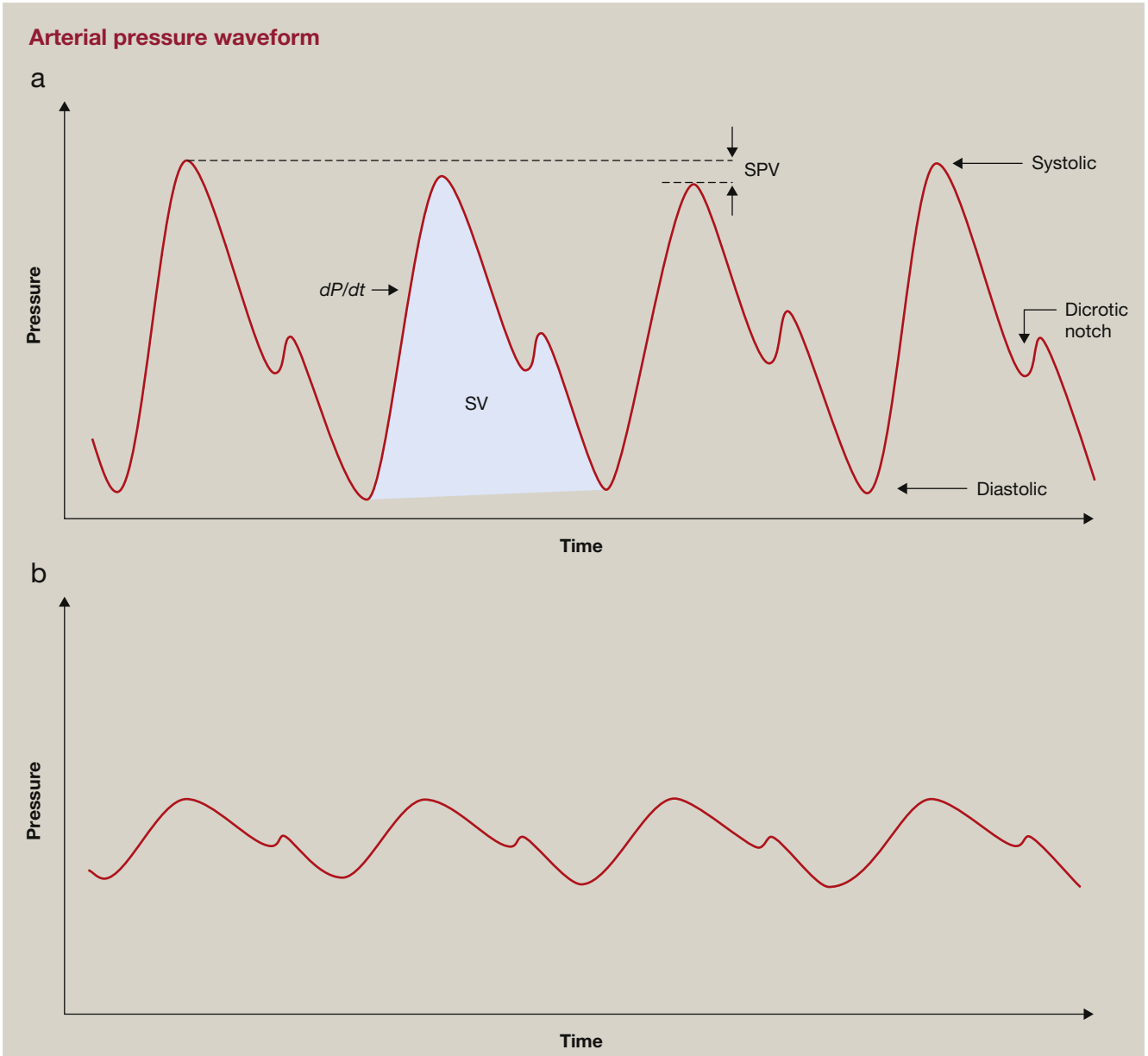
Advanced monitoring

Normally patients undergoing complex prolonged surgery or critically ill patients with major haemodynamic changes and/or fluid shifts benefit from the use of advanced monitoring techniques as they facilitate continuous assessment of physiological parameters and responses to therapy.

Invasive pressure monitoring

Arterial pressure monitoring: an arterial cannula allows for continuous arterial blood pressure measurements and repeat sampling for arterial blood gas analysis. The system consists of a 20/22G cannula inserted into an artery. This is connected to a transducer via a low compliance saline filled tube which is continually flushed to prevent blockage. The transducer is placed level with the heart and requires calibration. The transducer converts the changing pressure signal in the fluid filled tube into an electrical signal that is proportional to the arterial pressure. This change is then amplified and displayed as a measure of pressure (Figure 2a).

The arterial waveform can be affected by damping, resulting in either an increase or reduction in the size of the waveform and



(a) A typical arterial pressure trace. The positions on the trace of systolic and diastolic pressures are highlighted, as is the dicrotic notch which represents closure of the aortic valve. The rate of pressure change per unit time, **dP/dt**, is an indication of myocardial contractility. The systolic pressure variation, **SPV**, can be used to indicate volume status. The area under the waveform represents the stroke volume (**SV**). **(b)** Shows a typical appearance of a damped arterial trace.

Figure 2

altered values of systolic and diastolic pressures (Figure 2b). Pressure transducers can be affected by zero drift where the displayed value changes despite the real value remaining constant.

Information that can be derived from the arterial waveform includes:

- arterial blood pressure and cardiac rate
- stroke volume and cardiac output from the area under the systolic part of the curve
- myocardial contractility from the systolic upstroke
- outflow resistance (afterload) estimated by the slope of the diastolic decay – slow fall vasoconstriction
- hypovolaemia may be indicated by a low dicrotic notch, narrow waveform, and large changes in systolic pressure with respiration so called 'respiratory swing' (Figure 2a).

Central venous pressure (CVP) monitoring: a central venous catheter (CVC) inserted via one of the great veins can measure pressure on the right-side of the heart. CVP is equal to right-sided atrial pressure which reflects right ventricular preload in stable conditions. A low CVP is taken to indicate hypovolaemia and a high CVP indicates hypervolaemia, this association being used to guide fluid therapy. A systematic review by Marik[3] found no association between CVP and circulatory status or prediction of fluid responsiveness. The authors recommended that CVP should no longer be routinely measured but in reality it is often measured, and central venous access is still required for the delivery of vasoactive or irritant drugs.

Central venous oxygen saturation monitoring ($ScvO_2$): $ScvO_2$ measures central venous oxygen saturation level from veins draining the head and upper body using a CVC inserted in the internal jugular vein. $ScvO_2$ is measured through reflection spectrophotometry using fibreoptic channels in the CVC. Low $ScvO_2$ values (below 60%) may indicate poor oxygen delivery or increased oxygen consumption.

Cardiac output (CO) monitoring techniques

Invasive and minimally invasive devices are available to evaluate cardiac output. The devices may be calibrated or non-calibrated and the values displayed can be directly measured or derived. They all seek to measure variables that correlate with volaemic status and fluid responsiveness.

Pulmonary artery catheter (PAFC): PAFC is a flow-directed balloon tipped catheter with ports and a distal thermistor probe. It is normally inserted via the right internal jugular vein. The balloon is inflated in the right atrium and carried by blood flow through the right ventricle and pulmonary artery until the balloon wedges in a pulmonary vessel. The pressure is called the pulmonary capillary wedge pressure and indicates left ventricular preload. The PAFC allows the measurement of cardiac output through a themodilution technique. A known volume of cold solution is injected through a proximal port of PAFC. The change in blood temperature is measured by the distal thermistor. Analysis of the temperature change–time curve allows a calculation of cardiac output. Technology now allows continuous cardiac output monitoring using a heating coil in the part of the PAFC in the right ventricle. Reliability of PAFC parameters is reduced by mitral incompetence, intracardiac shunts and changes in blood flow during respiration.

Mixed venous oxygen saturation can be measured from the PAFC by catheter tipped oximeter probe or blood gas analysis. It provides information regarding oxygen consumption and adequacy of oxygen delivery (DO_2). Values below 70% may indicate oxygen consumption is high and DO_2 may need to be augmented. The PAC-Man trial[4] showed no clinical benefit in use of PAFC although it is still in common use in most cardiac centres.

Dilution techniques to measure cardiac output: indocyanine green dye, lithium chloride (LiDCOplus^{Tm}; see below) or ice cold saline can be injected via a central vein and the changes detected in a peripheral artery with an appropriate sensor. Using the same principle as the thermodilution technique in PAFC, a concentration or temperature–time curve is produced allowing cardiac output to be calculated. The advantage of this technique is that it is less invasive than PAFC. This technique is used in a number of minimally invasive cardiac monitors and the LIMON monitor (liver function).

Minimally invasive CO monitors: these devices can be categorized into arterial waveform analysis, and Doppler technologies.

Arterial waveform analysis: the arterial waveform can be used to estimate stroke volume through pulse contour or power-analysis. This is based on the assumption that the area under the curve of the systolic part of the arterial pressure waveform is proportional to stroke volume. The stroke volume is multiplied by heart rate to give cardiac output. These devices (Box 2), in addition to providing continuous cardiac output and stroke volume may also estimate stroke volume variation (SVV) and pulse pressure variation (PPV). To obtain values for PPV and SVV the patient should be mechanically ventilated. These are dynamic measurements of volume status and have been shown to be accurate in predicting fluid requirements in critically ill patients. Poor quality arterial waveform, arrhythmias, rapid changes in haemodynamics and changes in intrathoracic pressure will all affect the accuracy of these instruments.

Oesophageal Doppler monitoring (ODM): the ODM is a flexible probe inserted into the oesophagus until the tip, which contains an ultrasound probe, lies parallel to the descending aorta. The ODM measures red cell velocity in the descending aorta using the Doppler principle. A predetermined nomogram (based on height, weight, sex) estimates the aortic cross-sectional area and hence the stroke volume and cardiac output can be calculated. The measurement of peak velocity (PV) gives an indication of cardiac contractility, and corrected flow time (FTc) provides an indication of intravascular fluid status. Diathermy interferes with ODM function and errors may occur with arrhythmias or if patient demographics lie outside the nomogram range. CardioQ-ODM^{TM} combines information from arterial waveform analysis to allow continuous cardiac output measurements when diathermy in use.

The ODM and arterial waveform analysis devices are the most common devices used in UK anaesthetic practice to optimize

Minimally invasive cardiac output monitors –based on arterial waveform analysis

FloTrac/EV1000™

- FLoTrac sensor attached to arterial line
- Calibrated using intermittent thermodilution technique requires CVC insertion (EV1000 monitor)
- Pulse contour analysis to generate CO/SV/SVV
- **FloTrac™ only:** Relies on pulse contour analysis to generate CO/SV/SVV

LiDCOplus™

- Calibrated system using intermittent lithium thermodilution technique. Requires a CVC and an arterial line
- Arterial waveform analysis using pulse power analysis to determine SV
- Reliability affected by lithium medication
- **LiDCOrapid™** is uncalibrated version relying only on pulse power analysis of arterial waveform

PICCOplus™

- Thermistor tipped arterial catheter inserted in either radial, brachial, axillary, femoral vessel
- CVC for transpulmonary thermodilution calibration
- Pulse contour arterial waveform analysis
- Measures CO, SV, SVR, extravascular lung water (lung oedema)
- **ProAQT™** uncalibrated uses PICCO algorithm to calculate CO, SV, SVV

All systems require good arterial waveform to provide effective measurements

Box 2

fluid and vasoactive therapy in high risk surgical patients to help reduce perioperative morbidity and mortality.

Echocardiography: echocardiography combined with flow Doppler allows quantitative assessment of atria, ventricles, myocardium, valves and pericardium. Ejection fraction and stroke volume can also be estimated. Transoesophageal echocardiography (TOE) is mainly used in cardiac surgery to provide perioperative assessment cardiac structure and function. Perioperatively, stroke volume using the Doppler technique, preload and fluid responsiveness can all be measured with a TOE.

Limon monitor: this is non-invasive monitor of liver function and splanchnic perfusion. It measures the plasma disappearance rate and 15-minute retention rate of indocyanine green dye (ICG). It requires venous access to inject dye and uses a sensor to detect ICG. A fall in ICG clearance indicates either a reduction in liver blood flow or liver dysfunction. It is useful in the monitoring of patients with liver dysfunction and can provide information regarding prognosis of liver failure patients who are critically ill. It can be used to evaluate liver function in organ recipients and risks assess patients undergoing liver resection.

Neurological monitoring

Specialized monitoring is essential in neurological patients in the operating room and ICU to prevent ischaemic and mechanical injury to the nervous system. The systems currently available may be broadly classified into those that monitor intracranial pressure and blood flow dynamics and those that monitor brain electrical activity.

Monitors of intracranial pressure and blood flow dynamics

Intracranial pressure (ICP) measurement: ICP is usually measured with devices placed into the lateral ventricle of the brain, subdural space, or directly into the brain parenchyma. The monitor is traditionally inserted via a burr hole in the right frontal region but may vary dependent on patient factors, i.e. pathology, coagulopathy, device accuracy, reliability, complication rates, and ease of insertion. In the presence of hydrocephalus, however, an intraventricular device is preferred because it can also be used for therapeutic CSF drainage.

Measuring ICP allows medical or surgical treatments to reduce elevated ICP and improve cerebral perfusion pressure (CPP). Studies have shown that elevated ICP carries a poor prognosis and treatment of elevated ICP reduces mortality. The most common indication for ICP monitoring is acute closed head injury as per the guidelines of The Brain Trauma Foundation.[5] Other indications for ICP monitoring include post-operative care and oedema secondary acute fulminate hepatic failure.

There are basically two types of ICP monitors; the first allows concurrent drainage of CSF while ICP is being measured whereas the second provides ICP data only.

Intraventricular catheter (IVC): the catheter is inserted into the lateral ventricle of the brain and connected to a pressure transducer zeroed at the level of the tragus, allowing waveform analysis and recalibration. The intraventricular catheter measures global ICP. The major advantages include it is the most accurate and reliable ICP monitor; it allows therapeutic CSF drainage, and can measure intracranial compliance. Disadvantages are catheter blockage, high risk of brain trauma and of haemorrhage at insertion, and infection with prolonged use (1–5%). It may be difficult to insert in patients with small ventricles due to high ICP.

Intraparenchymal monitor and subdural monitors: these use fibreoptic/strain gauge transducer-tipped catheter systems. The transducer-tipped catheter can be placed within the brain parenchyma, or the subdural space. The pressure monitor gives both digital and waveform displays. The advantages of these systems are that they are almost as accurate as an IVC, easier to insert (especially in patients with high ICP) and are associated with fewer complications. Disadvantages: the transducer requires calibration pre-insertion and cannot be re-zeroed once inserted, therefore may be subject to zero drift, may measure localized ICP not global ICP, and are unable to drain CSF.

Jugular bulb oximetry: jugular venous oximetry is a method of analysing the balance between oxygen supply and demand in the brain. A jugular oximetry catheter is inserted by retrograde cannulation of the internal jugular vein with correct placement confirmed by lateral neck X-ray. Jugular oxygen saturation (SjO_2) and blood gas analysis can be measured by intermittent blood sampling and continuous SjO_2 monitoring can be achieved using a fibreoptic sensor.

Problems include: Normal SjO_2 possible even in presence of significant brain pathology, focal ischaemia may not be apparent, and infratentorial injuries are not monitored by this method.

SjO_2 monitoring has been used to detect cerebral ischaemia following traumatic brain injury (TBI), during neurosurgical and cardiopulmonary bypass procedures and in acute liver failure complicated by cerebral oedema.

Transcranial Doppler ultrasonography (TCD): TCD is a non-invasive bedside monitoring technique using the Doppler principle to evaluate flow haemodynamics in the basal cerebral vessels. The middle cerebral artery (MCA) is normally used as it carries 80% of the ipsilateral carotid artery blood flow and its diameter changes little during normal physiology. A pulsed ultrasound signal is transmitted through a temporal bone window and the beam focused to optimize the signal. A waveform is displayed of systolic, diastolic and mean blood flow velocity and provided the vessel diameter is constant a change in velocity is proportional to change in cerebral blood flow.

Important clinical applications of TCD include diagnosis of cerebral vasospasm and monitoring response to treatment following aneurysmal subarachnoid haemorrhage and TBI, TCD can monitor cerebral compliance post TBI, TCD combined with ICP and arterial pressure monitoring can help in optimizing CPP post TBI, diagnosis of cerebral hyperaemia or vasospasm post carotid surgery or stenting, and diagnosis of intraoperative cerebral embolization during carotid surgery and cardiopulmonary bypass procedures.

Widespread use of TCD is limited as it is very operator dependent and 10–20% of patients have an inadequate transtemporal acoustic window for measurements.

Cerebral oximetry (near infrared cerebral spectroscopy NIRS): NIRS is a non-invasive monitor of regional cerebral oxygen saturation (rSO_2). It uses infrared light (700–900 nm) and measures the mixed vascular oxygen saturation using reflectance spectroscopy. Infrared light can pass easily through skin and bone and most absorption is from haemoglobin. The thin skulls of neonates allow the signal to be transmitted from one side of skull to another, in adults emitting and detecting diodes are placed on forehead. The main source of error is extracranial blood saturation contaminating rSO_2 values.

Factors affecting the balance between oxygen consumption and delivery to the brain will result in a reduction in cerebral oxygenation and a reduction in cerebral oximetry values. NIRS is used extensively in adult and paediatric cardiac surgery although evidence of clinical benefit is equivocal.

Brain tissue oximetry: brain tissue oximetry directly measures the oxygen tension of brain tissue extracellular fluid ($PbtO_2$) using a polarographic cell at the tip of an intraparenchymal microcatheter. This may be combined with ICP and brain temperature monitoring. $PbtO_2$ probes can be inserted into the region at high risk for ischaemia as determined by CT perfusion studies following TBI.

Cerebral microdialysis: this tracks the levels of metabolites in the brain using microdialysis. A fine double-lumen catheter is placed into brain parenchyma and slowly perfused with an isotonic fluid collected in a chamber for analysis. The slow constant movement of fluid allows molecules to diffuse along a concentration gradient across the semipermeable membrane. Compounds commonly measured include levels of lactate and pyruvate, glutamate, and glucose. An elevated lactate, and lactate-pyruvate ratio may be associated with poor neurologic outcomes in SAH and TBI.

Multimodal monitoring following ABI is the current recommendation to help reduce the risk of secondary brain injury through ischaemia.

Brain electrical activity monitors

Electroencephalography (EEG): EEG represents the electrical activity of the brain and is a monitored using up to 20 scalp electrodes producing waveforms that require specialist interpretation. A continuous EEG for a minimum of 48 hours has >90% sensitivity in detecting non-convulsive seizures in comatose patients. Current recommendations include EEG in all patients with ABI and unexplained altered consciousness, in patients with convulsive status epilepticus who do not return to baseline within 60 minutes after medication, during therapeutic hypothermia and within 24 hours after rewarming.

In anaesthetic practice, devices using a processed EEG signal or stimulus-evoked electrical activity which is converted to an index of depth of anaesthesia are now recommended for patients undergoing general anaesthesia with total intravenous drugs and muscle relaxants and patients at high risk of awareness. The monitors represent the depth of anaesthesia as a number between 0 (no electrical activity) to 100 (awake), a value of 40–60 is regarded as acceptable for general anaesthesia.

Evoked potentials (EP) and electromyography (EMG): intraoperative neuromonitoring is useful in patients at risk of neurological complications during surgery. EP devices measure the electrical response in the nervous system in response to a stimulus and can measure activity in specific neural pathways. EP can be divided into two types, sensory or motor depending on the pathway being stimulated. EP monitoring may be used during scoliosis and posterior fossa surgery. EMG measures muscle response or electrical activity in response to a nerve's stimulation of the muscle. It is often used during thyroid and parotid surgery to monitor integrity of the recurrent laryngeal and facial nerve respectively.

Point-of-care testing (PoCT)

The term PoCT refers to the performance of diagnostic tests carried out at or near a patient. In fact PoCT includes the invasive and non-invasive monitoring devices discussed already, but in general it is used to describe the rapid specific testing of bodily

fluid at the bedside. All PoCT within UK hospitals must be performed to the same quality standards as testing undertaken within accredited Blood Sciences laboratories.[6]

Common features of PoCT devices to ensure effectiveness include the following: Simple to use, Reagents and consumables are robust in storage and usage, Quality control mechanism, sensitive and specific, results should be concordant with an established laboratory method, safe to use, and connectivity to EPRS.

The main advantage of PoCT is to generate immediate results to the clinician allowing real time patient management that can improve patient outcome.

Other advantages of PoCT include: Ability to measure multiple parameters on a single sample, and decreased iatrogenic blood loss as PoCT requiring blood only small volumes, Fewer redundant tests, real time trend analysis, and reduced pre-analytic error.

Disadvantages of PoCT mainly centre on ensuring the accuracy of the result through correct use of the equipment by a properly trained operator, detection of erroneous results, regular quality control testing and knowledge of factors that interfere with PoCT performance.

Non-coagulation testing

Dipstick test: this is the simplest PoCT available and involves urine, blood or gastric sample being applied to a porous pad containing reagent and the colour change compared to a chart to determine the result. Dipsticks can detect one or up to ten analytes and a small reading device using reflectance technology can be used to reduce potential user error. Typical uses include determining the pH of aspirate following NG placement to ensure correct placement, urine testing for leucocytes or blood if infection is suspected.

Blood glucose monitoring: small portable monitors measure the concentration of glucose from a small drop of blood (skin prick) using a biosensor strip incorporating an enzyme usually glucose oxidase. Glucose concentration is detected by either photometric or electrochemical methods, the result being displayed in mmol/L (UK). Regular perioperative measurement of blood glucose using PoCT is now a standard of care in the UK.

Haemoglobin: in the Haemacue™ device a small sample of blood is added to a micro-cuvette contain dried reagent that haemolyses the red cells. The free haemoglobin is converted into azide-methaemoglobin. This stable coloured complex is measured photometrically at 570 nm. A second measurement is taken at 880 nm for compensation of turbidity. A high sensitivity and specificity has been described for this method, and it is the most common PoCT method for measuring haemoglobin in clinical practice.

Blood gas analysers: these are bench top devices that use electrochemical, ion selective electrodes and optical sensors to measure blood gases but also electrolytes and haemoglobin in whole blood. These measure pH, partial pressure of carbon dioxide and oxygen, and concentrations of ions (sodium, potassium, chloride, bicarbonate) and metabolites (glucose, lactate). The i-STAT™ is a handheld device that uses a variety of single use cartridges to perform blood gas, electrolyte and haematological measurements dependent on the type of cartridge selected. The cartridges use thin film sensors and microfluidic technology to carry out the measurements. Istat™ is a cost-effective device for use in emergency departments.

Coagulation testing

Traditional laboratory methods of evaluating clotting such as prothrombin time (PT), activated partial thromboplastin time (aPTT), platelet count, fibrinogen and international normalized ratio (INR) are time consuming (>45 minutes turnaround time) and have minimal predictive power for perioperative bleeding. The latter tests only provide information on the plasma phase of coagulation up to fibrin formation and provide no information on platelet function. Furthermore, in the situation of massive surgical haemorrhage these tests are too slow to provide useful clinical information to the anaesthetist to evaluate the clotting abnormality and blood product requirements. Using these tests to guide therapy will necessitate an empirically based replacement regime, based on clinician experience due lack of real time measurements.

In comparison, viscoelastic (VCA) PoCT devices such as the TEG™ (thromboelastography) and the ROTEM™ (thromboelastometry) use whole blood to provide information on all phases of coagulation, clot initiation to clot retraction and fibrinolysis. Health technology assessments suggest VCA devices are cost-effective in perioperative management of bleeding in trauma, cardiac and liver transplant surgery.[7]

Viscoelastic PoCT devices: TEG™ and ROTEM™ exploit the elastic properties of the clotting blood. Whole blood (300–360 μl; device dependent) is placed into a sample cup heated to 37°C in which a pin is suspended by a torsion wire and either the cup (TEG™) or the pin (ROTEM™) rotates. As the blood clots, bridges of platelets and fibrin form between the cup and the pin transmitting the torque of the cup to the torsion wire which it is continuously recorded. Both devices produce graphical and numerical displays of the results of the whole clotting process. Table 2 shows the most commonly used parameters derived from VCA monitoring and Figure 3 shows a typical tracing. Both devices, by using suitable activators or inhibitors, can examine the contribution of different components of the coagulation process, for example; fibrinogen –clot strength, or heparin effect.

INR PoCT: INR monitors will provide an optical or electrochemical measurement of prothrombin time following activation of coagulation with human recombinant tissue factor. A timer records how long it takes until the blood is clotted and the INR is displayed. Values correlate well with laboratory based results, and are normally accurate in an INR range of 0.8–8.0. Sources of error include improper storage of strips, heparin, and delay in applying drop of blood to the strip. In the perioperative setting where surgical delay may be critical, INR PoCT provides a rapid result in comparison to a laboratory INR test that can take >60 minutes.

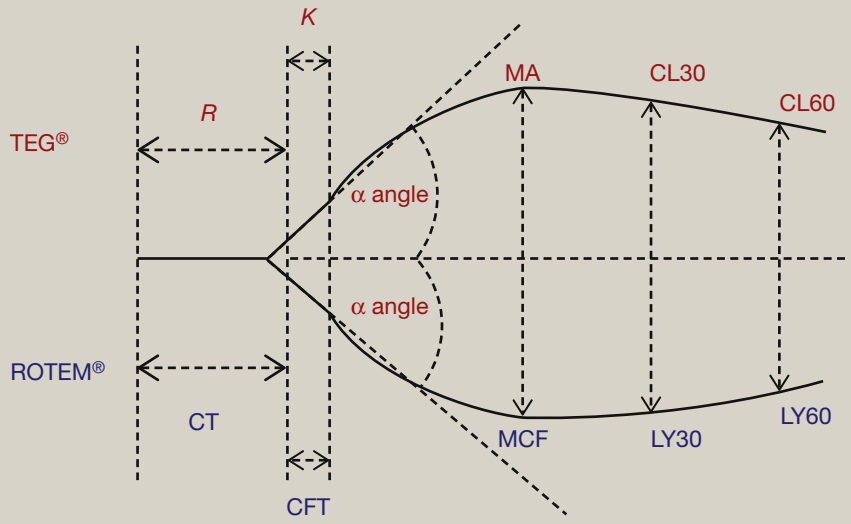
Activated clotting time (ACT) PoCT: ACT PoCT monitoring is mainly used to monitor the effect of heparin administration in patients on cardiopulmonary bypass. The Hemochron™ device

Most commonly used parameters from viscoelastic tracing and their significance[8]

Measurement	TEG™ Nomenclature	ROTEM™ Nomenclature	Significance
Time to an amplitude of 2 mm	Reaction time or R time	Clotting time (CT)	Informs about thrombin generation. Prolongation is associated with clotting factor deficiency, inhibitors or anticoagulants
Time from 2 mm to 20 mm	K time	Clot Formation Time (CFT)	Depicts how fast a visible clot is formed. Depends on thrombin, thrombin generation, fibrinogen and platelets
Angle formed by a tangential line to the curve starting from the split point	α – Angle	α – Angle	Closely related to the K time but more precise because it can be determined even when the split does not reach 20 mm of amplitude.
Greatest width of the tracing	Maximal amplitude (MA)	Maximal clot firmness (MCF)	Mainly affected by platelets and the fibrinogen level
% reduction of MA or % reduction of MCF 30 and 60 mins after clotting time	CL30 and CL60	LY30 and LY60	Useful in the diagnosis of hyperfibrinolytic states

Table 2

Typical TEG and ROTEM tracings[9]



TEG Thromboelastography; ROTEM, rotational thromboelastometry: R, reaction time; K, Time from amplitude of 2mm to amplitude of 20mm; MA, maximal amplitude: CT, clotting time: CFT, clot formation time; MCF, maximal clot firmness; α, α-angle (angle formed by a tangential line to the curve starting from the split point; LY30, lysis at 30 min; LY60, lysis at 60 min. (See Box 2 for more details.)

Figure 3

used in many cardiac centres measures ACT by using a tube containing Celite (clotting activator) and a ferromagnetic bar to which is added 0.5 ml of blood. The tube is heated to 37°C and gently rotated. As clotting begins the rotation of the bar is detected. The ACT is measured in seconds - the greater the number, the greater degree of anticoagulation, normal baseline value is 120 140 s, values >450 s are required for cardiopulmonary bypass.

Summary

This article gives an overview of available monitoring devices from basic ward devices to highly specialized devices used only in critical care areas. The advancement in microprocessor technology has resulted in highly complex equipment which produces multiple physiological and derived data which can be difficult to interpret. It is important for today's clinician to have

an understanding of the workings and limitations of the monitoring equipment he/she uses to ensure the patient is managed safely and appropriately. ◆

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