Cardiovascular monitoring in neonatal intensive care

Neonatal intensive care units care for infants and neonates with a range of pathologies, including prematurity and its complications, respiratory infections, metabolic and immunological disorders and congenital heart disease. Whatever the reason for admission to intensive care, all children will have cardiovascular (CVS) monitoring. The purpose of this article is to provide an overview of the different methods of CVS monitoring.

Cardiac index
Cardiac index (CI) is the cardiac output divided by body surface area and is expressed as litres/minute/metres². Thus it is possible to compare the cardiac output of patients of 5kg and 50kg.

Carrying oxygen in the blood
Oxygen content of arterial blood
Once oxygen has been inspired and has passed from the alveolus into the blood, it is transported via the pulmonary veins to the left side of the heart and on into the systemic arterial circulation. Oxygen is carried in the blood in two ways:

- in association with the haemoglobin molecule, as oxyhaemoglobin
- a small (for most purposes negligible) amount of oxygen is carried in solution in the blood.

Haemoglobin
Haemoglobin is the molecule that carries oxygen to the cell and the means by which carbon dioxide is transported from the cell to the lungs. It has a high affinity for oxygen in the arterial circulation yet an affinity for carbon dioxide in the venous circulation. It comprises four subunits: two alpha and two beta polypeptide chains, each carrying a haem group. Oxygen binds reversibly to the ferrous iron atom of each haemoglobin molecule, forming oxyhaemoglobin.


Key points

1. The function of the cardiovascular system is to deliver inspired oxygen to sites of demand in the body.
2. Haemoglobin is central to the transport of oxygen within the body.
3. CVS monitoring interprets different stages of this physiological process.
4. Careful interpretation of CVS monitoring give information about the adequacy of cardiac function and tissue oxygenation.
tissues that have an oxygen demand. Haemoglobin therefore plays a central role in the availability of oxygen to the body. The oxyhaemoglobin dissociation curve (FIGURE 2) describes the relationship between the partial pressure of oxygen and oxygen saturation – as the partial pressure increases, more oxygen molecules bind to haemoglobin until a limit (saturation) is reached. At this point the curve becomes almost flat, forming its characteristic ‘S’ shape (FIGURE 2). Several factors affect haemoglobin’s affinity for oxygen and these are often a result of disturbed physiology, for example an increase in hydrogen ions (i.e. acidosis) will decrease oxygen affinity and ‘shift’ the curve to the right, so oxygen is ‘given up’ more readily to the acidic tissue. Other factors that affect the dissociation curve include temperature (hyperthermia induces a ‘right-shift’), carbon monoxide (‘left-shift’ due to its powerful affinity for haemoglobin – two hundred times that of oxygen) and 2,3 diphosphoglycerate (2,3 DPG) – a product of glycolysis in erythrocytes. Increased concentrations of 2,3 DPG occur in hypoxaemia and anaemia and induce a ‘right-shift’ in the dissociation curve, so the availability of oxygen to tissues is again enhanced at times of particular need.

The cells within the tissues that require oxygen obtain it by diffusion from the distal capillaries.

**Monitoring**

In thinking about the cardiovascular system there are three key questions:

- Is there evidence of cardiac dysfunction?
- Is the tissue perfusion pressure adequate?
- Is there any indication of tissue hypoxia?

The answers to these questions can be found in the clinical examination of the infant and the monitors that surround them.

**Clinical observation**

This is the simplest and most easily performed method of assessing the adequacy of an infant’s CVS. It includes:

- Heart rate
- Pulse volume
- Capillary refill time
- Markers of end-organ perfusion, i.e. urine output, neurological state and skin colour/temperature.

**Heart rate**

This is easily assessed at the bedside and requires no specialist equipment. The infant heart does not respond to increased metabolic demand by increasing stroke volume (Starling Law) but rather by increasing the number of ejections per minute. Therefore an increased heart rate may reflect increased demand, for example hypovolaemic states, seizures and the Systemic Inflammatory Response Syndrome (SIRS). In the NICU setting however, other factors may result in tachycardia, such as agitation, pain and non-sinus arrhythmias.

**Pulse volume**

The volume of an arterial pulsation may reflect the amount of blood ejected in each
cardiac cycle. This is difficult to quantify on a clinical basis, but nevertheless is a useful method of assessment. A disparity between central pulses (palpable) and peripheral pulses (impalpable) usually indicates a cardiac problem or hypovolaemia.

**Capillary refill time**
Blanching an area of skin by applying direct pressure and counting the time taken (in seconds) for it to regain its colour is known as the capillary refill time (CRT) (FIGURE 3). CRT has long been regarded as a quick and reproducible method of assessing circulatory status. However the traditional emphasis has been in the context of resuscitation rather than the post-resuscitation (ICU) phase, where doubts exist regarding its usefulness in reflecting CVS function.

**Markers of end-organ perfusion**
Assessment of end-organ function may reflect the adequacy of the organ’s blood supply and therefore (indirectly) the patient’s cardiac output. Skin colour and temperature can be assessed quickly, but their reliability in assessing cardiac function is low, especially in the ICU patient.

**Non-invasive monitoring**
The NICU patient will invariably be subjected to a variety of non-invasive methods of cardiovascular assessment. Although many of these methods are also used outside the ICU environment, within it they are commonly utilised in combination and are observed on an almost continuous basis.

**Non-invasive blood pressure measurement**
Measurement of systemic blood pressure (BP) is virtually universal and is vital in the assessment of organ perfusion. It is also an indicator of CO and therefore an important guide to therapy, but it should be remembered that systolic BP is a product of CO and systemic vascular resistance. For instance in the child with sepsis, a low systemic BP may be due to vascular failure rather than low CO (as is commonly the case in adults).

Non-invasive measurement of blood pressure (NIBP) is widely used in all areas of health care. The traditional method of using a mercury sphygmomanometer and stethoscope has been superceded by automated devices such as the Dinamap. However automated devices may not correlate closely with other methods. In the NICU setting, NIBP can be integrated into the overall monitoring system, allowing repeated estimations of NIBP at set intervals, the pressure is then displayed on the monitor screen alongside other parameters.

**Electrocardiogram**
The electrocardiogram (ECG) utilises the heart’s electrical activity (depolarisation of the conducting system and cardiac myocytes) during the cardiac cycle. Continuous ECG monitoring is now ubiquitous in NICU and neonatal intensive care settings. It may be centralised (i.e. all patients’ ECGs displayed at a central monitor) or monitored at the bedside, or both. The ECG is primarily useful as an indication of heart rate, when peripheral perfusion is poor, for monitoring of bradycardia associated with apnoea and desaturations, and as an alert to the possibility of an arrhythmia. Should an arrhythmia be suspected then a 12-lead ECG is mandatory.

**Echocardiography**
The echocardiogram is a vital tool in assessment of cardiac function in the NICU (FIGURE 4). It is usually performed transthoracically. It will provide information regarding cardiac size, preload, contractility and afterload which, together with heart rate, are the major factors that influence cardiac output. Its role has also been expanded to the non-specialist for rapid diagnosis of, for example, cardiac tamponade.

**Pulse oximetry**
The arterial haemoglobin oxygen saturation can be derived by analysing the ratio of pulsatile to total transmitted red light transilluminating a region of tissue such as the earlobe or fingertip. This difference in peak optical density of pulse waves forms the basis of modern pulse oximetry. Pulse oximetry is a widely-used non-invasive technique but there are caveats to its use, for instance in a poorly-perfused extremity, anaemia or increased skin pigmentation. It cannot distinguish between carboxy- and oxyhaemoglobin and in methaemoglobinemia the measurement is unreliable. The latest pulse oximeters aim to minimise the artefact that derives from patient movement.

**Cerebral monitoring**
Individual organs have been targeted for assessment of cardiovascular function and historically the brain has been subject to a variety of methods of both invasive and non-invasive monitoring. In neonates, alterations in the integrated electroencephalogram, monitored by a cerebral function monitor, may give the first indication of cardiovascular inadequacy. Most recently developments in peri-operative assessment of depth of anaesthesia or cerebral blood flow during neurosurgery have stimulated...
developments. Near-infra-red spectroscopy (NIRS) is a global, non-invasive, continuous method of monitoring cerebral oxygen saturation \(^1\) (FIGURE 5). Its use in neonates is currently experimental and not routinely used. In practice a probe is applied to the skin (usually the forehead) which emits light, similar to a pulse oximetry probe. Its accuracy is heavily dependent on it distinguishing a signal from the brain rather than the intervening tissue (e.g. skin, muscle and bone) \(^2,3\).

The tissue saturation derived is thought to be weighted to the greater proportion of venous blood in the area sampled. The readout is expressed as a percentage and the usual value is in the 60-80% range. Values lower than 42% are thought to indicate dangerous tissue hypoxia. Whilst there are limitations to NIRS, studies confirm its response in situations of rapid cerebral desaturation, e.g. during systemic hypoxia \(^3\). However, the hypoxia and hypoperfusion concomitant with such a situation will inevitably compromise the efficacy of the NIRS itself (e.g. by extra-cerebral signal contamination) \(^4\). In the ICU setting, changes in cerebral blood flow (greatly influenced by the partial pressure of CO\(_2\) in the blood) or vascular tone can alter the arteriovenous distribution of blood in the scalp and other extra-cerebral tissues differently to that of the brain, thereby distorting the cerebral saturation reading \(^5\). Some authors have postulated that biological variations in transcranial optical pathlength and cerebral haemoglobin concentration account for intersubject differences in NIRS reliability \(^6\).

**Invasive cardiovascular monitoring**

**Intra-arterial blood pressure monitoring**

Intra-arterial blood pressure (IABP) is a well-established method of monitoring a patient's cardiovascular status. A pressure transducer measures the IABP and displays an arterial waveform via an intra-arterial cannula (commonly inserted in the radial, umbilical or posterior tibial artery). The cannula also allows regular sampling of intra-arterial blood for analysis. The arterial waveform may also be analysed (pulse contour analysis) as it reflects the stroke volume and cardiac output, but must still be calibrated against CO measured by another method \(^7\).

**Arterial blood gas analysis**

Analysis of blood obtained from an arterial source provides vital information regarding a patient’s cardiovascular status. Arterial blood gas (ABG) analysis originated in the late 1950s following the work of Severinghaus in developing a combination of pH, PCO\(_2\) and PO\(_2\) electrodes to create a blood gas analyser \(^8\). During the next decade, Clark developed the analyser further, enabling measurement of blood lactate \(^9\). During the next decade, Clark developed the analyser further, enabling measurement of blood lactate \(^9\). Lactate is produced at a cellular level as a result of anaerobic metabolism. It is an important marker of cardiovascular function as an increase in blood lactate reflects tissue hypoxia. This may be as a result of low cardiac output or reduced tissue oxygen extraction \(^10\).

**Mixed venous saturation**

A fall in mixed venous oxygen saturation below 60% (usually determined from a central venous blood sample analysed in a blood gas analyser that contains a co-oximeter) can be an early indicator of impaired tissue oxygen delivery (from a low haemoglobin or low CO) or increased tissue oxygen consumption (it may precede an increase in lactate and the onset of acidosis) \(^11\). The fall reflects an increased arteriovenous oxygen difference \(^1\) and as such represents the balance between oxygen delivery (DO\(_2\)) and tissue oxygen demand \(^12\). At a constant oxygen consumption and arterial oxygen concentration, the relationship between CO and mixed venous oxygen saturation is not linear – i.e. a small fall in mixed venous oxygen saturation may represent a larger fall in CO \(^1\). In addition, the superior vena cava (SVC) saturation, the most commonly obtained value in NICU practice, has been found to consistently overestimate ‘true’ mixed venous saturation in established shock states \(^13\). ‘True’ mixed venous blood is obtained from the pulmonary artery, as this contains both inferior vena cava and SVC blood, as well as a contribution from the coronary sinus.

**Central venous pressure**

The venous system is a reservoir that contains about 70% of the total blood volume at any given time \(^1\). There is a pressure gradient between the capillary venous pressure (about 15mmHg) and right atrial pressure (about 5mmHg) and it is this gradient that aids the return of blood to the right atrium \(^2\). Several factors influence venous return, such as gravity and intrathoracic pressure. A measure of central venous (right atrial) pressure represents cardiac pre-load \(^1\) and reflects the ‘volume status’ of the patient. It is sometimes referred to as the ‘filling pressure’ \(^14,15\). Monitoring of CVP is more common in paediatric intensive care units and is rarely utilised in neonatal practice.

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**TABLE 1. Summary of cardiovascular monitoring methods.**

<table>
<thead>
<tr>
<th>Physiological point</th>
<th>Clinical methods</th>
<th>Non-Invasive monitoring</th>
<th>Invasive monitoring</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart</td>
<td>Heat rate</td>
<td>ECG; Echocardiogram</td>
<td></td>
<td>Direct invasive cardiac monitoring is usually used post-cardiac surgery (e.g. left atrial pressure)</td>
</tr>
<tr>
<td>Arteries</td>
<td>Pulse volume</td>
<td>NIJB</td>
<td>IABP</td>
<td></td>
</tr>
<tr>
<td>Capillaries</td>
<td>CRT</td>
<td>Pulse oximetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vital organs</td>
<td>Urine output;</td>
<td>Regional oximetry (e.g. NIRS); Tissue PaO(_2)</td>
<td>Arterial blood gas analysis; Mixed venous saturation</td>
<td>Skin colour and temperature are unreliable indicators of cardiac function</td>
</tr>
<tr>
<td>Veins</td>
<td></td>
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<tr>
<td>Central veins</td>
<td>Filling</td>
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<tr>
<td>CRT: Capillary refill time; NIRS: Near-infra red spectroscopy; CVP: Central venous pressure</td>
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Conclusions

Babies in NICU are subjected to a wide variety of methods of cardiovascular monitoring, whether in the form of clinical observation or more sophisticated invasive and non-invasive techniques (TABLE 1). All these methods of monitoring are ultimately concerned with the same fundamental process: that of monitoring delivery of oxygen to the tissues of the body. An appreciation of the physiology of that delivery is essential if cardiovascular monitoring is to be used effectively and, more importantly, interpreted correctly.

References