Pulse oximetry revisited

Dr Liesel Bösenberg
Specialist Physician and Fellow in Critical Care
Kalafong Hospital
University of Pretoria
Topics that will be discussed and dissected:

• Revisiting physiology
• Contour analysis of the plethysmographic curve
• Non-invasive monitoring of peripheral perfusion
• Pulse oximetry in the esophagus
• Near infrared spectroscopy
Physiology:

• In 1937 Alrick Herzman developed ‘photoelectric plethysmograph’
• ‘takes advantage of the fact that the absorption of light by a transilluminated tissue varies with its blood contents
• Lambert-Beer Law: light absorption according to optical density
• Current technology developed in the 1970’s
• Measures and is dependant on two main components:
• Arterial wave form generation
• Detection of oxyhemoglobin and deoxyhemoglobin and calculating SaO$_2$
• Oxyhemoglobin absorbs light at peak 660nm (red)
• Deoxyhemoglobin @ 940 nm (infrared)
• Two light emitting diodes placed opposite photoreceptor
• Photoreceptor detects the light frequency through the tissue in between (finger or earlobe)
• Signal and waveform generated
• Signal is sampled at 25 x/sec
• Signal output is averaged over preceding 5-15 sec to minimize calculation error (lag time)
How it works:

Figure 1. How Pulse Oximetry Works

To measure oxygen saturation (SpO₂)—the percentage of hemoglobin molecules in the blood carrying their full potential of oxygen—the pulse oximeter probe is attached to the patient’s finger. Red and infrared light pass through the patient’s blood, and the amount of light received by the detector on the other side indicates the amount of oxygen that is bound to the hemoglobin. (Oxygen attaches to the heme portion of hemoglobin molecules in the red blood cells.) Each hemoglobin molecule can carry up to four oxygen molecules. Oxygenated hemoglobin (oxyhemoglobin or HbO₂) absorbs more infrared light than red light, while deoxygenated hemoglobin (Hb) absorbs more red light than infrared light. By comparing the amounts of red and infrared light received, the instrument can calculate the SpO₂. Illustration by Anne Rains.
• NB: Pulse oximeters measure oxygen saturation and not oxygen content and therefore does not measure actual tissue oxygenation.
Extrinsic factors that can influence accuracy:

- Insensitive in detecting early hypoxaemia in patients with high partial pressure of oxygen

- Oxymeters measure oxygenation which is related to partial oxygen pressure according to the oxyhemoglobin dissociation curve

- Interference by other haemoglobins that absorb light over similar spectrum e.g. Carboxyhemoglobin, methemoglobin, foetal hemoglobin, sickling red blood cells

- Anaemia/ hyperbilirubinaemia per se does not affect accuracy of the oximeters
• Methylene blue, indocyanine green, indigo carmine can give falsely low readings
• Black, blue and green nail polish can give low readings, acrylic nails not a problem
• Inaccurate readings also with ambient fluorescent or xenon lights
• Motion artefacts can be problematic
• Severe hypotension, low Q, vasoconstriction and hypothermia reduces pulsatile blood flow in tissues
• This reduces signal strength and quality
Intrinsic factors that can influence accuracy:

• LEDs and photoreceptors are cheap and mass produced
• Accuracy of pulse oxymeters fall with falling saturation and might be unreliable if $\text{SaO}_2$ below 70%
• The actual frequency admitted might differ up to 15 nm higher or lower than correct frequency
• However with $\text{SaO}_2$ above 90% the margin of error is +/- 2%
Clinical applications:

• Screening tool and continuous monitoring
• It has been shown to decrease the length of stay in ICU unit
• It can assist in the titration of oxygen in ventilated and non-ventilated patients
• It has been shown to decrease the frequency of arterial blood gas sampling in both groups
Recent advances:

Multi–wavelength pulse oxymetry can differentiate between the different types of haemoglobin and indicate total hemoglobin in a non-invasive way (pulse oxyhemoglobinometers)

Current Opinion in Critical Care 2006, 12:269–271
The Plethysmographic waveform:
Contour wave form analysis:

• In 1860 Ettiene Jules-Marey invented a device that measured the contour of the radial pulse
• The Plethysmographic wave form resembles the arterial invasive pressure trace
• It is not a direct analogue of arterial pressure or cardiac output but the waveform analysis may give useful information of the cardiovascular system in a non-invasive way
• Helpful in detecting pathologies that might alter the vascular tone e.g arteriosclerosis, endothelial dysfunction
Contour analysis of digit volume pulse:

- The amplitude of the pulsatile component of the curve is influenced by respiration, sympathetic nervous system activity and other factors that influence local perfusion.
- The shape remains constant.
- Alrick Herzman: crest time, the duration of the ascent of the primary wave, the height of the inscissura of the catacrotic limb.
- Loss of rebound wave with hypertension and arteriosclerosis.
- Classification of the waveform.
Classification of the digital volume pulse (DVP) waveform according to Dawber et al. [36]. With increasing age and/or presence of vascular disease, the waveform changes from class 1 to class 4. The change in contour can be interpreted in terms of earlier arrival of a pressure wave reflected from the peripheral circulation (see Fig. 4). With increasing stiffness of the conduit arteries, the reflected wave arrives early and its contribution moves from the diastolic to the systolic component of the DVP. bis, bisferiens.
• Class 1 in younger individuals
• Class 4 in older individuals or individuals with established CAD
Plethysmographic curve to assess microvascular circulation

- The PPG signal has been suggested to reflect changes in peripheral perfusion.
- The ratio between pulsatile and non-pulsatile components of the pulse oximetry signal is indicative of peripheral perfusion (non-invasive index).
- Peripheral perfusion index of 1.4 indicates an abnormal peripheral perfusion in CC patients.
Plethysmographic curve to assess macrocirculation

- Pulse oximetry has been shown useful to detect systolic blood pressure.
- The signal of the oxymeter might be lost with a Q < 2.4 l/min/m^2 and a very high SVR_{mean}.
- In severe TI the venous flow becomes pulsatile and the measured curve does not reflect systolic pressure.
- With vasodilatation the PPG amplitude increases with enhanced respiratory variation.
Plethysmographic curve to assess volume responsiveness

• Analysis of the respiratory variation of plethysmographic signal can indicate blood volume status in mechanically ventilated patients

  □ \( \Delta \) POP > 13 % before fluids , sens 80%, 90 % spec to distinguish between responders v.s non-responders

Current Opinion in Critical Care 2008, 14:348–353
Noninvasive monitoring of peripheral perfusion

Alexandre Lima
Jan Bakker
Nice article to read:

- Use of Peripheral Perfusion Index Derived From the Pulse Oximetry Signal as a Noninvasive Indicator of Perfusion
- Alexandre Pinto Lima, MD, Peter Beelen, RN, Jan Bakker, MD, PhD
- Crit Care ed. 2002;30(6) © 2002 Lippincott Williams & Wilkins
Non-invasive monitoring of peripheral perfusion

Fig. 1 The pulsation of arterial blood causes a pulsating volume variation. Peripheral perfusion index (PFI) is calculated as the ratio between the arterial pulsatile component ($I_P$) and the nonpulsatile component ($I_{NP}$). $I_0$ Source light intensity; $I$ light intensity at the detector.
Table 1 Measurement methods to study peripheral perfusion (CRT capillary refill time, \(dTC-p\) temperature gradient central-to-peripheral, \(dTP-a\) temperature gradient peripheral-to-ambient, \(Tskin-diff\) forearm-to-fingertip skin-temperature gradient, \(PFI\) peripheral perfusion index, \(NIRS\) Near-infrared spectroscopy, \(Hb\) deoxygenated hemoglobin, \(HbO_2\) oxygenated hemoglobin, \(HbT\) total hemoglobin, \(StO_2\) tissue oxygen saturation, \(Cyt\) cytochrome \(a\), \(OPS\) orthogonal polarization spectroscopy, \(FCD\) functional capillary density, \(LDF\) Laser Doppler flowmetry, \(PtcO_2\) oxygen partial pressure in the skin, \(PtcCO_2\) carbon dioxide partial pressure in the skin, \(Tc-index\) transcutaneous oxygen index, \(Pst\) sublingual tissue PCO\(_2\), \(Pst-aCO_2\) gradient between \(Pst\) and arterial PCO\(_2\))

<table>
<thead>
<tr>
<th>Method</th>
<th>Variable</th>
<th>Advantage</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinical assessment</td>
<td>Warmth and coolness skin</td>
<td>Depends only on physical examination; valuable adjunct for hemodynamic monitoring in circulatory shock</td>
<td>Difficult interpretation in distributive shock</td>
</tr>
<tr>
<td></td>
<td>CRT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body temperature</td>
<td>(dTc-p)</td>
<td>Validated method to estimate dynamic variations in skin blood flow</td>
<td>At least two temperature probes required; does not reflect the variations in real time</td>
</tr>
<tr>
<td>gradient</td>
<td>(dTp-a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Tskin-diff)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse oximetry</td>
<td>PFI</td>
<td>Easily obtainable; reflect real time changes in peripheral blood flow</td>
<td>Not accurate during patient motion</td>
</tr>
<tr>
<td>NIRS</td>
<td>(Hb), (HbO_2), and (HbT)</td>
<td>Assessment of oxygenation in all vascular compartments; can be applied to measure regional blood flow and oxygen consumption</td>
<td>Requires specific software to display the variables</td>
</tr>
<tr>
<td></td>
<td>(StO_2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Cyt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPS</td>
<td>FCD</td>
<td>Direct visualization of the microcirculation</td>
<td>Observer-related bias; semiquantitative measure of perfusion</td>
</tr>
<tr>
<td>LDF</td>
<td>Microvascular blood flow</td>
<td>Useful method to evaluate endothelium-dependent vascular responses</td>
<td>Small sampling volume for cutaneous blood flow measurement; does not reflect heterogeneity of blood flow</td>
</tr>
<tr>
<td>Transcutaneous</td>
<td>(PtcO_2/PtcCO_2)</td>
<td>Direct measurement of (PtcO_2/PtcCO_2); early detection of peripheral hypoperfusion</td>
<td>Necessity to frequently change the sensor position; requires blood gas analysis</td>
</tr>
<tr>
<td>oximetry</td>
<td>(Tc-index)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sublingual capnometry</td>
<td>(Pst)</td>
<td>Direct measurement of tissue PCO(_2) noninvasively</td>
<td>Requires blood gas analysis</td>
</tr>
<tr>
<td></td>
<td>(Pst-aCO_2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Orthogonal polarization spectral

- Probe placed under the tongue to assess microcirculation
- Used in septic patients and cardiogenic shock patients
- It has been used to monitor microcirculatory improvement of dobutamine and nitroglycerine in volume resuscitated septic patients
Laser Doppler flowmetry:

- Non-invasive, continuous microcirculatory monitoring of blood flow in many tissues e.g. neural, muscle, skin, bone & intestine
- The principle is measuring doppler shift - the frequency change that light undergoes as the RBC moves past the probe
- Limited to skin
In the oesophagus:

Figure 7. Reflectance oesophageal pulse oximetry probe.
Fig. 2 A Diagram of a distal tip of the NIRS optical cable. B With 25 mm spacing ($d$) between emission and detection probes, approx. 95% of the detected optical signal is from 23 mm of tissue penetration
NIRS uses the principles of light transmission and absorption to measure concentrations of haemoglobin and oxygen saturation.

Greater tissue penetration than oxymetry and gives global assessment of oxygenation in all vascular compartments (art, ven and capillary).

In animal models of haemorrhagic shock, NIRS has shown sensitivity in detecting visceral and skeletal muscle ischaemia.

NIRS in brachioradialis, deltiod and tibialis anterior of trauma patients to detect compartment syndrome.
NIRS: A Standard of Care for CPB vs. an Evolving Standard for Selective Cerebral Perfusion?

John M. Murkin, MD, FRCPC

- Standard of care for vascular / cardiothoracic e.g. CABG for detection of cerebral malperfusion and hypoxaemia (INVOS)
- Detection of spinal ischaemia during aortic surgery