Principles of pulse oximetry

This chapter is at least loosely associated with Section F12(i) from the 2017 CICM Primary Syllabus, which expects the exam candidates to be able to *"describe the principles of pulse and tissue oximetry, co-oximetry including calibration, sources of errors and limitations".* Abuse of punctuation notwithstanding, this syllabus item appears relevant to the revising exam candidate, as pulse oximetry has appeared in past Primary Exam papers (Question 3 from the first paper of 2008 and Question 5 from the second paper of 2013). In fact, it has even found its way into the Fellowship Exam (Question 3 from the first paper of 2006). Fortunately, some of the college comments were spectacularly informative, and the trainees were left with a very clear idea of what was expected. Unfortunately, as there have been no college SAQs regarding co-oximetry or tissue oximetry, we are somewhat in the dark with regards to what is relevant. As such, only some minimum of attention is devoted to these areas at the end of this chapter; in terms of exam results, pulse oximetry is where the money is.

In summary:

- Principles fundamental to pulse oximetry
  - Different absorption of different light wavelengths by haemoglobin species
  - Isolation of the pulsatile arterial signal because of pulse-related changes in optical distance
- Different light absorption by haemoglobin species:
  - Two wavelengths (660 and 940 nm) are used in pulse oximettry
  - Deoxyhaemoglobin absorbs more light at 660nm and oxyhaemoglobin absorbs more light at 940 nm.
- Quantification of haemoglobin species concentration
  - Beer Law: *the concentration of a given solute in a solvent is determined by the amount of light that is absorbed by the solute at a specific wavelength*
  - Thus, concentration of oxyhaemoglobin and deoxyhaemoglobin can be determined from their absorption of the two wavelengths
- Determination of pulsatile signal
  - Absorption-over-time signal from arterial blood is pulsatile, whereas signal from venous haemoglobin and tissue is not.
  - When the arteries pulsate, the distance travelled by light though them changes
  - One can therefore use Lambert's Law (*equal parts in the same absorbing medium absorb equal fractions of the light that enters them).*
  - Thus, one can compare the ratio of pulsatile and nonpulsatile absorbance to produce R, the ratio of absorbance at any given time
- Calibration with empirically measured data
  - R is meaningless unless it can be related to oxygen saturation;
  - A series of saturation measurements and R values have been collected from healthy individuals in the 100-75% saturation range, and extrapolated to 0%
  - This array of data is used by the pulse oximeter control circuit as a lookup table to p
- Correction for ambient light
  - The pulse oximeter LEDs strobe at a high frequency (400-900 Hz)
  - When the LED is off, the photometer measures the absorption of ambient light, and subtracts this from the signal measured when the LEDs are on.
  - This eliminates the contribution of (most) ambient light
- Essential design elements of a pulse oximeter include:
  - LED light sources
  - A photometer
  - A control circuit
  - A user interfce with display and alarm functions
- Limitations of pulse oximetry are:
  - Inevitable difference with ABG oximetry due to processign artifact
  - Inabiulity to detect PO_2 or discriminate between haemoglobin species e.g carboxyhaemoglobin
  - Spurious results in the presence of carboxyhaemoglobin and methaemoglobin
  - Errors to detect pulse with poor perfusion, nonpulsatile ECMO flow or patient movement
  - Increasing inaccuracy in the extrapolated range of calibration values (low oxygen saturation, below 50%)

Fortunately, this is a topic with very good literature representation. It would appear as if every qualified anaesthetist has at one stage or another published a review article on this topic. Excellent free papers include Sinex (1999), Kamat (2002), Jubran (1999), and Jubran again (2015). One could list more, but there is a real risk here of becoming inundated with numerous sources of the same information. A trainee with some sort of deeply misplaced interest in this topic is invited to look at both the Jubran articles, as they present slightly different information. There may also be a small weird group of candidates who will find joy in Webster (1997), which is essentially a 256-page book for people who want to design and build pulse oximeters.

The principles of light absorbance and the Beer-Lambert Law

The Beer-Lambert law, or the Lambert-Beer law (or the Beer–Lambert–Bouguer law, or more accurately the Bouguer-Lambert-Beer law if you respect academic primacy) is basically a mathematical description

of the relationship between the concentration of a substance in a solution and the change in the characteristics of light which passes through that solution. In its standard form, the law can be stated in the following manner:

> *The measured absorbance for a single compound is directly proportional to the concentration of the compound and the length of the light path through the sample*

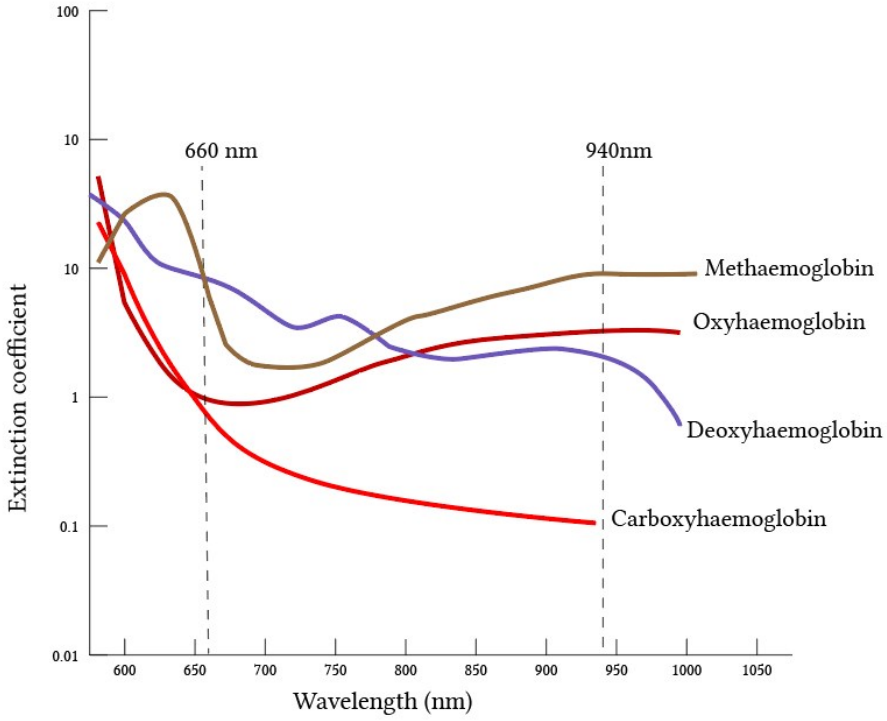
This underpins the principles of using light absorbance to detect the quantity of the substance of interest in the object which you are transilluminating. Specifically, Beer's law is what underpins the concentration measurement, and Lambert's law deals more with the identification of the pulsatile signal, as it is concerned with attenuation due to optical distance through the sample. These can be summarised as:

> Beer's law: the concentration of a given solute in a solvent is determined by the amount of light that is absorbed by the solute at a specific wavelength.
>
> Lambert's law: equal parts in the same absorbing medium absorb equal fractions of the light that enters them.

Though it is extremely unlikely that one would ever be expected to separate the Beer from the Lambert in an exam setting, it is probably worth knowing that the Beer-Lambert law is a composite of both concepts, correlating absorbance to both the concentration and the optical path through the substance.

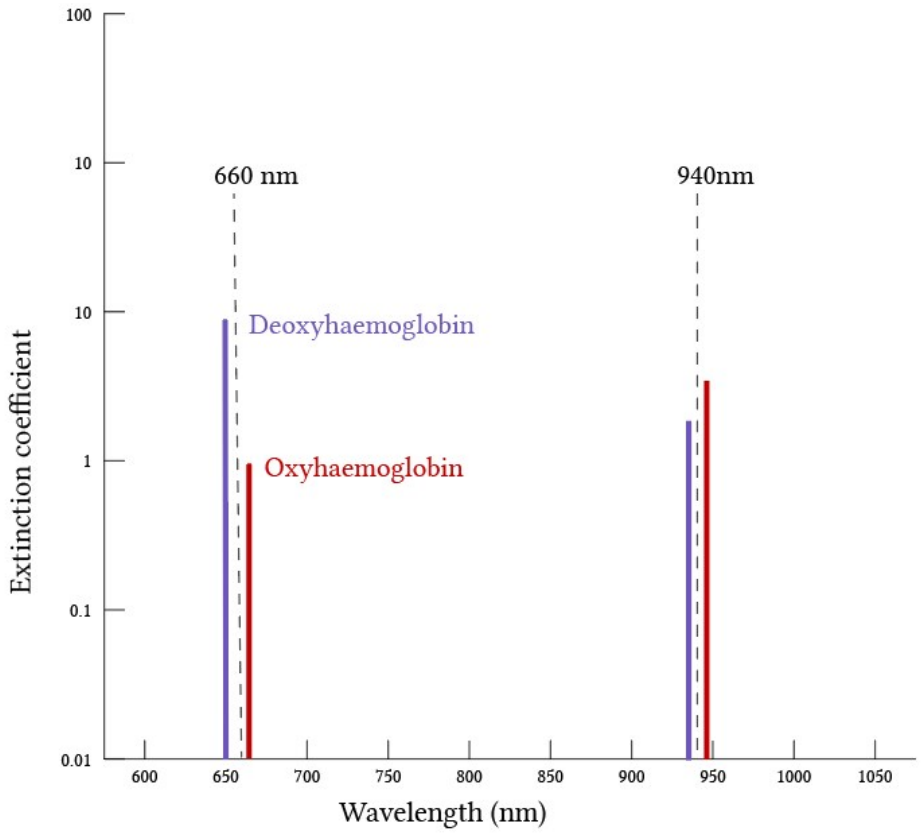
Differential absorbance of haemoglobin species

Elsewhere, there is an entire chapter dealing with the absorption spectroscopy of haemoglobin species, and it will suffice to report here that in the red part of the spectrum, oxygenated haemoglobin absorbs less light than deoxygenated haemoglobin, while the reverse occurs in the infrared region. If one were to plot the absorbance ("extinction coefficient") of different species over wavelength, one would produce a graph which looks something like this one (a toddlery coloured-in version of the one from Jubran, 2015):



Most ABG analysers have access to sophisticated and expensive light sources and are able to test about two hundred wavelengths simultaneously, which allows them to report this sort of spectrum histogram. Fingertip pulse oximeters are usually cheap and disposable, and so usually only measure a couple of wavelengths, which is actually enough. Specifically, the key wavelengths are 660 nm (red) and the 940 nm (infrared).

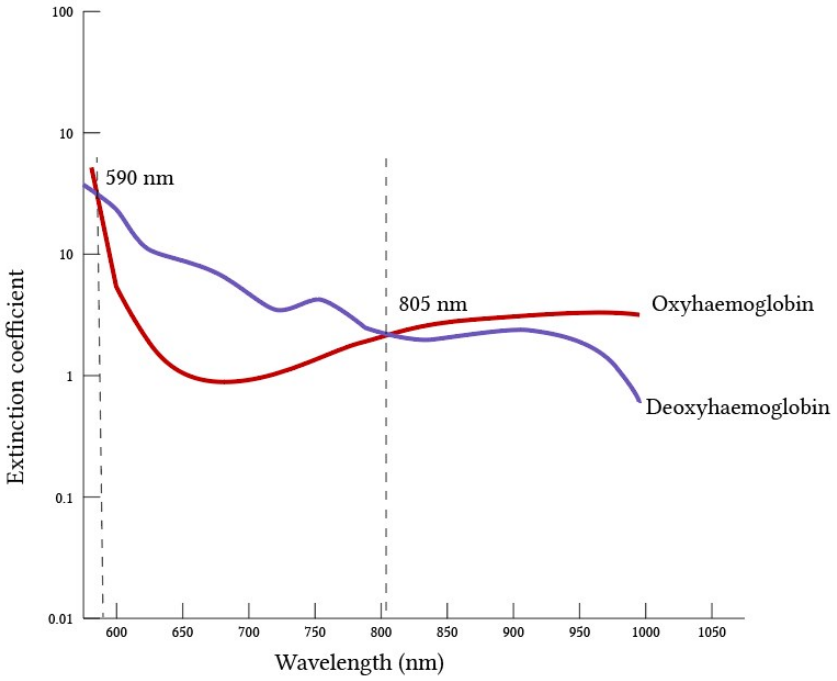
Anyway, it's 660 and 940 nm. If one were to limit one's visible spectrum to these two colours, the histogram above is reduced to this:



The take-home message from all this is the fact that oxyhaemoglobin and deoxyhaemoglobin are sufficiently different at these select wavelengths that only these two wavelengths are necessary to tell them apart. Oxyhaemoglobin absorbs less light than deoxyhaemoglobin in the red region, and the reverse is true in the infrared.

Correction for haemoglobin concentration

Note that on the absorption spectrum diagram, there are two wavelengths at which oxyhaemoglobin and deoxyhaemoglobin both have the same extinction coefficient. These are called "isosbestic" points, a spectroscopy term referring to a wavelength or frequency at which the total absorbance of a sample does not change during a chemical reaction (*"iso"* meaning "equal" and *"sbestos"* meaning "extinguishable").



So, at these isosbestic points, oxyhaemoglobin and deoxyhaemoglobin are indistinguishable. What is the point of knowing this? Well: if one eliminates the difference between oxyhaemoglobin and deoxyhaemoglobin, what one ends up measuring at these wavelengths is the *total* haemoglobin absorbance, which according to the abovementioned eponymous law is directly proportional to the total haemoglobin concentration. The point of this is to be able to then correct the other absorption data (from the non-isosbestic points, for the other species of haemoglobin). If one does nothing to correct for haemoglobin concentration, the pulse oximeter will become confused and measure something spurious, particularly as the patient becomes more hypoxic. Severinghaus & Koh (1990) demonstrated a negative bias of up to 15%, i.e. under conditions of hypoxia, in the anaemic patient the pulse oximeter would read an even lower SpO_2, deceiving the intensivist. The silver lining, according to the authors, was that *"it is fortunate that these errors are protective, in the sense that they overestimate the degree of desaturation in anemic subjects where the harm could be greatest"*.

Elimination of ambient light contribution

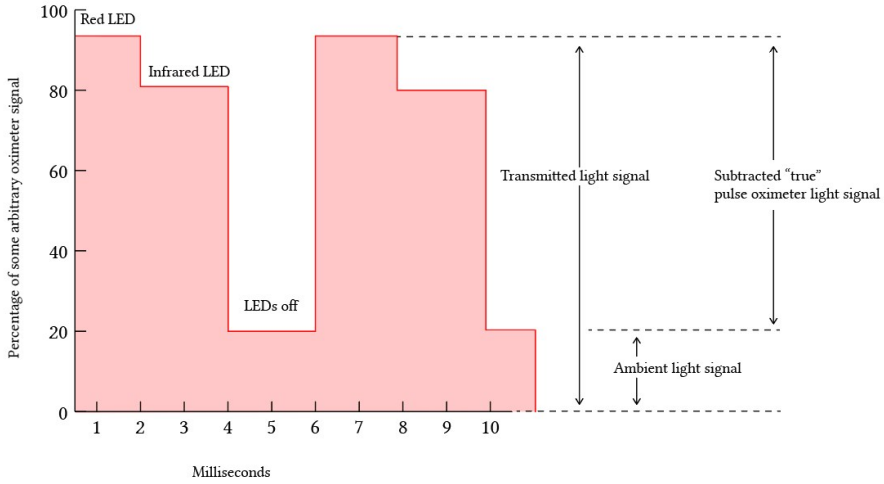
So, you are now measuring the absorbance of haemoglobin at different wavelengths. However, you are not in a sterile laboratory, aiming your beam at a calm blood sample. Most pulse oximeters do their best work when attached to a patient, which potentially means receiving light not only from the calibrated 660/940nm light sources but also transmitted light from the fluorescent examination lights, reflected from the gaudy nail polish, and from ambient sunlight, and so forth.

These are non-trivial light sources, as most of them are substantially more powerful than the oximeter LEDs. From this, it logically follows that one should expect some level of interference with the reading. Some early case reports suggested this might be the case. For example, Amar et al (1989) found that bright fluorescent lights caused a drop in measured SpO_2 among three children undergoing neurosurgery, and Block et al (1987) found that the heart rate measured by the oximeter was falsely

increased due the interference from the bright light of a cystoscope.

That ambient light interferes with pulse oximetry has historically been the firm belief of end-users, most likely also including CICM examiners. As such, it would be unwise for the exam candidate to challenge these beliefs with evidence. However, at least in modern designs of oximeter probes, ambient light interference is minimal. Fluck et al (2003) tested such equipment, and found that under a series of experimental lighting conditions (including incandescent, quartz-halogen, infrared and fluorescent light sources) the change in measured oxygen saturation was minimal, varying by one decimal point of a per cent.

The reason for this lack of interference is the fact that a modern LED light source cycles on and off about 500 times a second. This patent describes how, when the LED is off, the detector keeps recording to measure a "dark signal". This represents the contribution of the ambient light to the measurement. This signal is then subtracted from the next measurement collected when the LED light source is turned on:



This works just fine when ambient light is constant, but may still fail when it is also flickering with a high frequency. Ralson et al (1991) discuss how this interaction of tow flickering light sources might fool the SpO_2 sensor into detecting a false pulsatile waveform. One answer to this was to run the LED switching at mains frequency (60Hz) so that it is synchronised with all the local fluorescent lights; the other was to run them at a preposterously high frequency (up to 900 Hz), expecting that there will be no sources of flickering light of an even higher frequency in the usual hospital setting. From manufacturer data, it appears that the latter approach was ultimately widely adopted.

Isolation of pulse waveform

As is pointed out above, the pulse oximeter light source is not shining through a nice dilute sample of pureed erythrocytes (which is in fact what one gets in the blood gas analyser). It is pointed at a fingertip, with skin, nail bed, bone, ligament and venous blood all standing in the way. The measured signal, therefore, is a composite of many absorbances. How does one eliminate them?

The answer was discovered completely randomly by Takuo Aoyagi in the early 1980s; he was trying to get an ear probe to measure his dye dilutions for cardiac output monitoring and found a pulsatile signal which interfered with the measurements. This pulsatile artifact turned out to contain the information

regarding arterial oxygen saturation, which ended up being the thing that brought pulse oximetry into the mainstream (whereas before, one would have to "blanch" the fingertip or earlobe using pressure, to eliminate the confounding effects of the venous signal).

The trick was to create a "ratio of ratios", comparing the pulsatile signals to non-pulsatile signals in each wavelength, and then comparing the resulting signal differences. It's brilliantly simple if one thinks about it:

$$R = \frac{AC_{660} / DC_{660}}{AC_{940} / DC_{660}}$$

Where

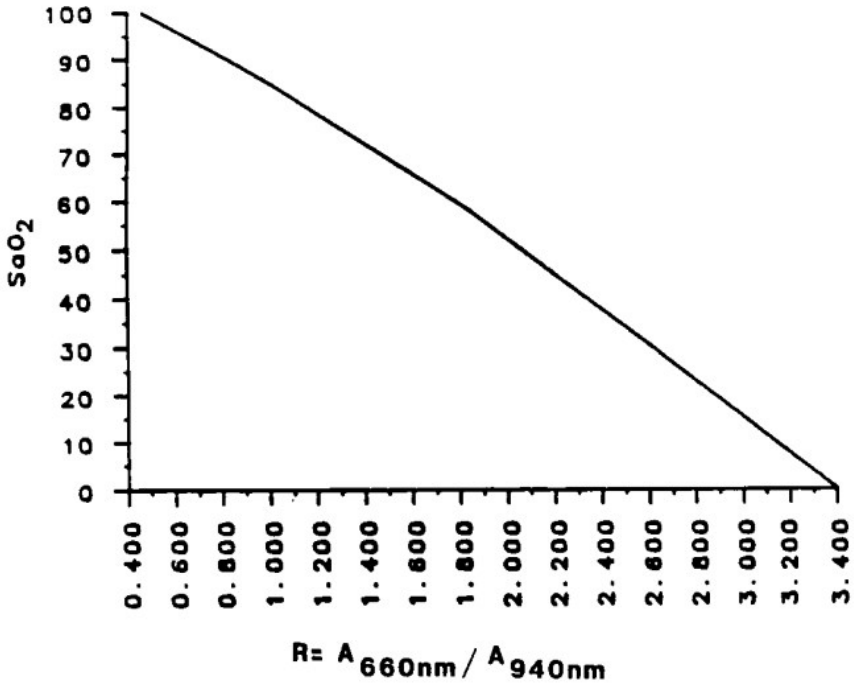
- R= ratio of absorbance of the pulsatile and non-pulsatile elements, and
- AC and DC are the pulsatile elements and non-pulsatile elements of the signal, at their respective subscripted wavelengths

This pulsatile signal change is not due to some change in the arterial oxygenation which occurs with every heartbeat (arterial blood stays uniformly oxygenated between beats), or with the arrival of extra haemoglobin in front of the sensor (arterial haematocrit is also sable between beats). The main reason for the change in absorbance is the optical distance. As arteries expand with the arterial pulse, the distance between the probe and the sensor increases, and the absorbance increases proportionally (this is where Lambert's law comes in).

At the end of this, one ends up with a number (R), rather than an SpO_2 reading. To relate this number to the saturation of haemoglobin, one needs to calibrate R.

Calibration of pulse oximetry

The relationship between any given R value and the corresponding SpO_2 was derived empirically, by recording the arterial oxygen saturation at different R values in a group of healthy volunteers.



Most textbooks, when this comes up, will usually produce this abovestolen calibration curve provided by Ohmeda to Pologe (1987), which extends all the way to 0mmHg. Clearly even Ohmeda would not asphyxiate their healthy volunteers down to 0% SpO2, which means some of that curve must be extrapolated. In fact, most of it must be, because even desperate volunteers usually won't agree to desaturate below 75-80% SpO_2. Thus, the R-value lookup table in every pulse oximeter is empirically calibrated only within some survivable range of SpO_2, but becomes increasingly less and less accurate at low values. Webb et al (1991) report unretrievable data from Severinghaus (1989), who was able to test pulse oximeters from multiple manufacturers down to an SpO_2 of 50%, and found that the majority were slightly underestimating the saturation (i.e. when it reads sats of 50%, the sats are really 55%). How much does this information matter, outside of the CICM exam setting? One is left to decide for themselves the clinical relevance of achieving a 0.1% range of SpO_2 measurement accuracy in their desperately hypoxic cyanosed patient.

System components of the typical pulse oximeter

From the discussion above, the basic component requirements of a pulse oximeter must be:

- Light sources (typically LEDs)
- A light detector (typically a photodiode)
- An opaque probe housing to minimise ambient light bleedthrough
- A signal amplifier and noize filter
- An integrated circuit controller and signal processor
- Electronic storage which contains calibration data
- Compliant connector which integrates into other monitoring systems, or
- A user interface with graphical display functions
- An alarm, ideally with an adjustable range

This is of course not an exhaustive list, but these components probably represent some sort of essential minimum (i.e. a pulse oximeter without even one of them would be severely crippled in its function).

Limitations of pulse oximetry

An entire range of articles (typically from the early 1990s) focus on the limitations of pulse oximetry, i.e. mainly the various ways in which the oximeter probe could produce numbers which do not agree with the gold standard (ABG). As such, a long answer is possible to the question, "what are the limitations of pulse oximetry". The college answer to lists *"quality of product, bias, precision and accuracy ... insensitivity to PaO_2"* as limitations of the technique, and that is probably as little as you could afford to write on the subject. Ideally, a competent answer should include at least the headings from the 1991 series of articles by Ralston & Webb. What follows is an exhaustive reference, a list which cannot possibly (and should not) be memorised for exam purposes:

- Physical limitations of the measurement technique:
    - Processing: ABG machines lyse RBCs and will therefore have a slightly different saturation measurement because of the change in sample pH (it will be trivially right-shifted)
    - Temperature difference: the oximeter measures the patient's "true" saturation at whatever their temperature happens to be, whereas the ABG oximeter adjusts its results to a blood temperature of 37 degrees, which can lead to a discrepancy (though this also is not an inaccurate reading, strictly speaking)
- Sources of error in signal measurement
    - Ambient light: as discussed above, ambient light can interfere with oximetry, although it would have to be flickering light of a certain (high) frequency
    - Nail polish
    - Oedema
- Error due to a failure to detect a pulse
    - Poor signal quality due to poor pulsatility of flow (shock, tourniquet, VA ECMO, etc)
    - Choice of probe site
    - Uninterpretable pulsatile signal due to
        - Erratic flailing movements of the patient
        - Arrhythmia
    - Venous pulsation (eg. severe TR)
- Interference with absorbance
    - Presence of haemoglobins other than standard vanilla haemoglobin
        - Carboxyhaemoglobin
        - Methaemoglobin
        - Foetal haemoglobin
    - Intravascular presence of dye, eg. methylene blue, indigo carmine, indocyanine green and fluorescein
- Sources of error in signal processing
    - The calibration table does not go down to the lowermost saturation ranges, as this is difficult to measure in a population of volunteers
    - The calibration table is also racially biased: dark skin causes falsely low readings (Feiner et

al, 2007)

The college answer lists "*insensitivity to PaO_2*" as one of the limitations of the technique, which is somewhat strange considering how little PaO_2 contributes to total oxygen carriage. It is analogous to criticise the speedometer of a train as inaccurate for not taking into account the added velocity of a passenger walking through the carriages.

Co-oximetry

A co-oximeter is a device which, like the pulse oximeter, is able to use Lambert's law to identify the arterial haemoglobin from tissue and venous signal. Unlike the standard pulse oximeter, the co-oximeter uses multiple different light wavelengths to determine the concentration of other haemoglobin species. Typically, it is able to report the concentration of carboxyhaemoglobin and methaemoglobin, in addition to standard oxyhaemoglobin and deoxyhaemoglobin. The device is usually a handheld model, and is usually not disposable because of the increased cost (but the reusable fingertip probes are designed to survive the autoclave).

So, at this stage one might point out that most modern ABG machines are outfitted with quite a sophisticated array of sensors, and which are able to generate the same results. What role, then, is there for continuous co-oximeter monitoring? One can conceive of several such scenarios. For instance, imagine a situation where one is managing a patient who is receiving a large dose of nitric oxide, where methaemoglobinaemia is a serious concern.

Previous chapter: Arterial blood gas interpretation

Next chapter: End-tidal capnometry

References

Sinex, James E. "Pulse oximetry: principles and limitations." *The American journal of emergency medicine* 17.1 (1999): 59-66.

Jubran, Amal. "Pulse oximetry." *Critical care* 3.2 (1999): R11.

Jubran, Amal. "Pulse oximetry." *Applied Physiology in Intensive Care Medicine 1*. Springer, Berlin, Heidelberg, 2012. 51-54.

Jubran, Amal. "Pulse oximetry." *Critical Care* 19.1 (2015): 272.

Kamat, Vijaylakshmi. "Pulse oximetry." *Indian J Anaesth* 46.4 (2002): 261-8.

Kyriacou, Panayiotis, Karthik Budidha, and Tomas Y. Abay. "Optical techniques for blood and tissue oxygenation." *Encyclopedia of Biomedical Engineering, ed R. Narayan (Oxford: Elsevier)* (2019): 461-472.

Severinghaus, John W., and Shin O. Koh. "Effect of anemia on pulse oximeter accuracy at low saturation." *Journal of clinical monitoring* 6.2 (1990): 85-88.

Fluck, Robert R., et al. "Does ambient light affect the accuracy of pulse oximetry?." *Respiratory care* 48.7 (2003): 677-680.

Amar, David, et al. "Fluorescent light interferes with pulse oximetry." *Journal of clinical monitoring* 5.2 (1989): 135-136.

Block, Frank E. "Interference in a pulse oximeter from a fiberoptic light source." *Journal of clinical monitoring* 3.3 (1987): 210-211.

American Association for Respiratory Care. AARC Clinical Practice Guideline: Pulse oximetry. Respir Care 1991;36(12):1406–1409

Ralston, A. C., R. K. Webb, and W. B. Runciman. "Potential errors in pulse oximetry: I. Pulse oximeter evaluation." *Anaesthesia* 46.3 (1991): 202-206.

Webb, R. K., A. C. Ralston, and W. B. Runciman. "Potential errors in pulse oximetry: II. Effects of changes in saturation and signal quality." *Anaesthesia* 46.3 (1991): 207-212.

Singh, Anupam Kumar, et al. "Comparative evaluation of accuracy of pulse oximeters and factors affecting their performance in a tertiary intensive care unit." *Journal of clinical and diagnostic research: JCDR* 11.6 (2017): OC05.

Severinghaus, J. W. "Pulse oximetry uses and limitations." *ASA Convention*. 1989.

Ralston, A. C., R. K. Webb, and W. B. Runciman. "Potential errors in pulse oximetry III: effects of interference, dyes, dyshaemoglobins and other pigments." *Anaesthesia* 46.4 (1991): 291-295.

Severinghaus, John W. "Takuo Aoyagi: discovery of pulse oximetry." *Anesthesia & Analgesia* 105.6 (2007): S1-S4.

Tremper, Kevin K. "Pulse oximetry." *Chest* 95.4 (1989): 713-715.

Feiner, John R., John W. Severinghaus, and Philip E. Bickler. "Dark skin decreases the accuracy of pulse oximeters at low oxygen saturation: the effects of oximeter probe type and gender." *Anesthesia & Analgesia* 105.6 (2007): S18-S23.

Pologe, Jonas A. "Pulse oximetry: technical aspects of machine design." *International anesthesiology clinics* 25.3 (1987): 137-153.

Webster, John G. *Design of pulse oximeters*. CRC Press, 1997.