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Pitfalls and common errors of anaesthetic monitoring devices. Part 1: Pulse oximetry

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ABSTRACT: Pulse oximetry is the most commonly used piece of monitoring equipment in general practice. It gives non-invasive objective information on oxygenation and pulse rate and subjective information on pulse quality. Like all electronic anaesthetic monitoring devices pulses oximeters can be used to improve the safety of anaesthesia; however, over-reliance on their use has a number of pitfalls. Foremost is the potential for erroneous measurement. Poor pulse quality, light interference, movement, pigmented tissue can all effect the accuracy and reliability of pulse oximetry. Understanding how the pulse oximeter works and how to assess signal quality is vital if pulse oximeters are to be used in an appropriate fashion. This allows the anaesthetist to ensure that the readings being given and recorded are realistic, which in turn helps decision making and ensures timely intervention.

Electronic monitoring devices are becoming increasingly sophisticated and more and more commonly utilised in veterinary anaesthesia. They play a crucial role in safe anaesthesia, but are unable to improve safety in isolation; all the information produced by such devices needs to be collated and interpreted by the person monitoring the patient before decisions can be made and actions taken. As such, monitoring devices should be considered as an extension of the anaesthetist's senses and not a replacement of them (Merry, Cooper, Soyannwo, Wilson, & Eichhorn, 2010). It is also vital to recognise that careful continuous clinical observation is required in all patients, as parameters such as depth of anaesthesia cannot easily be assessed through monitoring devices and that skilled professionals can rapidly identify, confirm or disprove a crisis is occurring.

Electronic monitors are prone to failure, so in order to get the most out of your monitoring devices you need to understand how the monitor gets the numbers it displays. This is important so that you can understand and learn to recognise common errors made by the monitor and how to troubleshoot them. It is far too easy to ignore a piece of monitoring that alarms continually despite there being no problem; there is a real tendency to either silence the alarm or turn it off altogether. This, however, can be a dangerous and potentially life-threatening error, as at some point you may ignore the alarm when it is actually giving accurate readings and telling the truth about the patient's condition. The opposite is also true, it is possible to believe a piece of monitoring when it is not presenting data reflecting the current condition of the patient, thus lulling the anaesthetist into a false sense of security or prompting them to make an unnecessary intervention. Alarms can also be distracting and may take attention away from the patient, which may also be detrimental.

Pulse oximetry

Probably the most utilised piece of electronic monitoring in both human and veterinary anaesthesia, the humble pulse

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oximeter is also the most prone to error. It is the one piece of monitoring that has evidence for its use in veterinary anaesthesia in that it reduces fatality rates when used in cats (albeit to no greater a degree than continuous pulse monitoring) (Brodbelt, Pfeiffer, Young, & Wood, 2007). Desaturation is a significant, rapidly progressive crisis that can be life-threatening. A recent study found that believable and clinically significant desaturation (desaturation that triggered the anaesthetic to perform an intervention to counter it) occurred in 1 in 37 anaesthetised small animal patients (McMillan & Darcy, 2016).

Mechanism of measurement

Pulse oximetry provides a non-invasive estimate of the saturation of arterial haemoglobin with oxygen. The pulse oximeter relies on the principle that oxy- and deoxy-haemoglobin absorb different wavelengths of light to differing degrees (basically that oxygenated blood is "more red" than de-oxygenated blood). In addition, it gives information on pulse rate, rhythm and quality.

Pulse oximeters alternate between transmitting two waveforms of light, at red and infrared wavelengths, through (transmittance) or onto (reflectance) a pulsatile tissue bed (Magee, 2012). A photodetector is then used to assess the absorption of the red and infrared light that passes through or reflects off the tissue. The amount of light of each wavelength absorbed depends on a number of factors; with most being absorbed by non-pulsatile tissues such as skin, muscle, connective tissue, bone and venous blood, but a smaller pulsatile component by arterial blood (see **Figure 1**). As the non-pulsatile component is constant it is subtracted and ignored, and the pulse oximeter then mathematically derives the ratio of absorption of red and infrared light in the pulsatile component in order to estimate SpO_2.

As such, pulse oximetry relies on constant and minimal absorption from other tissues and good pulsatile flow through the tissue.

Limitations

It is important to recognise that pulse oximetry gives an idea of how well haemoglobin is saturated with oxygen and not how much oxygen is being carried in blood. In general, pulse oximeters are considered to be accurate to 2%–3% within the range of 70%–100%. Pulse oximeters do not give beat-to-beat changes in SpO_2 and generally average their readings every 5–20 s. This means that there is a small lag which may be significant in the rapidly desaturating patient and where there are significant fluctuations in SpO_2.

Even without the relatively slow response time, SpO_2 can be considered as a late indicator of hypoxaemia, particularly when a patient is being supplemented with oxygen, as patients with healthy lungs receiving supplemental oxygen should have a PaO_2 of about 500 mmHg (SpO_2 100%) and PaO_2 will have dropped to about 100 mmHg at a SpO_2 95% and 60 mmHg at SpO_2 of 90%. This means lung function will have deteriorated significantly before a believable change in SpO_2 is observed. Therefore, SpO_2 is most useful at times where the patient is being transitioned between room air and oxygen and vice versa (e.g. induction and recovery), where patients are not receiving supplemental oxygen, or where the patient has poor lung function (**Figures 2a** and **2b**). The continuous pulse monitoring function of the pulse oximeter may actually be the more useful function of pulse oximetry in many or even most patients.

Pulse oximetry also gives little information on how well a patient is ventilating, especially if the patient is receiving 100% oxygen. This is because hypoxaemia associated with hypoventilation is easily countered and masked by supplementing oxygen.

Alongside these inherent limitations there are also a number of additional factors that can influence their accuracy and reliability.

Poor perfusion

Where an animal has poor perfusion in the area being monitored by the pulse oximeter (whether due to low blood pressure, poor contractility or vasoconstriction) it is likely that the pulse oximeter will not function properly. For example, where alpha-2 agonists such as (dex)medetomidine are used as anaesthetic premedication, the pulse quality is often reduced. The smaller the vessels being monitored and the more non-pulsatile tissue between the sensor and transmitter, the worse the effect of low perfusion will be. Therefore, this is a particular problem for small patients.

The signal quality of pulse oximetry can also reduce over time due to compression of the vessels in the tissue being monitored by the probe. This is one of the most common causes of a pulse oximeter error, particularly when used on an animal's tongue, and especially in cats. It can be managed by regularly moving the probe and potentially by placing a moist swab between the probe and tongue.

Reduced haemoglobin levels

As pulse oximetry estimates the proportion of oxy-haemoglobin and not the absolute amount, low haemoglobin levels should have little effect on SpO_2 readings. However, the amount of absorption in the pulsatile component is reduced when there are low levels of haemoglobin in arterial blood, and therefore anaemia may affect the accuracy of pulse oximetry (Lee, Tremper, & Barker, 1991). In severely anaemic and hypoxaemic patients, SpO_2 generally under-reads due to increased scatter of the transmitted light; however, this erroneous reading can be considered as advantageous as it gives an earlier

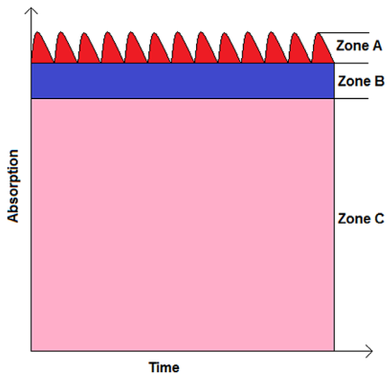

Figure 1. A graphical representation of the absorbance of red and infrared light when it is transmitted through a vascular tissue bed. Zone A is the pulsatile component comprising absorption via arterial blood and SpO_2 is calculated from this part of the signal. Zones B and C combined make up the non-pulsatile component and absorb the vast bulk of the transmitted light. Zone B is venous blood whilst Zone C is bone, muscle, connective tissue and skin. Absorption from Zones B and C is subtracted and ignored from the total signal leaving only the absorption from Zone A to be used in SpO_2 calculation. Anything that decreases Zone A (e.g. poor perfusion) or increases Zones B and C (e.g. pigmented skin or a thick tissue bed) decreases the signal to noise ratio and makes the pulse oximeter less accurate

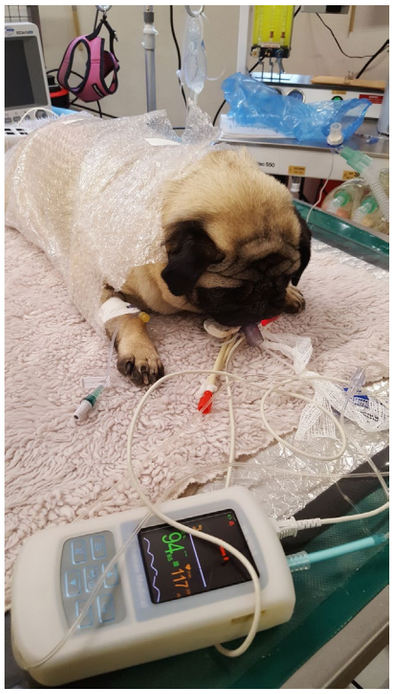

Figure 2a. A pulse oximeter being used to monitor an intubated brachycephalic dog during the recovery period. The biggest risk of desaturation is during induction, when animals are often apnoeic after breathing room air, and recovery, where animals are still under the effects of anaesthetic agents but are moved from 100% O_2 to breathing 21% O_2 (room air). Monitoring SpO_2 comes into its own during these periods; however, often this is the time before the pulse oximeter is placed on the patient or after it has been removed

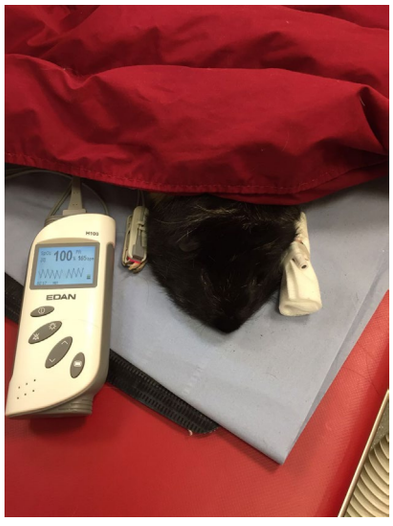

Figure 2b. A pulse oximeter being used to monitor a guinea pig in recovery. Modern pulse oximeters are able to effectively detect even small pulsations, but despite this they are still prone to error

indication of deterioration. The effect in normoxaemic patients is minimal.

Altered haemoglobins

As pulse oximetry relies on the ratio between deoxy- and oxy-haemoglobin, the presence of altered haemoglobin states such as methaemoglobin and carboxyhaemoglobin significantly alters the accuracy of SpO_2 readings (Chan, Chan, & Chan, 2013). The presence of methaemoglobin, as seen in paracetamol toxicity in cats, will give SpO_2 readings of around 85%, regardless of the true saturation. The presence of carboxyhaemoglobin, seen as a sequelae of smoke inhalation, tends to give falsely elevated readings as carboxyhaemoglobin has similar absorption of red light as oxy-haemoglobin. SpO_2 is generally elevated by the percentage proportion of carboxyhaemoglobin present.

Altered absorption

Pulse oximeters may struggle to penetrate through hairy or pigmented skin (or tongues in the case of the Chow and the Sharpei) or thick tissue beds as this increases non-pulsatile absorption (**Figure 3**). Hair may also decrease the contact between the probe and skin, reducing penetration further.

Although the literature has differing opinions, pulse oximetry is likely to be accurate even in severely jaundiced patients, as bilirubin has minimal absorption of red and infrared light (Chan et al., 2013). However, if the jaundice is caused by immune-mediated haemolytic anaemia, signal quality and therefore accuracy may be reduced.

Increased levels of lipid in the blood may also effect pulse oximeter accuracy; however, the degree of effect is not entirely clear at this time (**Figure 4**) (Langton, 2014).

Injection of dyes such as new methylene blue, which can be used to guide surgeries such as thoracic duct ligation and insulinoma removal, can affect SpO_2 measurement as it greatly absorbs infrared light. SpO_2 will be falsely lowered in patients that receive methylene blue as part of their procedure.

Vibration and patient movement

Although this is more of a problem in conscious patients, any sort of movement can interfere with pulse oximeter function. During dentals, for example, if the probe is on the tongue, the vibrations of the scaler and the constant movement can mean that it becomes an ineffective piece of monitoring unless an alternative site can be found. Toes, the prepuce, the vulva, inguinal or axillary folds or the area of the Achilles tendon can all be used as alternatives to the tongue for transmittance probes. Alternatively, reflectance probes can be used. Wet gauze swabs can be utilised to help secure probe placement

Figure 3. A partially pigmented tongue of a cross-breed dog. Modern pulse oximeters cope well with pigment, but pulse oximeter probes placed on toes and lips may struggle to get a reading if the skin is pigmented and hairy

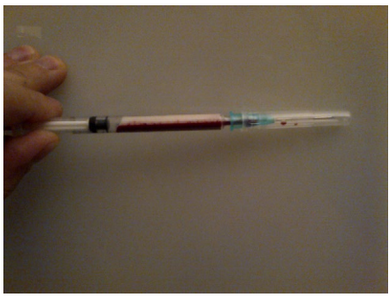

Figure 4. Severe lipidaemia has been reported to cause inaccuracy in pulse oximetry in a dog (Langton, 2014). Hyperlipidaemia can be seen in animals with metabolic disease, pancreatitis, severe obesity and following prolonged infusions of lipid emulsions such as Intralipid (for toxicities or as part of a total parenteral nutrition regime) or propofol (for prolonged sedation, anaesthesia or seizure control)

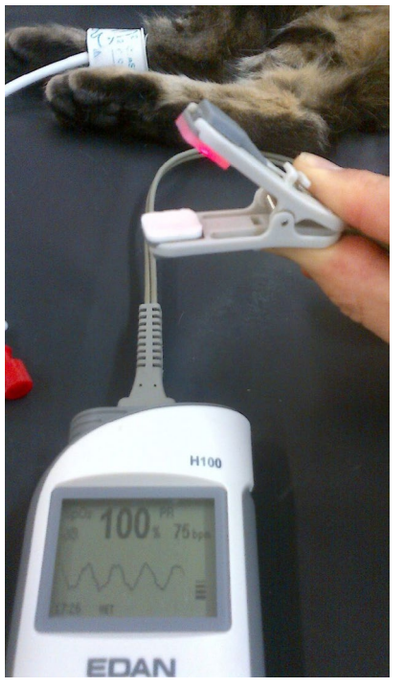

Figure 5. A convincing pulse waveform and SpO_2 reading given by ambient lighting. The pulsatile nature of fluorescent lighting can cause erroneous readings. Many modern probes are able to subtract this effect, but budget models may be effected. Covering the probe to block out ambient lighting can help eliminate this error

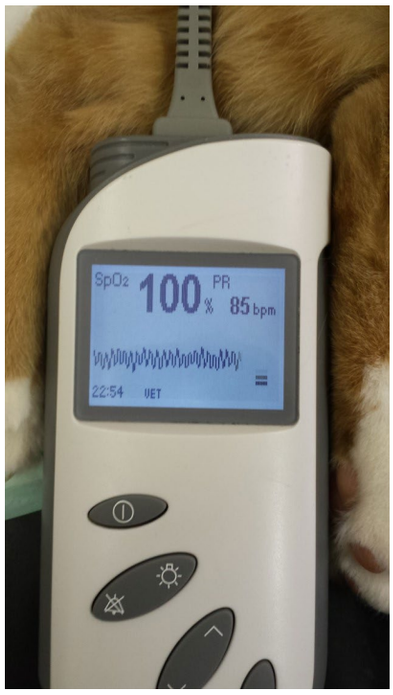

Figure 6a. A SpO_2 reading from a poorly placed pulse oximeter probe. Note the poor plethysmographic pulse waveform. This type of waveform should signal to the anaesthetist that the SpO_2 reading is unlikely to be accurate and that the probe placement should be checked

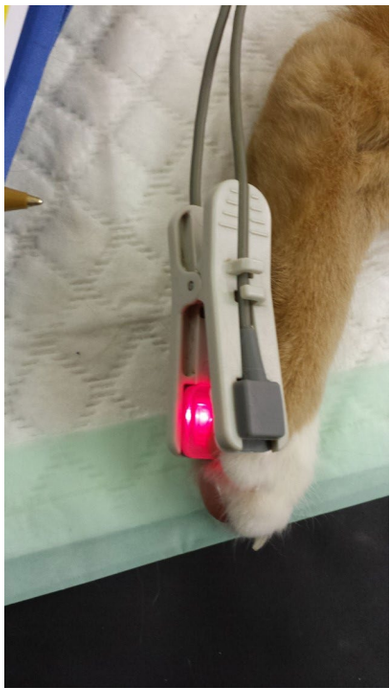

Figure 6b. The poorly placed pulse oximeter probe that gave the SpO_2 reading shown in Figure 6a. Note that the light from the illuminated LED can clearly be seen bypassing the tissue. This gives rise to the penumbra effect, which leads to erroneous SpO_2 readings

and encourage contact between the transmitting and receiving parts or the probe and the skin.

Ambient light, probe placement and electrical interference

Although the quality of pulse oximetry in general has improved immeasurably over the last 20 years, some pulse oximeters (often less expensive models) can still be significantly affected by ambient light, especially fluorescent strip lighting (**Figure 5**). This type of lighting is pulsatile in nature and can "confuse" the pulse oximeter.

If the probe is not placed completely over a tissue bed and some of the transmitted light can escape past the tissue and go straight to the receptor, this can lead to a falsely elevated pulse oximeter reading that tends to read 100% (**Figures 6a** and **6b**). Ensuring the probe is properly placed over tissue so the entire LED is transmitting through the tissue can reduce the likelihood of this error (which is termed the penumbra eff ect).

Low SpO_2

Pulse oximeters lose accuracy below 70% as they have not been calibrated below this point. This is unlikely to affect their usefulness as any reading around this low level is so hypoxaemic that it should stimulate any competent anaesthetist to intervene whatever the absolute value.

Figure 7. Double-counting of the pulse rate caused by a large "rebound pulse" secondary to elastic recoil of the major vessels (note the disparity between the false pulse rate in yellow from the pulse oximeter and the correct heart rate from the ECG). A high rebound pulse is common following medetomidine administration and can be misread by the monitor. The plethysmographic pulse trace should be checked and cross-referenced with other monitoring (e.g. manual pulse count or ECG) before the numbers are believed and recorded

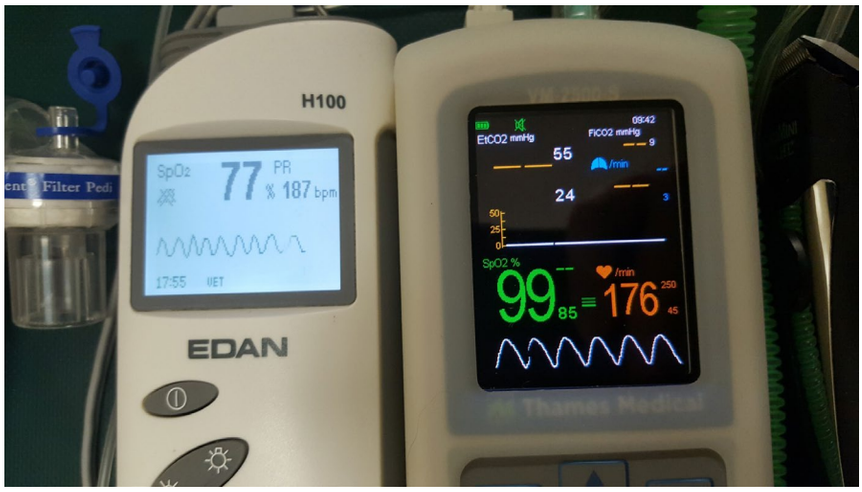

Figure 8. These pulse oximeters were placed on different parts of the same healthy animal just after induction. The pulse oximeter on the right (on the tongue) is showing a believable plethysmographic pulse waveform (note the waveform is regular and of good amplitude and shape). The SpO_2 reading from this monitor is more likely to be believable than the one from the pulse oximeter on the left, whose pulse waveform is more variable and inconsistent (note each wave varies from the next and the amplitude is much lower). Some modern pulse oximeters give a pulse index (P_I) to indicate pulse strength and therefore signal quality. P_I values greater than one are desirable for accurate SpO_2 readings

Other pulse oximeter errors

Another commonly encountered error produced by pulse oximeters is misreading of pulse rates. Elastic recoil of major vessels often gives an easily identifiable second and potentially even third smaller "after pulse" (**Figure 7**). The pulse oximeter may be unable to differentiate between these after pulses and a true pulse, which can lead to it misreading the pulse rate. Pulse rates double or triple of those in the patient are possible when this occurs. In my clinical experience this happens more commonly at lower heart rates especially when the patients are vasoconstricted (e.g. when an alpha-2 agonist has been used). Comparing the pulse rate obtained from the pulse oximeter to pulse and heart rates obtained by other methods (palpation, auscultation, electrocardiogram, Doppler) is a quick and effective way of ensuring that the pulse rate recorded is realistic.

So how can we assess the accuracy of a SpO_2 reading?

The large potential for error involved with the use of pulse oximetry does not mean that they are meaningless monitors. However, it does mean that we need to analyse the data being produced in a critical fashion taking into account what we know about pulse oximeter function before we believe the numbers it produces.

An assessment of signal quality should always be made when assessing SpO_2 whether the reading is normal or abnormal. This is best done by assessing a plethysmographic waveform and therefore pulse oximeters that display a pulse trace have a considerable advantage. If there are clear visible pulse waveforms on the plethysmograph the SpO_2 reported is far more likely to be accurate (**Figure 8**). Where there is little or no pulsations or a lot of interference the SpO_2 cannot be believed whatever the value (it is always tempting to believe it when it reads above 95%, but this is lulling you into a false sense of security!). Bleep bars and comparison of the pulse rate obtained to another form of monitoring as described previously can also be used to assess signal quality but is less reliable. It should be noted I have come across monitors that always display a pre-programmed perfect waveform when the pulse oximeter is on and that these monitors should be trusted to the same degree as those displaying a variable "live" waveform.

What to do when an abnormal reading is obtained?

Readings of below 95% should always initiate an investigation that should involve a thorough assessment of the patient, the anaesthetic machine (including the oxygen supply), breathing system and airway patency. The positioning of the probe should also be checked and moved because believable waveforms can be generated when the probe is not even on the patient (**Figure 5**)! Interventions (such as checking airway patency, administering a positive pressure breath, increasing the inspired oxygen concentration, etc.) can then be performed based on a holistic patient assessment.

Conclusion

Monitoring with electronic devices is fraught with problems. Knowledge of the mechanisms of measurement and the likely errors and pitfalls can assist the anaesthetist's decision-making during an anaesthetic and help ensure the patient is kept safe.

References

Brodbelt, D. C., Pfeiffer, D. U., Young, L. E., & Wood, J. L. (2007). Risk factors for anaesthetic-related death in cats: Results from the confidential enquiry into perioperative small animal fatalities (CEPSAF). *British Journal of Anaesthesia, 99,* 617–623.

Chan, E. D., Chan, M. M., & Chan, M. M. (2013). Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations. *Respiratory Medicine, 107,* 789–799.

Langton, S. D. (2014) Prolonged high dose propofol infusion associated with marked hyperlipidaemia as a source of inaccuracy in pulse oximetry. *British Journal of Anaesthesia e-Letters.* Retrieved from http://bja.oxfordjournals.org/forum/topic/brjana_el%3b12120

Lee, S., Tremper, K. K., & Barker, S. J. (1991). Effects of anemia on pulse oximetry and continuous mixed venous hemoglobin saturation monitoring in dogs *Anesthesiology, 75,* 118–122

McMillan, M., & Darcy, H. (2016). Adverse event surveillance in small animal anaesthesia: An intervention-based, voluntary reporting audit. *Veterinary Anaesthesia and Analgesia, 43,* 128–135.

Magee, P.T. (2012). Physiological monitoring: Principles and non-invasive monitoring. In A. J. Davey & A. Diba (Eds.), *Ward's anaesthetic equipment* (6th ed.). Saunders Elsevier.

Merry, A. F., Cooper, J. B., Soyannwo, O., Wilson, I. H., & Eichhorn, J. H. (2010). International standards for a safe practice of anesthesia 2010. *Canadian Journal of Anesthesia/ Journal canadien d'anesthésie, 57,* 1027–1034.

Multiple Choice Questions

1. Pulse Oximetry measures which of the following

(a) Oxygen saturation of haemoglobin

(b) Partial pressure of oxygen dissolved in the blood

(c) End tidal carbon dioxide

(d) Oxygen perfusion

2. In the McMillan & Darcy, 2016 study how many patients showed significant oxygen desaturation?

(a) 1 in 10

(b) 1 in 37

(c) 1 in 54

(d) 1 in 106

3. Which of the following drugs commonly used in anaesthetic premedication may interfere with perfusion and therefore pulse oximeter readings?

(a) Methadone

(b) Acepromazine

(c) Dexmedetomidine

(d) Buprenorphine

4. Methaemoglobin may be caused by which type of poisoning?

(a) Ethylene Glycol

(b) Smoke inhalation

(c) Theobromine

(d) Paracetamol

5. The two common types of pulse oximetry are:

(a) Reflectance and transmittance

(b) Transmittance and absorbance

(c) Reflectance and absorbance

(d) Reflectance and illuminance

6. What is the 'penumbra effect'?

(a) Where the pulse oximeter double counts

(b) Where the light from the illuminated LED clearly bypasses the tissue

(c) Interference from fluorescent strip lighting

(d) Elastic recoil from the vessel causing the pulse oximeter to misread

7. Which of the following does NOT typically cause altered absorption when utilising pulse oximetry?

(a) Hyperlipidaemia

(b) Injection of dyes intravascularly such as new methylene blue

(c) Bilirubin in the jaundiced patient

(d) Pigmentation of skin

8. When is measuring SpO_2 most useful?

(a) Induction and recovery of anaesthesia

(b) Monitoring the patient on 100% oxygen

(c) Monitoring during the maintenance period of anaesthesia

(d) Monitoring the conscious patient

9. If SpO_2 is 95% what is the approximate expected PaO_2?

(a) 500mmHg

(b) 100mmHg

(c) 50mmHg

(d) 1000mmHg

10. If an abnormal reading is detected on pulse oximetry, which of the following is the least appropriate action?

(a) Repeatedly move the probe

(b) Assess the pulse rate reading on the monitor with a manual pulse reading

(c) Assess the plethysmographic waveform for clear, visible pulse waveforms

(d) Thoroughly assess the patient

For the answers to the MCQs, please go to: http://www.bvna.org.uk/publications/veterinary-nursing-journal