21

Pulse oximetry and CO-oximetry

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The vast majority of oxygen in the bloodstream is carried on hemoglobin. Hemoglobin molecules of different morphology (i.e., deoxyhemoglobin, oxyhemoglobin) have different light absorption characteristics. Oximetry is the use of light to quantify the percentage of blood hemoglobin that is present as oxyhemoglobin (is bound to oxygen), and its laboratory use dates back to the 1930s. Oximetry can be used to measure the adequacy of hemoglobin oxygenation in a patient's blood. The earliest patient bedside oximeters were developed in the 1960s but did not receive common use because they often overheated skin and were uncomfortable. The pulse oximetric method used today was invented by Takuo Aoyagi in 1972 and was integrated into commercial monitors for use in humans in the early 1980s.[1]

Until pulse oximeters were introduced in the 1980s, there was no way to continuously monitor a patient's arterial hemoglobin oxygen saturation. The pulse oximeter uses a ratio of near-infrared and red wavelengths of light to determine the percentage of hemoglobin present as oxyhemoglobin, and it allows for continuous evaluation of a patient's blood oxygenation. Because of its continuous nature and the ease of use, pulse oximetry greatly reduced the incidence of lethal hypoxemia during anesthetic events and became a standard piece of monitoring equipment in human medicine during the 1980s. Until pulse oximetry was available, the only way to measure a patient's arterial oxygenation was to analyze blood *ex vivo*, which required time, expertise, expensive equipment, and did not allow for continuous monitoring.

A CO-oximeter is a benchtop analyzer that uses multiple wavelengths of light to recognize and quantify multiple hemoglobin species, including oxyhemoglobin, deoxyhemoglobin, carboxyhemoglobin (bound to carbon monoxide), and methemoglobin (denatured). CO-oximeter manufacturers use a number of proprietary algorithms to correct and calculate hemoglobin values.

Pulse oximetry and to some extent CO-oximetry have become firmly entrenched in the monitoring of anesthetized, acutely ill, and critically ill patients. This chapter focuses on the principles of oximetry and how to best use the technology to improve patient care.

Hemoglobin forms

Erythrocytes (red blood cells) are the primary oxygen transport system in the mammalian body. They contain hemoglobin, a protein (globin) with rings of ferrous iron (heme) that can bind, or become "saturated" with, oxygen. When oxygen is bound to the heme group, the hemoglobin is called **oxyhemoglobin** and transports oxygen through the arterial bloodstream to tissues. Oxyhemoglobin is bright red, which gives arterial blood its distinctive color. **Deoxyhemoglobin** (also known as reduced hemoglobin) is hemoglobin without oxygen bound to it, with intact heme groups available for oxygen binding. Deoxyhemoglobin is darker in color than oxyhemoglobin, which imparts venous blood with its darker color. Oxyhemoglobin and deoxyhemoglobin constitute 97%–98% of a normal mammal's total hemoglobin content, and they are together known as **functional hemoglobin** (see later).[2]

Hemoglobins that are incapable of binding oxygen, known as **dyshemoglobins,** include methemoglobin,

carboxyhemoglobin, and sulfhemoglobin. **Methemoglobin** occurs naturally and develops when the iron of the heme group is oxidized from the ferrous form to the ferric form. There are multiple enzymes that can convert methemoglobin back to deoxyhemoglobin, but when these pathways are no longer functional, the hemoglobin remains in the methemoglobin state. **Carboxyhemoglobin** is created when hemoglobin binds to carbon monoxide rather than to oxygen. Unfortunately, hemoglobin's affinity for carbon monoxide is >200 times its affinity for oxygen, which means that hemoglobin binding to carbon monoxide is very difficult to reverse. Carbon monoxide binding to hemoglobin prevents oxygen binding and carriage, which is why carbon monoxide toxicity can be fatal. **Sulfhemoglobin** is a very rare form of dyshemoglobin that is formed when hemoglobin reacts with sulfide in the presence of oxygen. This process occurs during the degeneration pathway of hemoglobin and in the formation of Heinz bodies.[3] A method of hemoglobin saturation measurement that takes into account the abnormal hemoglobin fractions such as carboxyhemoglobin and methemoglobin is said to report **fractional hemoglobin** saturation, discussed in more detail later.

Functional and fractional hemoglobin saturations

Hemoglobin is considered functional if it can bind, carry, and unbind oxygen. Oxyhemoglobin and deoxyhemoglobin are therefore together known as the functional hemoglobin species. The percentage of total functional hemoglobin that is oxygenated is called **functional hemoglobin saturation** (functional SO_2) and is calculated using this equation:

$$\text{Functional } SO_2 = [(HbO_2)/(HbO_2 + HHb)] \times 100 \tag{21.1}$$

where HbO_2 is oxyhemoglobin and HHb is deoxyhemoglobin. Standard pulse oximeters measure and report functional hemoglobin saturation; they do not take into account the abnormal hemoglobin species.[4]

Fractional hemoglobin saturation (fractional SO_2) refers to the ratio of oxyhemoglobin to all hemoglobin species present, including methemoglobin and carboxyhemoglobin. Fractional SO_2 is calculated as a percentage using this equation:

$$\text{Fractional } SO_2 = [(HbO_2)/(HbO_2 + HHb + COHb + MetHb)] \times 100 \tag{21.2}$$

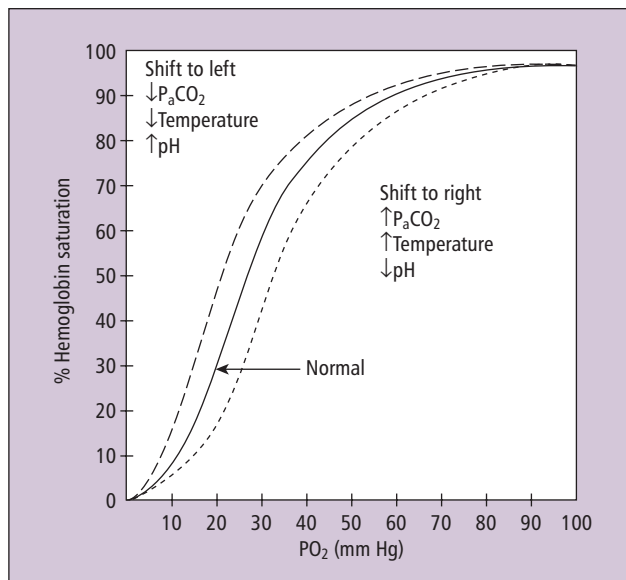where COHb is carboxyhemoglobin and MetHb is methemoglobin.

Figure 21.1 Oxyhemoglobin equilibrium curve. Note the sigmoidal relationship between partial pressure of oxygen and hemoglobin saturation with oxygen. Within the normal range of PaO_2 (on room air at sea level), hemoglobin saturation remains above 90% but drops precipitously below a PO_2 of 60 mm Hg. If the PO_2 were taken to infinity, the curve would be completely flat at a hemoglobin saturation (SO_2) of 100%. PCO_2, partial pressure of carbon dioxide in the blood; PO_2, partial pressure of oxygen in the blood.

Modern CO-oximeters and pulse CO-oximeters can measure the presence of all these hemoglobin species, so they can report fractional SO_2, although many can also be programmed to report functional SO_2 if the operator prefers. When a CO-oximeter is also capable of measuring sulfhemoglobin, that species is also included in the calculation used by that machine to report fractional SO_2.

Both functional and fractional SO_2 can provide valuable information about a patient's status. One must consider the information provided by both methods prior to selecting whether either or both values will be obtained. Functional hemoglobin saturation gives a good idea of lung function as reflected by the partial pressure of oxygen in arterial blood (PaO_2; see Fig. 21.1) in patients breathing room air. The relationship between functional SO_2 and PO_2 is relatively reliable, such that if one knows the SO_2, the PO_2 can be back-calculated. PaO_2 as estimated by pulse oximetry is one of the most common methods for quickly assessing lung function in patients with respiratory signs.

However, if abnormal amounts of dyshemoglobin are present, only fractional hemoglobin saturation accurately reflects the blood oxygen content and thus the dyshemoglobinemia's impact on the patient. Because

functional hemoglobin saturation considers only the percentage of normal hemoglobin species that is oxygen bound, it ignores conditions such as methemoglobinemia or carboxyhemoglobinemia but would still be superior at reflecting the patient's lung function. Take the following example:

A canine patient breathing room air at sea level has increased respiratory rate and effort, and has a total of 16 g of hemoglobin per deciliter of arterial blood. Of that hemoglobin, 13 g are oxyhemoglobin, 0.5 g are deoxyhemoglobin, 2.4 g are methemoglobin, and 0.1 g is carboxyhemoglobin.

$$\text{Functional SaO}_2 = [(13\,\text{g/dL})/(13\,\text{g/dL} + 0.5\,\text{g/dL})] \times 100$$
$$= 96\%$$

$$\text{Fractional SaO}_2 = [(13\,\text{g/dL})/(13\,\text{g/dL} + 0.5\,\text{g/dL}$$
$$+ 2.4\,\text{g/dL} + 0.1\,\text{g/dL})] \times 100 = 81\%$$

The functional arterial blood hemoglobin saturation of 96% indicates that the patient has a PaO_2 within the expected range and therefore makes lung dysfunction unlikely as the source of the dog's respiratory distress. The fractional SaO_2 reveals that only 81% of the dog's total arterial hemoglobin is saturated with oxygen, which suggests that the 2.4 g/dL of methemoglobin may be the source of its distress. Although the lungs are able to oxygenate the blood, the dysfunctional methemoglobin molecules make fewer of the dog's total hemoglobin molecules available for oxygen carriage to tissues; this can result in tissue hypoxia and respiratory signs.

Types of oximeters: What they measure and report

Oximetry is the use of light to quantify the percentage of blood hemoglobin that is present as oxyhemoglobin. **Pulse oximetry,** which yields an "SpO_2" measurement, specifically refers to the noninvasive measurement of functional hemoglobin in arterial blood using a bedside monitoring device that can detect an arterial pulse. Thus *standard pulse oximeters report functional hemoglobin saturation*. **CO-oximetry**, which (when performed on arterial blood) yields an "SaO_2" measurement, generally measures the presence of functional hemoglobins (oxy- and deoxy-) in addition to the presence of dyshemoglobins (usually carboxy- and met-). Therefore, CO-oximetry can report the fractional hemoglobin saturation, or the percentage of all hemoglobin in the body (not just the functional molecules) that is present as oxyhemoglobin. In an animal with a dyshemoglobinemia such as carbon monoxide toxicity, the fractional hemoglobin saturation will be lower than the functional

hemoglobin saturation (see previous example using methemoglobinemia). **Pulse CO-oximeters,** which combine the technology of a CO-oximeter and the bedside continuous nature of the pulse oximeter, are being used in humans as a noninvasive test for carbon monoxide toxicity and methemoglobin-inducing drug overdoses. Pulse CO-oximeters are not yet in routine use in veterinary medicine.

Pulse oximetry

The science behind a pulse oximeter

Understanding how a pulse oximeter functions can be of great value to the operator. Comprehending how the monitor works will allow the operator to recognize the limitations of the device and troubleshoot problems with readings.

A pulse oximeter estimates oxyhemoglobin percentage by using two wavelengths of light: red at 660 nm and infrared at 940 nm.[5] The machine emits these wavelengths of light from its probe's light-emitting diode (LED) into the patient's tissue bed. This emitted light reaches a receiver in the probe either by reflecting off the tissue or by through transmission to the receiving end of a probe, depending on the probe's style. A photo detector measures the received signal and sends the information to a signal-processing unit.

As this light is introduced into the tissue, each type of hemoglobin absorbs a different wavelength of light. The oximeter uses the differential light absorption characteristics of deoxyhemoglobin and oxyhemoglobin to calculate the arterial blood's functional hemoglobin saturation. The correlation of light absorption patterns and SpO_2 are based on human studies and experimentation, but it has been demonstrated that these calculations are accurate in veterinary patients.[6]

Surrounding tissues such as bone, fat, and venous blood also absorb light, so to target arterial hemoglobin in its measurements, the pulse oximeter considers only pulsatile (arterial) wavelength absorption in the calculations. Thus pulse oximeters function best when placed over tissue with good arterial (pulsatile) blood flow. Pulse oximetry measurements should only be trusted if the monitor displays the patient's correct pulse rate because light from other sources can reach and affect the probe's receiver.

Dysfunctional hemoglobin species also absorb some light at these wavelengths, and thus they can falsely elevate or depress readings if they are present in large amounts. For example, methemoglobin absorbs light at 660 nm *and* 940 nm, which shifts the reported "oxyhemoglobin" value toward 80%–85%, whereas carboxyhemoglobin can falsely elevate the SpO_2 because it absorbs

940 nm light like oxyhemoglobin.[5] Put simply, the presence of methemoglobin usually causes falsely depressed SpO_2 values, and carboxyhemoglobin usually causes falsely elevated SpO_2 values.

Equipment available

Many pulse oximeters are commercially available, both from human and veterinary medical supply companies. Models are available from Nellcor, Masimo, Cardell, Apexx, Respironics, and numerous other companies. Reviewing different brands and models is beyond the scope of this chapter; however, certain general guidelines should be followed. When selecting a pulse oximeter, many factors must be taken into account. Ease of use, probes available, battery life, and cost are just a few of the factors that must be considered before purchase. The newest models may or may not provide more accurate information. A study done at the University of Pennsylvania demonstrated that one older instrument provided more accurate SpO_2 values.[7] Therefore, it is recommended that any model of pulse oximeter be used within a facility prior to its purchase (most manufacturers and distributors allow for trial periods). Pulse oximeters that are independent units, as opposed to those that are part of multiparameter monitors, may be of greater use. These monitors are typically smaller with a longer battery life, allowing for more convenient cage-side monitoring.

Waveform display option

Many pulse oximeters are available with a waveform screen display option that reports the quality of the pulse being measured by the oximeter. The waveform screen displays a graphic interpretation of the peripheral pulse wave, which is called a photoplethysmograph (PPG). The PPG is generated using the pulse oximeter's 660 nm light wave to create an "image" of the pulse,[8] and the PPG's amplitude directly corresponds to pulse quality at the site. The PPG should have sinusoidal form with a small second shoulder on the wave.[9]

Sensor options

Many pulse oximeters have more than one sensor available. Although the lingual clip is the most common, some models include a reflectance/rectal sensor or an esophageal sensor. In the author's experience, a clip-style sensor is the most versatile and easiest to place. However, the models with rectal sensors can be of great use. Although these sensors may be difficult to use when inserted per rectum (feces often obscure the LED), they may be used to acquire readings from the tail.

Other equipment options

Other parameters to consider are whether or not alarms are preset for maximum and minimum acceptable values, cost of replacement probes and batteries, cost of replacement chargers, service contracts, and warranties.

Care and storage of pulse oximeters

When not in use, pulse oximeters should be stored on their chargers. The probe wire should be carefully looped either next to or around the monitor but not wound so tightly as to cause damage to the internal wires. As with any electronic device, care should be taken to avoid exposing the monitor to water, chemicals, and direct sunlight.

Probes should be cleaned in between each use following manufacturer's instructions. Most probes can be cleaned with mild soap and water; others tolerate cleaning with isopropyl alcohol or chlorhexidine. However, some diodes will be damaged by the use of chemicals.

Indications for pulse oximetry

Due to the relative ease of performing pulse oximetry, it is used often as a first test to assess a patient's oxygenation status. Compared with arterial blood gas measurements, pulse oximetry is noninvasive because it does not require vascular puncture or the removal of blood. It can be performed cage side, during anesthetic procedures, and when obtaining an arterial blood sample may be difficult. Pulse oximetry also allows for continuous monitoring, which is invaluable under potentially changeable conditions like general anesthesia and critical illness.

Although continuous pulse oximetry is vital to the safety of anesthetized patients, one must understand the relationship between PO_2 and SO_2 (see Fig. 21.1) to properly interpret an SpO_2 value in a patient receiving supplemental oxygen. FiO_2 is the fraction of oxygen in inspired gas. When a patient is breathing 100% oxygen (FiO_2 1.0), the patient's PaO_2 should be >500 mm Hg. Considering the relationship between PO_2 and SO_2 described in Fig. 21.1, note that the PaO_2 must drop well below 500 mm Hg (in fact, below 100 mm Hg) to change the SpO_2. Therefore, a patient can have a severe lung problem with inadequate oxygenating ability and still have an unchanged SpO_2 when receiving oxygen supplementation (as in general anesthetic procedures).

Patients who have changes in their respiratory pattern (increase in rate or effort) should have their SpO_2 checked. The acquisition of an accurate normal SpO_2 value is an easy way to rule out hypoxemia as the cause of a patient's respiratory distress.

It must be stressed that pulse oximetry does not assess ventilation. Ventilation determines and is indirectly determined by the partial pressure of carbon dioxide in the blood (PCO_2). Blood or end-tidal PCO_2 should be monitored in critically ill and anesthetized patients (see Chapters 22, Blood Gas Analysis, and 26, Capnography, for more information).

Performing pulse oximetry

Obtaining an accurate reading depends on many factors. Readings that are questionable cause delays in appropriate treatment. Before attempting to obtain a reading, make sure that the probe is clean and undamaged. If the model being used has different settings, use the setting that corresponds most accurately to the patient's heart rate. For example, pulse oximeters designed for human patients often have neonatal, pediatric, and adult settings. Use the neonatal setting for patients with higher heart rates and the adult setting for patients with lower heart rates; the setting used should reflect the pulse rate, not the size or weight of the patient.

Site selection

The next step is to select an appropriate site for a reading. Mucous membranes typically provide the most accurate readings (see Fig. 21.2a). Potential sites for use are listed in Table 21.1. The most common site used in anesthetized animals is the tongue, although this is not often well tolerated by conscious patients. The pinna may be the most accessible site but often gives erroneous results.[10] Occasionally inguinal skin folds can be used. The site selected should be warm, well perfused, and clean. If the patient is markedly hypovolemic or hypothermic, the site chosen should be as close to a central vessel as possible (tongue, lips) to provide the most accurate results.[10]

Artifactually low readings may be obtained from areas with poor arterial perfusion. Clipping fur from the site and cleaning it may help reduce interference. Pigmented tissue may give falsely low readings or no reading at all. The probe site should be moistened frequently with water or lubricant to help improve accuracy and to protect the underlying tissue because the clip can restrict local blood flow and the continuous light emission can burn if left in one place too long. If a continuous reading is necessary, the site should be checked often for damage and the probe rotated to a new spot at least every few hours. If the clip compresses the tissue to such an extent that blood is driven from the capillary space, falsely low readings may occur.

Reflectance probes may also be used on the tail base. By clipping the ventral aspect of the base of the tail, a large artery can be accessed for monitoring. Placing the probe against the skin and securing it in place with tape or flexible bandaging material can provide accurate readings. If this method is used, the patient should have the site monitored hourly for cleanliness and tissue damage that can occur from overly tight or wet bandages, or probe burns.

Obtaining a measurement

Once the probe has been attached to the site it may take several seconds for a pulse reading to be obtained. It is imperative that the pulse rate acquired by the pulse oximeter match the patient's actual pulse rate. If the pulse oximeter reads an incorrect number, the reading should not be trusted and another reading must be taken. Increased respiratory rate or effort and panting can register as a pulse rate and give incorrect values. See Protocol 21.1 for specific steps to acquire an SpO_2 reading.

Once it has been determined that the pulse rate displayed is accurate and the PPG shows a strong waveform, the SpO_2 can be determined. It should be noted that individual readings are of less value than multiple readings over a period of time. Patient trends should be closely monitored. Figure 21.2 shows different sites and PPG waveforms that may be seen during pulse oximetry measurements.

Factors interfering with pulse oximetry measurement

Some patients may present a challenge when attempting to obtain a SpO_2 reading due to physical problems. Jaundice can cause interference with red and infrared light. It also may be more difficult to obtain a pulse wave on obese animals or animals with significant edema. Patients suffering from peripheral vasoconstriction, vascular disease, or low cardiac output may not have enough blood flow to arteriolar beds to obtain an accurate SpO_2 value.[10,11] Patients with SpO_2 readings below 94% ideally should have arterial blood gas values obtained because pulse oximetry becomes less reliable at values below the normal range; many studies have demonstrated that pulse oximetry is inaccurate at saturation values below 80%.[11,12] Methylene blue has also been reported to interfere with pulse oximeter readings.[13] See Table 21.2[14,15] for a list of factors affecting the ability to obtain an accurate pulse oximeter reading.

It can be a significant challenge to obtain an SpO_2 reading from a cat. Not only are cats often more resistant to handling than dogs, they are more easily stressed and have fewer accessible sites for monitoring. Unfortunately, feline patients also present a challenge
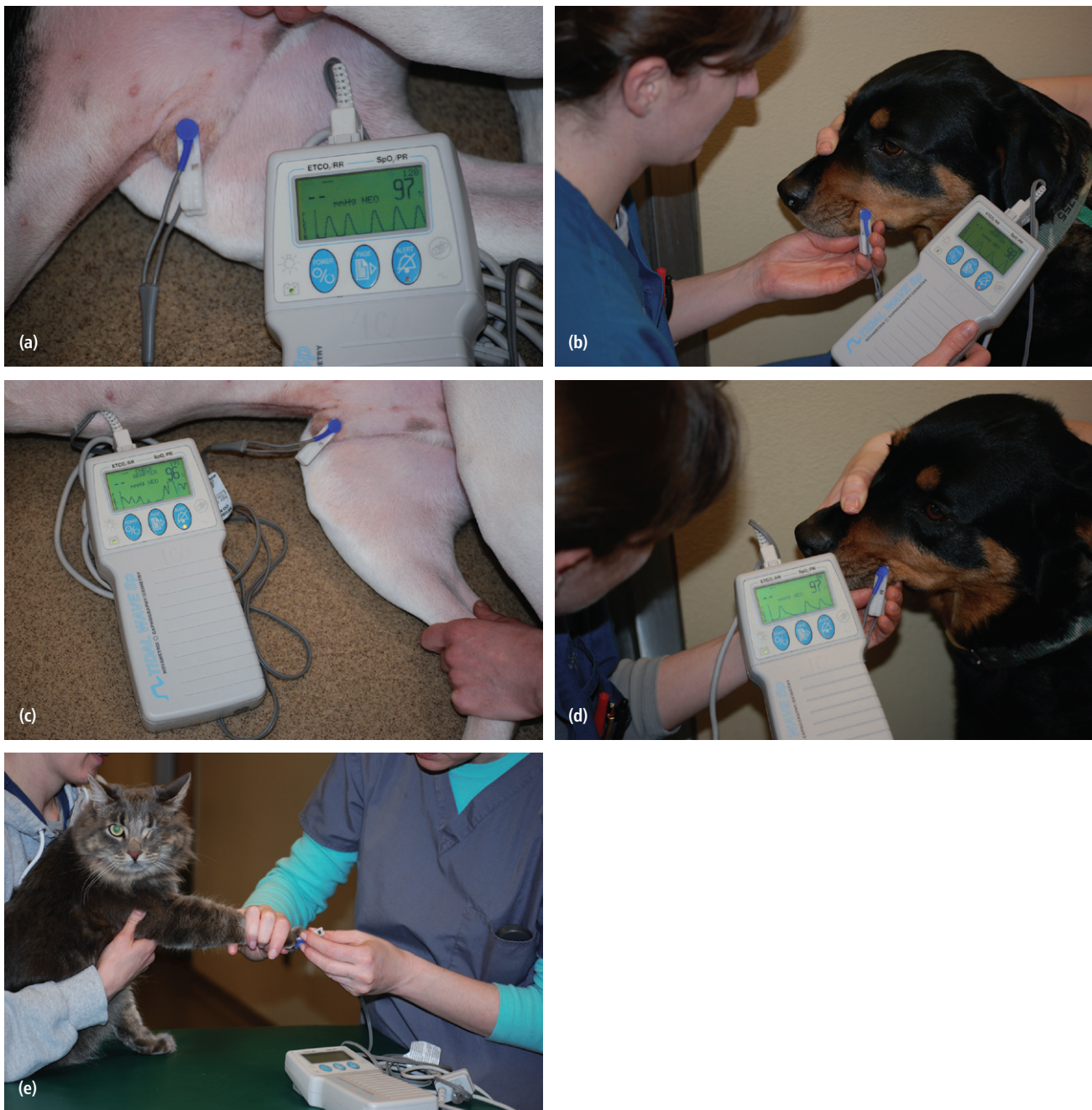
Figure 21.2 Obtaining a pulse oximetry reading. (a) The prepuce and other mucous membranes are generally good sites from which to measure SpO$_2$. (b) Obtaining a pulse oximetry reading on a dog's lip. (c) A pulse oximetry reading with a poor PPG waveform. This pulse oximetry reading should not be used; another site should be selected or blood gas analysis performed if necessary. (d) A high-quality pulse oximetry reading in a dog. Note the strong waveform and the small second shoulder (dicrotic notch) on the PPG, both marks of a high-quality graph. (e) Obtaining a reading on a cat's digits.

for obtaining samples for arterial blood gas analysis. Feline patients generally tolerate pulse oximeter clip placement on their digits more readily than on their lips.[10]

Patients with abnormal or unrepeatable SpO$_2$ values should have CO-oximetry or blood gas analysis per-formed to clarify the findings. When pulse oximetry is used as a guide to tailor or wean respiratory support, as is common in ventilator patients or those being weaned from supplemental oxygen, the patient's clinical signs must be considered in addition to the SpO$_2$ reading because the SpO$_2$ reading can be incorrect.

When an unexpected SpO_2 reading is obtained, patient evaluation is the first priority. Once patient stability is confirmed, external interference that may affect pulse oximetry readings should be investigated. Fiberoptic and fluorescent lights interfere with pulse oximeter readings.[16] Care should be taken in surgical settings when fiberoptics are present to avoid incorrect readings by covering the probe with a towel to prevent outside light from reaching the probe.

Problems can originate from the pulse oximeter itself. Some pulse oximeters have a PPG that expands to fill the screen, giving a false impression that the PPG is adequate. All models use human-based algorithms, and some of these algorithms have a difficult time differentiating between background patient movement and arterial pulses in veterinary patients. Damaged probes can give inaccurate values or no value at all. To quickly test a pulse oximeter's function, the operator can place the clip on a fingertip to confirm accuracy of the pulse rate and adequate SpO_2 reading. Table 21.3 provides guidelines for troubleshooting pulse oximetry problems.

Interpreting pulse oximeter readings

A pulse oximetry reading of 96%–98% is considered normal for a dog or cat breathing room air (20.9% oxygen) at sea level. Values less than 96% should be investigated. An SpO_2 or SaO_2 less than 92% indicates

Protocol 21.1 Performing pulse oximetry measurement

Items Required
- Pulse oximeter with clean probe
- Moistened gauze squares, if desired
- Clippers with clean blade, if fur removal is required

Procedure
1. Collect necessary supplies.
2. Select a site.
3. Prepare site as needed.
4. Turn monitor on and confirm it has powered on properly.
5. Place sensor on selected site.
6. Wait for monitor to obtain pulse rate.
7. Confirm that pulse rate obtained by monitor matches patient's pulse rate.
8. Check for a strong signal by observing the oximeter's waveform, if applicable for your machine.
9. If strong waveform is present and the reported pulse rate matches the patient's pulse rate, record value on patient's treatment sheet.
10. If waveform or pulse signal is poor, try another site.
11. If SpO_2 is unexpected or is dangerously low (<90%), notify doctor immediately and attempt confirmation at another site.
12. Consider the patient. Does the reading match the patient's clinical signs? If not, obtain another reading to confirm or consider additional measures (i.e., arterial blood gas).

Table 21.1 Common sites for pulse oximetry probe placement

Canine	Feline
Tongue	Tongue
Pinna	Pinna
Lips	Digits
Vulva/prepuce	Lips
Digits (small dogs)	
Gastrocnemius tendon	
Ventral base of tail	

Table 21.2 Factors that can affect the ability to obtain an accurate pulse oximetry reading[14,15]

Patient-Associated Problems	Monitor-Associated Problems	Environmental Problems
Pigmentation	Probe damaged (spring on clip broken, wires damaged)	Fluorescent light
Hair		Fiberoptic light
Site dry	Monitor not charged	
Panting or increased respiratory rate (movement artifact)	Monitor on wrong setting	
	Probe not placed correctly	
Shivering (movement artifact)	Dirty probe	
Aggression		
Jaundice (+/−)		
Poor perfusion		
Increased carboxyhemoglobin		
Increased methemoglobin		

Table 21.3 Troubleshooting pulse oximeter problems

Problem 1: Monitor does not give a reading
- Is the monitor on and fully charged?
- Is the probe attached to the patient?
- Is the site clean? If it is a mucous membrane, is it moist?
  - Clean and moisten site; move probe to different site
- Is the patient warm?
  - Patient is cold: warm patient to ≥98°F if physiologically stable
- Is the patient hypovolemic or peripherally vasoconstricted?
  - Underlying problem should be corrected per doctor's orders
- Does the patient have heart disease?
  - If patient has very poor cardiac output, pulse oximeter may not work; consider arterial blood gas

Problem 2: Monitor gives a reading, but the pulse rate is inaccurate
- Does the monitor's reported rate match the patient's respiratory rate?
  - If pulse rate on monitor matches respiration rate, move probe so that respirations do not interfere
- Does the patient have a varying pulse rate?
  - In the case of dysrhythmia, pulse oximeter may not work; consider arterial blood gas
- Move the probe to a different site

Problem 3: Reading given is below that expected
- Does the patient appear to be in distress?
  - Patient distressed: provide oxygen support and notify clinician
  - Patient not distressed: attempt another reading at a different location; consider interventions as for problem 1
- Does the given value match the clinical signs?
  - Matches clinical picture: provide oxygen and intervention as necessary
  - Does not match clinical signs: investigate further and attempt to obtain another reading; consider interventions as
    for problem 1

Problem 4: Reading given varies
- Does the patient have a varying pulse rate?
  - Patient pulse rate varies: pulse oximeter reading may be inaccurate; consider arterial blood gas
  - Patient pulse rate is consistent: may be related to mechanical problems (consider interventions for problem 1) or patient
    disease; notify clinician
- Does the patient have a varying pulse pressure?
  - Patient pulse pressure varies: pulse oximeter may not provide accurate values; consider arterial blood gas
  - Patient pulse pressure is consistent: may be related to mechanical problems (consider interventions for problem 1 or patient
    disease; notify clinician.

Problem 5: Reading given is higher than expected
- Does the patient appear to be in distress?
  - Patient in distress: provide oxygen support and notify clinician. Try to obtain another reading at a different site because falsely
    elevated values can occur
  - Patient not in distress : attempt to obtain another reading
- Does the given value match the clinical signs?
  - Investigate reasons for a greater than expected reading. Patient condition may be improving

severe hypoxemia. Lack of cyanosis should not be used as an indicator of proper oxygenation because cyanosis does not generally develop until arterial oxyhemoglobin is ≤85%.

It is important that the operator understands the relationship and the differences between SO_2 and PO_2. The partial pressure of oxygen in arterial blood or PaO_2 describes the oxygen dissolved in arterial plasma, whereas the SpO_2 describes the percentage of functional hemoglobin that is oxygenated in the arterial bloodstream. Hemoglobin can only become oxygenated when oxygen from the lung becomes dissolved in plasma and is thus available in the blood for binding to hemoglobin. Conversely, in the capillary where tissue oxygen levels

are low due to local oxygen consumption, the low local PO_2 leads to oxygen disassociating from the hemoglobin and moving down its concentration gradient into the cell for metabolism.

The PaO_2 is 80–110 mm Hg in a normal animal breathing room air at sea level. The relationship between PO_2 and SO_2 (as depicted in Fig. 21.1) is *not linear*. Above a PO_2 of ~100 mm Hg, huge changes in PO_2 (to 550 mm Hg, for instance, as is expected at an FiO_2 of 1.0) make almost no change in the SO_2 because hemoglobin is nearly 100% saturated already. Conversely, below a PO_2 of approximately 60 mm Hg, small decreases in PO_2 lead to enormous drops in SO_2 and therefore in the amount of oxygen that can be carried on hemoglobin to the tissues. Thus although 90% is considered a good "grade," it is absolutely *not* a good SpO_2: it signifies clinically relevant hypoxemia because the patient's PaO_2 is likely ≤70 mm Hg at an SpO_2 of 90%. Another thing to consider is that when a patient is receiving supplemental oxygen, any SpO_2 below 98%–100% may indicate a problem. For instance, a patient on 100% oxygen with an SpO_2 of 90% is physiologically safe but has compromised lung function that may become immediately and life-threateningly apparent once oxygen support has been removed.

CO-oximetry

The science behind a CO-oximeter

CO-oximeters are benchtop analyzers that measure hemoglobin oxygen saturation in a blood sample rather than through tissue. A CO-oximeter uses between four and eight different wavelengths of light, most between 475 nm and 600 nm, to measure the fractions of all relevant species of hemoglobin; values typically reported include total hemoglobin (tHb), oxyhemoglobin (O_2Hb), deoxyhemoglobin (HHb), methemoglobin (MetHb), and carboxyhemoglobin (COHb). Most CO-oximeters do not recognize sulfhemoglobin. If sulfhemoglobinemia is suspected due to applicable toxin ingestion, care should be taken when interpreting values provided by CO-oximetry. Sulfhemoglobinemia can cause a falsely elevated result for methemoglobin and a falsely decreased result for carboxyhemoglobin.[17]

To determine the total hemoglobin concentration (tHb) in a blood sample, CO-oximeters use **conductimetry** to estimate the sample's hematocrit (HCT). Whole blood conducts an electrical current due to the electrolytes in plasma,[4] but erythrocytes, leukocytes, and platelets do not. Alterations in conductivity of the blood then correlate to approximate cell counts, such that diminished electrical conductivity indicates an increase in the

Figure 21.3 Output from a multiparameter benchtop analyzer including a CO-oximeter.

ratio of nonconductive cells to conductive plasma (a higher HCT). Leukocytes and platelets do not have enough mass to affect conductimetry significantly,[18] so the CO-oximeter estimates the HCT based on the electricity transmitted through the sample. The CO-oximeter then uses a standard calculation to determine the tHb from the HCT.

Once the CO-oximeter has determined tHb, the percentages of tHb that are oxy-, de-, carboxy-, and methemoglobins can be calculated. The CO-oximeter directly measures each of the species' concentrations via spectrometric means as just described and then reports them in percentages of tHb. For example, carboxyhemoglobin percentage would be calculated as:

$$COHb, \% = (COHb/tHb) \times 100$$

Many CO-oximeters are combined with basic analyzers that also provide blood gas values, metabolites, and electrolytes. Some also report calculated values such as the alveolar-arterial oxygen gradient (A-a; see Chapter 22), bicarbonate concentration, and base deficit, which makes these machines good all-purpose analyzers for an intensive care setting or emergency department (see Fig. 21.3).

Equipment available

Many CO-oximeters are available from human biomechanical companies, although no company currently advertises a veterinary model. Human CO-oximeters may or may not yield accurate results in dogs and cats because species-specific algorithms are needed. Some models allow the operator to manually enter which species' blood is being introduced. The CO-oximeter

generally aspirates blood through a small probe and gives results rapidly on small sample sizes.

Maintenance of a CO-oximeter

Maintenance for most multivalue large CO-oximeters includes replacing a number of consumables at manufacturer-designated times in addition to replacing consumables when an error in calibration or quality control is detected. One highlight of the unit is the ability to preset the machine for automatic quality controls and calibrations. Some models automatically lock out any functions that do not pass quality control. Although this may lead to frustration among staff, it is essential to prevent errors in clinical judgment based on inaccurate readings.

Indications for CO-oximetry

Patients that will benefit from CO-oximetry include those that have known or suspected exposure to drugs that cause hemoglobin conversion to methemoglobin (see Box 21.1)[19–21] or those that have been exposed to carbon monoxide (as in smoke inhalation). Patients with high levels of carboxyhemoglobin can have normal SpO$_2$ values because pulse oximeters cannot differentiate carboxyhemoglobin from oxyhemoglobin. Patients in which carbon monoxide exposure is suspected should have CO-oximetry performed because "classic" bright red mucous membranes are not always seen.[22] Patients with brown or muddy mucous membranes, and those with unexplained respiratory distress, warrant CO-oximetry evaluation for methemoglobinemia.

Box 21.1 Substances known to cause methemoglobinemia[19–21]

Medications
- Azo dye (urinary antiseptic)
- Hydroxycarbamide (hydroxyurea)
- Local anesthetics
  - Benzocaine
  - Lidocaine
- Methimazole and propylthiouracil
- Methylene blue
- Metoclopramide
- Nitroglycerin, nitroprusside
- Sulfa antibiotics

Environmental toxins and human medications
- Acetaminophen
- Antimalarials
- Burning wood and plastic
- Naphthalene (mothballs)

Dyshemoglobinemias

Methemoglobinemia

Normal methemoglobin values in the canine and feline are less than 1%.[23] Values between 10% and 20% cause skin discoloration, usually most noticeable in the mucous membranes. Values above 20% yield clinical signs such as anxiety and dyspnea with exertion, and values between 30% and 50% cause fatigue, confusion, dizziness, and tachypnea. Values between 50% and 70% can lead to coma, seizures, and arrhythmias. Values above 70% are generally lethal.[24]

Carboxyhemoglobinemia (carbon monoxide toxicity)

Normal carboxyhemoglobin values in canine and feline patients are less than 1%. Although increases in methemoglobin percentages lead to consistent clinical signs, increases in carboxyhemoglobin values can cause a variety of signs at different degrees of elevation in individual animals. Most commonly, carboxyhemoglobin at 10%–20% causes nausea.[2] Values between 20% and 30% often cause dizziness and generalized weakness. If greater than 30% of hemoglobin is converted to carboxyhemoglobin, dyspnea during exercise and confusion occur. Once carboxyhemoglobin comprises 40% to 50% of an animal's total hemoglobin, the patient is likely to present with significant neurologic signs such as syncope, seizures, and severe obtundation.[2] Percentages of carboxyhemoglobin greater than 60% can cause hypotension, coma, respiratory failure, and death. Although household carbon monoxide poisoning is now rare due to improved home heating systems, CO-oximetry should be used to rule out carboxyhemoglobinemia in cases in which it is a differential.

Performing CO-oximetry

CO-oximetry is minimally invasive because it requires a small blood sample; arterial blood is required if arterial oxygen content information is desired, but venous blood is adequate to diagnose dyshemoglobinemia. Samples should be drawn from an artery or central vein whenever possible, and patient size and disposition should be considered when choosing a sampling site. Potential sampling sites include the dorsal pedal artery, the femoral artery, the jugular vein, and sublingual veins. More peripheral veins such as the cephalic and saphenous veins can be used but may not render accurate values in hypoperfused patients. Samples obtained from the tongue, usually from patients under anesthesia, are considered venous samples, but some studies have shown that these values are very close to arterial values in the normal patient.[25] If the sample is being taken from

a catheter, follow all appropriate scavenging techniques to ensure that the sample is not tainted with saline flush or intravenous fluids (see Chapter 47, Blood Sample Collection and Handling, for appropriate sampling techniques from indwelling catheters).

Benchtop CO-oximeters require anticoagulated samples, usually with sodium heparin or lithium heparin. Follow the unit manufacturer's guidelines when choosing an appropriate anticoagulant, although typically ethylenediaminetetraacetic acid (EDTA), citrate, oxalate, and sodium fluoride are not recommended.

Once the sample has been drawn it should be analyzed immediately, although sometimes immediate analysis is impossible. Although it has been established that ice-water storage for blood gas analysis samples is best,[26] follow all manufacturer guidelines concerning sample storage for CO-oximetry because often the manufacturer recommends samples be stored at room temperature. Once a blood sample has been obtained, it is imperative that it is well mixed and is not exposed to room air, which can falsely increase pH and oxygenation. Samples should be handled carefully to avoid hemolysis that could result in a falsely low HCT value.

Factors affecting CO-oximetry measurements

Several problems may arise while obtaining CO-oximetry measurements. Arterial samples must be used when one wishes to evaluate lung function or estimate PaO_2; venous samples will not suffice in such cases. Inadequate sample mixing, incorrect anticoagulant use, clot formation, air exposure, air bubbles, or prolonged hold time prior to analysis can all cause erroneous results. Some drugs such as hydroxocobalamin and cyanocobalamin (antidotes for cyanide poisoning) can cause interference because of their dark red color.[27,28]

Blood products and CO-oximetry

Bovine hemoglobin-based oxygen carriers such as Oxyhemoglobin (OPK Biotech, Cambridge, MA) do not interfere with CO-oximetry. Hemoglobin-based oxygen carriers, also known as Hb-200, carry oxygen differently than endogenous hemoglobin molecules, and therefore they have a different oxyhemoglobin equilibrium curve. This does not appear to affect CO-oximetry values, although it may affect CO_2 values: a 10% difference was found in calculated versus actual values.[29]

Other biologic products can lead to inaccurate CO-oximetry results. Patients that have received human albumin transfusions can have inaccuracies due to changes in electrolyte concentrations in the plasma.[18] It has also been shown that hyperbilirubinemia can cause falsely elevated COHb levels as measured by CO-

oximetry.[30] There are mixed opinions on whether fetal hemoglobin can interfere with carboxyhemoglobin readings,[31,32] but dogs, cats, and horses are born with 100% adult hemoglobin, which eliminates this concern in the species of interest.

The future of oximetry

Recently the Masimo Corporation (Irvine, CA) announced the world's first bedside pulse CO-oximeter using wavelengths of light absorbed by carboxyhemoglobin and methemoglobin. Pulse CO-oximetry was marketed to human emergency departments for use as a point-of-care monitor for carbon monoxide toxicities. Multiple studies have been performed to evaluate the accuracy of the pulse CO-oximeter in humans and have yielded mixed results.[33,34] These contradictory data suggest that more information needs to be gathered prior to relying solely on pulse CO-oximetry for diagnoses and assessments of hemoglobin function. Until pulse CO-oximetry becomes more reliable and veterinary studies are performed, obtaining intermittent CO-oximetry values obtained from a laboratory analyzer will have to suffice.

Summary

Both pulse oximetry and CO-oximetry have their places in veterinary medicine. It is essential to understand the limitations of both and when one modality would be preferred over the other. Appreciating the strengths and weaknesses of these monitors as diagnostic tools will lead to improved patient care and expedite diagnosis and treatment.

Acknowledgment

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