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HYPOXEMIA AND MONITORING PATIENT OXYGENATION

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PHYSIOLOGY
Maintaining an adequate content of oxygen in arterial blood is vital to maintaining oxygen delivery to the tissues. The lungs are responsible for the movement of oxygen into the blood. Once in the blood oxygen is carried in two forms. A very small proportion of the total oxygen content of blood is present dissolved in physical solution in plasma. This is measured as the partial pressure of oxygen or PO2. The majority (>98%) of oxygen is carried bound to hemoglobin and is measured as a saturation or SO2.

HYPOXEMIA
Hypoxemia is defined as a partial pressure of oxygen in arterial blood (PaO2) of less than 80 mmHg. A PaO2 less than 60 mmHg is considered severe hypoxemia and requires immediate therapy as it can be life threatening. It is important to note that hypoxemia is purely defined by the partial pressure of oxygen, it is not a reflection of total oxygen content or the adequacy of oxygen delivery to the tissues. For example a very anemic patient with normal oxygenating ability and a normal PaO2 is not hypoxemic but because of the lack of erythrocytes the blood has a low total oxygen content and insufficient oxygen delivery to the tissues.

Animals on oxygen therapy can have an abnormal or ‘less than expected’ ability to oxygenate, but as long as the PaO2 is greater than 80 mmHg these animals are not considered hypoxic.

Causes of hypoxemia:
1. Low fraction of inspired oxygen (FIO2)
2. Hypoventilation (only if breathing room air)
3. Venous Admixture
   a. Low ventilation/perfusion alveoli
   b. No ventilation/perfusion alveoli
   c. Anatomical vascular right to left shunts
   d. Diffusion defects

When a patient on a breathing circuit is found to be hypoxic the adequacy of the oxygen supply should be established immediately to rule out a low FIO2.

An elevated PCO2 (hypoventilation) can cause hypoxemia in animals breathing room air. Although hypoventilation will cause a reduction in the PaO2 it will not be significant enough to cause hypoxemia when supplemental oxygen is provided.

Venous admixture describes all the ways blood can pass from the right side of the heart to the left side of the heart without being adequately oxygenated. The most common cause of this is ventilation/perfusion (V/Q) abnormalities subsequent to pulmonary disease. Right to left anatomical shunts are uncommon and are usually accompanied by other clinical signs. Pulmonary diffusion defects are also uncommon in veterinary patients. Disease processes such are emphysema, oxygen toxicity and smoke inhalation are possible causes of a diffusion defect.

Oxygen Content
The total oxygen content of arterial blood (CaO2) is described by the following equation:

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CaO2 = ([Hb] \times SaO2 \times 1.34) + (0.003 \times PaO2) \text{ ml O}_2/100\text{ml}
\]

Where [Hb] is the concentration of hemoglobin, SaO2 is saturation of hemoglobin with oxygen and PaO2 is the partial pressure of oxygen dissolved in plasma. Each gram of Hb will bind 1.34 ml of O2 when fully saturated. 0.003 is the solubility coefficient of oxygen in plasma at body temperature.

From this equation it can be seen that the three factors contributing to oxygen content are hemoglobin concentration, the saturation of this hemoglobin with oxygen and the partial pressure of oxygen dissolved in plasma.

HEMOGLOBIN
Hemoglobin is responsible for transporting the majority of oxygen to the tissues. To ensure adequate delivery of oxygen to the tissues in a patient, there needs to be a sufficient quantity of functional hemoglobin. The quantity of hemoglobin in a patient can be measured directly or it can be approximated as one third of the packed cell volume.

\[
\text{SaO}_2
\]

The saturation of hemoglobin with oxygen is responsible for the vast majority of oxygen transport around the body. The degree of hemoglobin saturation is determined by the PaO2 as this pressure is the driving force for movement of oxygen into the red blood cell. The relationship between PaO2 and SaO2 is described by the hemoglobin oxygen dissociation curve.

Blood gas machines calculate SaO2 from the measured PaO2 (via the hemoglobin oxygen dissociation curve). If saturation is measured via a pulse oximeter it is called SpO2. Normal SaO2 is 99-100%. An SaO2 of 95% is equivalent to a PaO2 of ~80 mmHg, SaO2 of 90% is equivalent to a PaO2 of ~60 mmHg, hence an SaO2 measurement of less than 90% is associated with severe hypoxemia.

\[
\text{PaO}_2
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From the equation for CaO2 it can be appreciated that the PaO2 has a very minor contribution to the total quantity of oxygen transported to the tissues. Despite this the PaO2 is essential to adequate tissue oxygenation because it determines the SaO2. The partial pressure of oxygen dissolved in plasma is dependent on the amount of oxygen in the alveoli and on how many well ventilated alveoli are exposed to venous blood to allow the transfer of oxygen to occur. Lung function determines how many alveoli are ventilated adequately and how many pulmonary blood vessels pass ventilated alveoli. Most pulmonary diseases will alter this ventilation perfusion relationship leading to a reduction in the expected PaO2.

CLINICAL MONITORING
Clinical reasons to measure oxygen related parameters:

- Assess oxygenation status of patient
- Assess effectiveness of oxygen therapy
- Monitor changes in pulmonary function

What can we measure in the clinical setting?

- Mucous membrane color
- SpO2
- PaO2
- PvO2
MUCOUS MEMBRANE COLOR
Cyanosis is the blue discoloration of mucous membranes that is associated with arterial hypoxemia. Although the presence of cyanosis is a certain sign of hypoxemia, it is important to realize it is a very late sign. It requires 5g/dl of deoxygenated hemoglobin for cyanosis to be visible so the appearance of pink mucous membranes is not a reassurance that the animal has adequate oxygenation. Factors such as anemia and the type of ambient lighting can impair the ability to identify cyanosis.

PULSE OXIMETRY
Hemoglobin changes shape with the binding of oxygen. The wavelengths of light reflected from oxygenated hemoglobin differ from that reflected from deoxygenated hemoglobin. Oximetry is the use of spectrophotometry to detect the patterns of reflected light. This information determines the percentage of oxygenated hemoglobin present, the SpO2. Pulse oximetry has been designed to only recognize light reflected with alternating intensity to try to focus on information from arterial blood only.

Pulse oximetry is non-invasive and the technology has become widely available so it is a very valuable tool in monitoring the oxygenation status of a patient. Unfortunately accuracy can be a problem with pulse oximetry. It was designed for co-operative, hairless human patients and so its adaptation to veterinary medicine brings some inherent issues. The standard pulse oximeters emit only two wavelengths of light and assume that there is only oxyhemoglobin and deoxyhemoglobin present. If a significant amount of carboxyhemoglobin is present this will be read as oxyhemoglobin and a falsely high SpO2 will result. Methemoglobin will tend to read as an SpO2 of 85% despite the real SpO2 being lower than that.

Because pulse oximetry requires pulsatile blood flow, hypotension or peripheral vasoconstriction may affect the accuracy of the readings. Movement of the patient can confuse the probe and it may mistakenly take readings of tissue or veins. Hairless skin or pigmented skin can make the readings spurious low or prevent the equipment from making any reading at all. In veterinary patients the easiest, most reliable readings tend to come from unpigmented mucous membranes in anesthetized patients.

Ways to maximize the accuracy of the pulse oximetry reading:
- Chose a site that has minimal pigmentation and is warm and thin. Mucous membranes are ideal.
- Protect the probe from ambient light (e.g. cover it with a cloth)
- Encourage the patient to be still for the reading
- Take continuous readings or multiple readings, never believe the first reading taken
- Ensure the heart rate displayed by the pulse oximeter is the same as the patient’s heart rate at that time
- If the reading does not correlate with the animal’s clinical picture take an arterial blood gas or persist with more readings before believing it

Important concepts regarding pulse oximetry
- SpO2 is a measure of the saturation of hemoglobin with oxygen but gives NO information regarding the quantity of hemoglobin. So an anemic patient would be expected to have a normal SpO2 but the total oxygen content of the arterial blood would be low, compromising tissue delivery
- Animal’s breathing room air should have maximally oxygenated hemoglobin if they have normal lung function (e.g. 99-100%) corresponding to a PaO2 ~ 110 mmHg. Animals on supplemental oxygen can have increased PaO2 (110-500 mmHg) but the SpO2 will still read 99-100%. For this reason the pulse oximeter is a very insensitive monitor of changes in oxygenation for patients on oxygen (e.g. anesthetized animals).
- If an animal is on supplemental oxygen and has a true SpO2 reading of < 99%, it is of concern given that it should be 99% on room air!
- SpO2 < 95% represents hypoxemia, SpO2 < 90% is severe hypoxemia
- Small changes in SpO2 are associated with substantial changes in PaO2.

ARTERIAL BLOOD GASES
The arterial blood gas sample must be collected from an artery, either by direct puncture or via an indwelling catheter. Appropriate sample handling is important to avoid pre-analytical errors. An effort needs to be made to ensure heparin dilution or exposure of the sample to the air does not occur. The sample should be run as soon as possible. If there is a delay prior to analysis the sample should be capped and stored in ice water.

The normal PaO2 in a patient breathing room air at sea level is 80-120 mmHg. A PaO2 of less than 80 mmHg is considered hypoxemic. Less than 60 mmHg is considered severely hypoxemic.

Patients breathing supplemental oxygen should have a PaO2 higher than 120 mmHg, but how high should it be?
A good rule of thumb is the ‘5 x rule’. A patient’s PaO2 (at sea level) should be 5 x the inspired oxygen percentage (FIO2). For example, a patient on room air is breathing 21% oxygen and so the PaO2 should be ~ 105 mmHg. A patient on 100% oxygen should have a PaO2 of ~500 mmHg. A patient on 40% FIO2 should have a PaO2 of ~ 200 mmHg.

The PaO2 is the most sensitive measure of lung function and effectiveness of oxygen therapy.

When monitoring changes in pulmonary function it is common to have several PaO2 measurements taken on varying inspired oxygen concentrations. A popular approach to compare these sequential PaO2 measurements is the PaO2:FIO2 ratio (or P:F ratio). In this approach the FIO2 is recorded as a decimal (0.21 - 1.0) instead of as a percentage. The normal ratio is ~500, a ratio of 200-300 is associated with moderate lung dysfunction and a ratio of < 200 is associated with severe lung dysfunction.

VENOUS BLOOD GASES
The partial pressure of oxygen in venous blood (PvO2) provides very little information regarding patient oxygenation. PvO2 is dependent on the arterial oxygen content, cardiac output and oxygen consumption by the tissues. As a result there are numerous factors that can alter PvO2 and the oxygenation of arterial blood is only one of them. To ensure
all tissue beds receive adequate oxygen a minimum partial pressure of oxygen in end capillary (venous) blood of 21 mmHg is required. Normal \( \text{PvO}_2 \) in patients’ breathing room air is 40-50 mmHg. A \( \text{PvO}_2 < 30 \) mmHg value is clinically concerning and requires intervention. Blood samples for evaluation of \( \text{PvO}_2 \) need to be taken from a central vein such as the jugular vein, vena cava or pulmonary artery. Peripheral samples may reflect local blood flow phenomena that often are not representative of the global patient status.

\( \text{PvCO}_2 \) is generally 3-6 mmHg higher than arterial values and in most patients it can be used as a reliable reflection of \( \text{PaCO}_2 \).

REFERENCES