Pitfalls and common errors of anaesthetic monitoring devices part 3: Capnography

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ABSTRACT: In order to use an electronic monitoring device safely and effectively it is important to know how the equipment generates the numbers that we record on our anaesthetic records. This way, we can be more confident that the data realistically represent the physiology of our patient. Understanding the common pitfalls and errors that each piece of monitoring is prone to can help us recognise when to intervene rather than putting a number down to a quirk of the monitor. This third article in the series explores the capnograph.

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CAPNOGRAPHY - measuring the adequacy of ventilation

Ventilation is the act of moving gas in and out of the lungs in order to permit gas exchange; specifically, the uptake of oxygen and elimination of carbon dioxide. As carbon dioxide diffuses and equilibrates so rapidly, it can be used to measure the adequacy of ventilation. Strictly speaking, only the arterial concentration of carbon dioxide ($PaCO_2$) truly represents the ventilation status of a patient, but this requires arterial blood gas analysis. However, since arterial CO_2 concentrations approximate the more easily measurable alveolar CO_2 concentrations ($PA'CO_2$), determining the CO_2 concentrations of alveolar gases at the end of expiration (end tidal carbon CO_2 or $PET'CO_2$) using capnography can therefore be used to assess the adequacy of ventilation instead.

The concentration of expired CO_2 depends on:

1) Alveolar ventilation
2) Pulmonary perfusion and thus venous return and cardiac output
3) Metabolism and CO_2 production

Although there are some species differences, normal $PaCO_2$ in most conscious healthy mammals is between 35-45 mmHg; this can be considered as "normocapnia". Normocapnia is maintained by altering minute ventilation (minute volume), which is determined by the patient's respiratory rate and tidal volume. *It is important to recognise that respiratory rate is only one component of ventilation and minute volume and tidal volumes are also critical.* Hypoventilation, caused by a reduction in minute volume, results in accumulation of CO_2 in the body (increased $PaCO_2$) whereas hyperventilation increases elimination of CO_2 (decreased $PaCO_2$). Basically, if ventilation increases $PaCO_2$ decreases and if ventilation decreases $PaCO_2$ increases

Mechanism of measurement

Capnographs are commonly part of multiparameter anaesthetic monitors but can also be separate monitors or just coupled with pulse oximeters (**Figure 1**). A capnograph continuously measures the concentration of carbon dioxide throughout the respiratory cycle and displays both a waveform and an end-tidal (end of expiration) carbon dioxide concentration ($PET'CO_2$). In comparison a capnometer only displays the $PET'CO_2$ value. The principle of measurement is that any gaseous molecule with two or more dissimilar atoms (e.g. carbon dioxide CO_2, nitrous oxide N_2O but not oxygen O_2 or nitrogen N_2) is able to absorb infra-red light at particular wavelengths. The spectrum

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Figure 1. Capnograph (white trace and numbers) as part of a multiparameter monitor (above) and as part of a handheld monitor with pulse oximetry (right). Note the multigas analyser output in the lower left corner of the multiparameter monitor which is able to measure inspired and expired nitrous oxide and isoflurane concentrations and calculate oxygen concentrations

of infra-red wavelengths absorbed is gas dependent, with each gas's absorption spectrum acting like a fingerprint. Carbon dioxide has a peak of absorption at 4.28 µm and this consequently is the wavelength used in most capnographs.

In a capnograph analyser, inspired and expired gas travels through a chamber into which 4.28 µm wavelength infra-red light is transmitted. The sample chamber can either be positioned within the patient's gas stream (between the endotracheal tube and breathing system) or connected to a sampling line that takes gas from a sample port (again between the endotracheal tube and breathing system) (**Figure 2**). These are called mainstream and sidestream capnography respectively.

A photodetector measures the amount of infra-red light that passes through the gas in the chamber. The amount of infra-red absorbed is proportional to the number, and therefore concentration, of carbon dioxide molecules within the chamber (a physical principle known as Beer's law). A microprocessor then converts the absorption into a graphical representation and calculates the PET'CO_2 (the capnograph trace, **Figure 3**). The capnograph calculates PET'CO_2 at the point where there is a sudden drop off in CO_2 concentrations (**Figure 4**). This value is generally recorded on the anaesthetic record, but examination of the waveform can be exceptionally useful to identify a number of breathing patterns, abnormalities, adverse events and crises (**Figure 5(a)–(f)**). Due to the factors that affect PET'CO_2, capnographs can be used to confirm endotracheal tube placement, ensure the patency of the airway and breathing system, confirm cardiac output, highlight impending cardiac arrest, monitor the success of cardiac compressions during cardiopulmonary resuscitation, as well as monitoring the adequacy of ventilation and identifying bronchoconstriction, bucking a mechanical ventilator amongst other issues.

Figure 2. A: a sidestream capnography airway adapter; B: a heat and moisture exchange device for airway humidification with a sidestream capnography adaptor, C: a needle being used to sample gas from an endotracheal tube for a sidestream capnograph D: a mainstream capnograph adapter; E: a low deadspace mainstream capnography adapter for smaller patients (not the narrow central lumen – red arrow)

What is the data output of a capnograph?

Most capnographs display an end-tidal CO_2 concentration (PET'CO_2), a respiratory rate and a graphical representation of CO_2 concentration against time. They may also give inspired CO_2 concentrations as a marker of rebreathing. PET'CO_2 is most commonly read in millimetres of mercury (mmHg), and less often in kilopascals (kPa) or percentage of the gas mixture.

Limitations and specific errors

Since PET'CO_2 only estimates PA'CO_2 and $PaCO_2$, there are a number of limitations to consider when interpreting the values that a capnograph gives. Not recognising this can lead to a false sense of security when something is going wrong or an inappropriate intervention when there is no significant problem. Both can be harmful.

Collision broadening & narrowing

The accuracy of CO_2 measurement using capnography can be affected by the gas mixture (Raemer & Calalang, 1991). Molecules of gas in a mixture are continuously vibrating, moving and colliding with each other. Each collision passes energy from one molecule to another. Molecules at higher energy states vibrate more and will absorb more infrared light, while those in lower energy states vibrate less and will absorb less infrared light. Consequently, higher energy gas molecules can appear to be present at a falsely elevated concentration as the molecules take up a larger volume while lower energy molecules appear to be present in falsely decreased concentrations when measured using infrared light transmission. This phenomenon is termed collision broadening or narrowing. Use of nitrous oxide in a gas mixture causes collision broadening, which can potentially increase PET'CO_2 by 5-10 mmHg if the gas mixture contains 50-66% nitrous oxide. Oxygen results in collision narrowing, but only causes minimal CO_2 under reading.

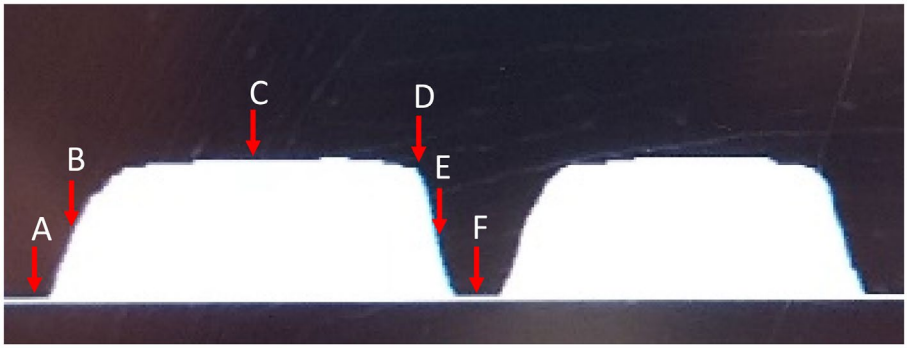

Figure 3. A pair of normal capnograph traces. A = the start of expiration, the patient breathes out deadspace gas containing no CO_2; B = expiratory upstroke, the patient breathes out mixed deadspace and alveolar gas; C = the alveolar plateau, where the patient is breathing out alveolar gas; D = the start of inspiration, end-tidal CO_2 is measured here; E = inspiratory downstroke, the sudden reversal of gas flow during inspiration rapidly drops CO_2; F = inspiratory baseline, if the patient is not rebreathing this should return the capnography trace to 0

Figure 4. A normal capnograph output; the large 44 is the end-tidal carbon dioxide measurement (PET'CO_2 in mmHg), the 0 is the measured inspiratory carbon dioxide measurement (INS or FI'CO_2) and the 30 is the measured respiratory rate (Airway respiratory rate/AwRR). Note the more narrow capnography trace due to the faster respiratory rate

Capnographs can deal with collision broadening in a number of ways. Basic capnographs do not take into account the gas mixture but can be calibrated using the gas mixture intended to be used (e.g. two thirds nitrous oxide and one third oxygen, or pure oxygen) in order to overcome this problem. Nevertheless, the anaesthetists should be cognisant of the fact that the CO_2 concentrations displayed may be artificially high if nitrous oxide is being used in this situation. Other capnographs allow the manual input of the percentage of nitrous oxide and oxygen in the gas mixture to allow the microprocessor to adjust the measured CO_2 concentration according to the gas mixture used (**Figure 6**). Finally, more complex capnographs are able to measure multiple gases (including nitrous oxide and volatile agents such as isoflurane or sevoflurane) allowing the microprocessor to automatically adjust the measured CO_2 according to the gas mixture used (Lower left corner **Figure 1**).

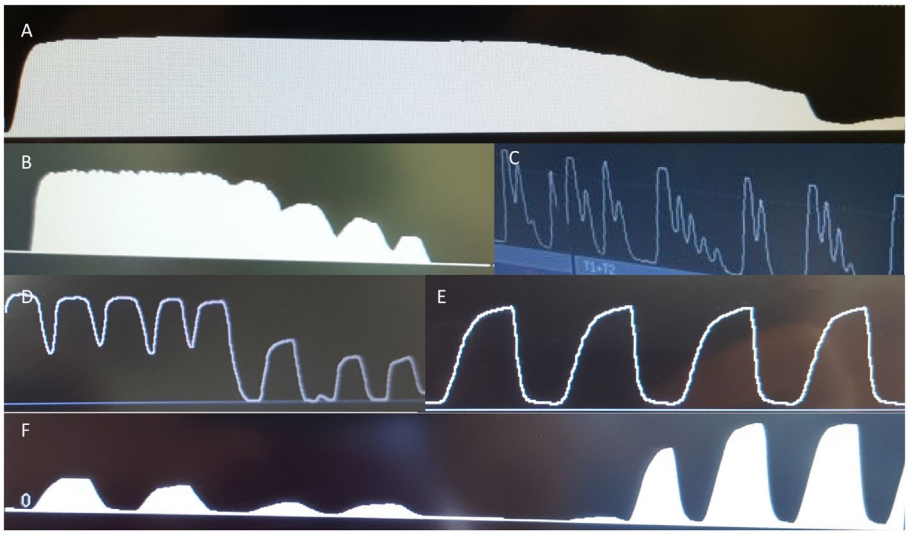

Figure 5. Non-classical and abnormal capnography traces. A: Slow respiratory rate giving a slow decline in CO_2 (note the long "tail"), B&C: cardiogenic oscillations (low and high heart rate respectively), D: rebreathing using a non-rebreathing system (note the failure of the trace to return to the zero baseline and then the correction following an increase in fresh gas flow), E: obstructive trace note the "shark fin" appearance, F: trace that could indicate either an airway leak or alternatively impending cardiac arrest (note the slow return to a normal trace when the cuff is reinflated.)

Dilution

Small patients on non-rebreathing anaesthetic breathing systems (e.g. a T-piece or Bain) often have a dilution artefact giving falsely low readings due to the relatively high fresh gas flow to tidal volume ratio. In conditions where dilution is thought to be yielding artefactually low measured PET'CO_2, the fresh gas flow can be reduced to the lowest rate at which the patient does not re-breathe in order to give the most accurate reading. It is important to remember, that should the animal's minute volume increase, the fresh gas flow will need to be increased accordingly to prevent rebreathing. Breathing system allowing the use of more economical fresh gas flows, such as the Lack, circle or Humphrey ADE have less dilutional artefact. The dilutional effect might also be more pronounced in sidestream compared to mainstream capnographs, especially at higher sampling rates.

Prolonged expiratory pause & cardiogenic oscillations

The classic capnograph trace describes the patient inspiring immediately at the end of expiration, resulting in the sudden reversal of gas flow and drop off of CO_2 concentration (**Figure 4**). However, this does not necessarily occur in all animals under anaesthesia, especially when breathing spontaneously. Instead of inspiring immediately after expiration, there can be an expiratory pause during which the patient is no longer breathing out CO_2 but the residual CO_2 around the sample chamber or port continues to be measured or sampled. Over time the CO_2 concentration reduces as it continues to be eliminated by the fresh gas flow of the breathing system. In this situation the CO_2 trace tails off slowly (**Figure 5**) and the capnograph fails to recognise a breath has been taken, as there is no sudden drop-off in CO_2 concentration. It therefore will not register a PET'CO_2 or respiratory rate. Assessment of the trace is therefore important, and if an accurate PET'CO_2 reading is required, two manual positive pressure breaths can be administered.

Oscillations can often be seen in the "tail" of the capnograph trace when cardiac

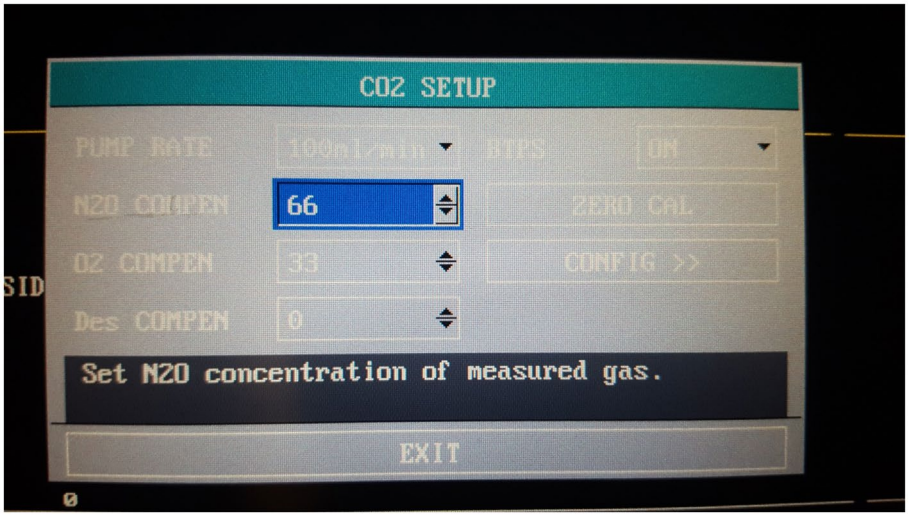

Figure 6. Menu display of a monitor that can compensate against collision broadening when nitrous oxide is added to the inhaled gas mixture

output is good (**Figure 5**). These generally occur at low respiratory rates with a significant expiratory pause as described above. Although generally referred to as cardiogenic oscillations, they are probably caused by blood flowing through the pulmonary circulation rather than the movement of the heart squeezing out additional gas from alveolae. The capnograph may read each oscillation as a separate breath if they are big enough, wildly exaggerating the respiratory rate and displaying fluctuating PET'CO_2 values starting at the actual PET'CO_2 value before dropping until the next breath is taken.

System leaks and disconnections

A common cause for inaccurate CO_2 measurement is a system leak. This is most commonly around the cuff of the endotracheal tube, but can be anywhere around the patient capnograph connector of or the sampling line in sidestream models. The leak often causes a loss in the sharp definition of the capnography trace (**Figure 5**), and a leak that develops during anaesthesia (e.g. a slowly deflating endotracheal tube cuff) can mimic the trace of an animal in impending cardiac arrest (**Figure 5**). It is therefore important to check pulses, anaesthetic depth and other monitoring, as well as checking for a leak if this occurs.

Warm-up times, zeroing and calibrating

Capnographs, particularly sidestream models, often have a lag time during which they "warm up", calibrate and zero after they are turned on and before they start to work. Therefore, they should be turned on well in advance, such as when the anaesthesia and surgery team are doing pre-induction checks so that the capnograph will be ready to work immediately after induction. Many models will intermittently (often every 15 minutes or so) zero and calibrate whilst in use. In this time there is no capnograph trace, but if the patient is still breathing and the circuit and airway are patent chest, abdominal and reservoir bag movements can be observed (**Figure 7**). Normally monitors will display a message such as "zeroing capnograph" or similar during this period (**Figure 7**).

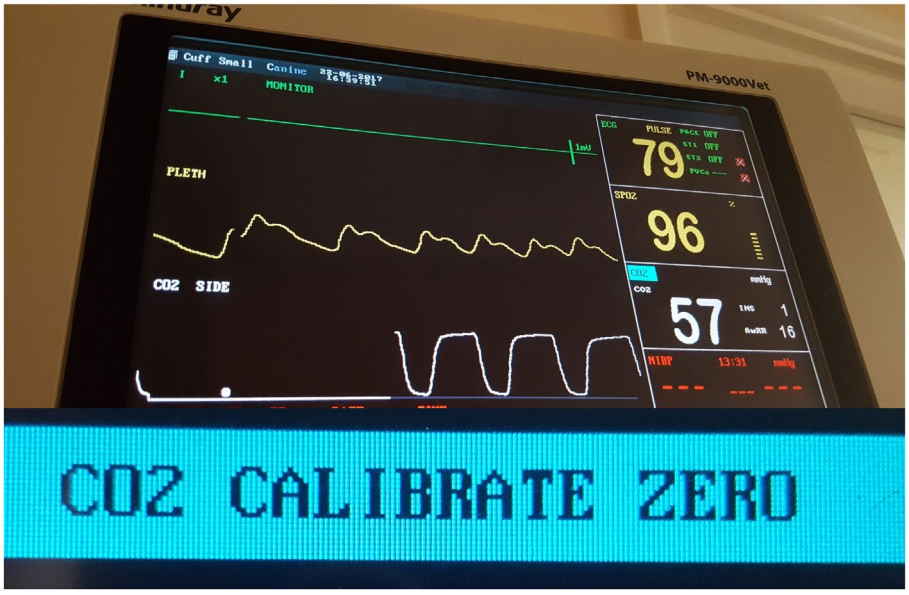

Figure 7. Above: capnograph trace during calibration & zeroing, the trace remains at zero despite the patient continuing to breathe, Below: the warning message that gets displayed in the banner at the top of the screen

Deadspace fraction and ventilation perfusion mismatch

Typically PET'CO_2 will be 3-5 mmHg lower than $PaCO_2$, as inevitably there is some deadspace gas in the terminal airways that has not undergone gas exchange but will dilute the alveolar gas. Increased alveolar deadspace caused by lung units being well ventilated but poorly perfused increases this discrepancy and in some patients may reach 15-30 mmHg. In some circumstances PET'CO_2 can actually exceed $PaCO_2$ if ventilation perfusion mismatch is significant and poorly ventilated but well perfused lung units are the last to empty.

Tachypneoic or panting anaesthetised animals will expire predominantly dead space or mixed dead space/alveolar fractions of tidal volume rather than alveolar volume, preventing the alveolar plateau from being reached, thus measuring PET'CO_2 considerably lower than the actual Pa'CO_2. These patients also commonly rebreathe CO_2. Administering a manual positive pressure breath can allow a more accurate PET'CO_2 to be obtained.

Increased inspired CO_2

Inspired CO_2 (the capnography trace failing to return to zero) can have a number of causes. Firstly, it can be caused by a failure to eliminate CO_2 from the breathing system, caused by inadequate supply of fresh gas flow in non-rebreathing systems or exhaustion of the soda lime in rebreathing systems Equipment deadspace, such as an excessively long endotracheal tube or too many attachments between the endotracheal tube and breathing system, can also cause rebreathing. Panting may cause rebreathing that does not respond to increasing the fresh gas flow as the pause between expiration and inspiration is insufficient for CO_2 to be eliminated. Finally, failure of valves in a circle system can also cause rebreathing.

How can we assess the accuracy of capnography reading?

The importance of interpreting the capnograph waveform has already been discussed and is key to assessing whether the readings given can be trusted. The trace should therefore be considered before looking at the numbers generated. If the trace is square, with a sudden inspiratory drop, the PET'CO_2 is likely reasonably accurate within the limitations described above. It is important to note, that animals such as cats and rabbits have taller, thinner capnography traces due to shorter expiratory times and faster respiratory rates (**Figure 3**). If any of the alternative traces described above are observed, the PET'CO_2 value should be viewed with scepticism and probable causes investigated and corrected as necessary. Please also note that most erroneous PET'CO_2 values are artificially low, therefore if the PET'CO_2 is significantly higher than normal, interventions should be made to correct the hypoventilation and obtain a more believable PET'CO_2 value.

What to do when an abnormal reading is obtained?

Hypoventilation can be classified as $PaCO_2$ (or PET'CO_2) over 45 mmHg and is commonly encountered during anaesthesia as most anaesthetic drugs cause dose-dependent depression of the respiratory centre and a subsequent reduction in minute volume. The solution to hypoventilation is either to reduce the depth of anaesthesia, or instigate intermittent positive pressure ventilation (IPPV), or both. Some anaesthetists would instigate IPPV for any patient whose $PaCO_2$ rose above normal levels, whilst others argue that the adverse effects of IPPV (which include damage to the lungs and reduced venous return) are worse than the adverse effects of mild hypoventilation and subsequent hypercapnia, choosing to instigate IPPV only at a PET'CO_2 of 50-55 mmHg unless there is a specific reason to intervene earlier. This is termed "permissive hypercapnia". Given the low availability of mechanical ventilators in general practice and the labour intensive nature of manual IPPV, permissive hypercapnia may be a more suitable threshold in most cases, unless there are specific reasons to maintain a normal or low PET'CO_2.

Hyperventilation ($PaCO_2$<35 mmHg) can be encountered with pain, hyperthermia and under a light plane of anaesthesia. Generally this requires correction of the underlying cause.

Conclusion

The capnography is potentially one of the most useful pieces of electronic monitoring giving information on ventilation, cardiac output and a range of adverse events. However in order to utilise it effectively its inherent weaknesses need to be understood. Knowledge of these pitfalls can ensure that adverse events are not missed, crises are rapidly identified and that interventions are not made unnecessarily.

For general information on capnography visit: www.capnography.com

Reference

Raemer, D. B., & Calalang, I. (1991). Accuracy of end-tidal carbon dioxide tension analyzers. *Journal of Clinical Monitoring*, 7, 195–208.

Multiple Choice Questions

1. The concentration of expired CO_2 does not depend on:

(a) Alveolar ventilation

(b) Pulmonary perfusion, venous return and cardiac output

(c) Metabolism and CO_2 production

(d) The fraction of inspired oxygen

2. Normal $PaCO_2$ is considered to be:

(a) 10-25mmHg

(b) 25-35mmHg

(c) 35-45mmHg

(d) 45-55mmHg

3. Hypoventilation can be caused by an increased minute volume leading to an accumulation of CO_2 in the body?

(a) True

(b) False

4. PET'CO_2 is typically how much lower than $PaCO_2$?

(a) 1-2mmHg

(b) 3-5mmHg

(c) 8-10mmHg

(d) 10-15mmHg

5. Which of the following is a common cause of hyperventilation?

(a) Pain

(b) Depression of the respiratory centres

(c) Overdose of anaesthetic agent

(d) Splinting of the diaphragm

6. A solution to hypoventilation may be:

(a) Increase the depth of anaesthesia

(b) Administer analgesic drugs

(c) Reduce the patient's temperature

(d) Decrease the depth of anaesthesia

7. Use of nitrous oxide in a gas mixture may lead to collision broadening and the capnography over-reading the expired CO_2 concentration:

(a) True

(b) False

8. The physical principle governing infra-red light absorption proportional to the concentration of CO_2 in a capnograph is:

(a) Beer's law

(b) Pasquale's law

(b) Poisson's law

(b) Newton's law

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