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How Do I Know that My Patient is Alive? Mini Series

Session 2: Capnography

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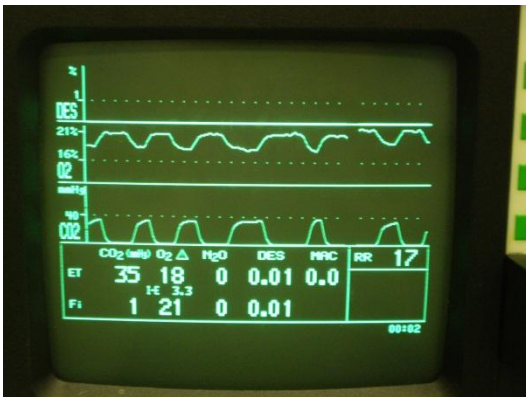


CAPNOGRAPHY

Introduction

In 1990, Clarke and Hall reported a survey of anaesthetic mortality in U.K. small animal practice. This revealed an overall mortality of approximately 0.24% for dogs and 0.29% for cats. Further analysis of their figures sub-divided mortality rates into 0.12% and 0.18% for healthy dogs and cats, respectively, and 3.13% and 3.33% for 'sick' dogs and cats, respectively. More recently, Dr. David Brodbelt of the RVC has completed a much more detailed prospective Confidential Enquiry into Peri-operative Small Animal Fatalities (CEPSAF), reporting overall mortality figures of 0.17% and 0.24% for dogs and cats respectively. Healthy dogs and cats had mortality rates of 0.05% and 0.11%, respectively, while 'sick' animals had figures of 1.33% and 1.4% for dogs and cats, respectively. Thus, these figures show that small animal anaesthetic mortality has decreased in the last 20 years since the Clarke and Hall study, but this may be put into perspective when one considers that overall anaesthetic mortality in humans (including sick patients) is of the order of 0.001%.

For the purposes of CEPSAF, an anaesthetic-related death was defined as "perioperative death within 48 hours of termination of the procedure, except where death was due solely to inoperable surgical or pre-existing medical conditions". Perhaps one of the most alarming issues to arise from the study was the timing of anaesthetic-related death: almost 50% of dogs and >60% of cats that died, did so in the recovery period, with around 50% of them succumbing within the first 3 hours after termination of the anaesthetic, and many animals were unattended at this time. This suggests that greater attention should be made to continued observation, monitoring and support of animals in the post-anaesthetic period.

Although a number of factors influencing anaesthetic mortality are outwith the anaesthetist's control (e.g. body weight, age), others may be subject to manipulation and may allow a reduction in anaesthetic-related deaths. CEPSAF identified a number of areas where improvements may easily be made:

a) the high death rate in both dogs and cats during the anaesthetic recovery period suggests that improved observation and support may be required throughout this time, with greater attention paid to continued monitoring of the vital body systems, and supplementation of inspired oxygen in higher risk animals,
b) the association between endotracheal intubation and mortality in cats implies that greater care must be taken when performing this procedure,
c) fluid therapy should be carried out cautiously in cats, with both the volume and rate of administration carefully controlled

d) monitoring of pulse quality and use of pulse oximetry should be advocated

Interestingly, aside from the use of pulse oximetry, of the 117 centres included in the CEPSAF study:
-95 could monitor ECG - *but only 20 routinely used it*
-56 had non-invasive blood pressure (NIBP) monitoring - *but only 23 routinely used it*
-26 had capnography - *but only 24 routinely used it*

This is of concern, as analysis of serious peri-operative incidents in human anaesthesia has demonstrated that:
-pulse oximetry alone would have detected 40-82%
-pulse oximetry + capnography would have detected 88-93%
-pulse oximetry + capnography + NIBP would have detected ~93%

Consequently, the take-home message should be that, if anaesthetic monitoring equipment is available, it should be utilised in all anaesthetised patients, but particularly so in the high risk groups.

Dave Brodbelt's PhD thesis can be accessed and downloaded at:
http://www.rvc.ac.uk/Staff/Documents/dbrodbelt_thesis.pdf

Carbon dioxide and its measurement

Carbon dioxide (CO_2) is a waste product produced by all cells of the body during aerobic metabolism. It must be excreted otherwise severe acid base derangement can occur due to an increase in hydrogen ion concentration following the formation of carbonic acid. CO_2 diffuses out of cells into the blood and is transported to the lungs via the circulatory system. Within the lung, CO_2 diffuses across the alveolar membrane and is subsequently exhaled. The amount, or concentration, of CO_2 can be measured within the blood or at the mouth.

The principal ('gold standard') method of assessing respiratory function is by measuring the partial pressure of carbon dioxide in arterial blood ($PaCO_2$). To do this involves obtaining an arterial blood gas sample and running it through a blood gas analyser. This technique is invasive, subject to error, and has a learning curve associated with it.

CO_2 is eliminated from the body *via* the lungs. In patients with normal lung function, at the end of expiration the levels of CO_2 in the alveoli should have equilibrated with those in the pulmonary capillaries supplying those alveoli. Thus, if we could measure the CO_2 concentration in the last part of the expired gas coming from the lungs (the 'end tidal' breath) we would have a good indication of the carbon dioxide levels in the arterial blood.

CO_2 concentration is commonly measured by the method of infrared absorption, although many other methods are available. Capnography is a technique whereby a small probe/connector is placed adjacent to the patient's airway (most commonly by placement between the breathing system and the

endotracheal tube, although some machines are able to sample *via* nasal prongs), and then analysis of the airway gases is performed to produce a continuous graphical display of CO_2 concentrations *versus* time. The trace so produced is known as a **capnogram** while the machine that produces the trace is termed a **capnograph**.

Two main types of capnograph are available:

1. Non-diverting or mainstream analysers - CO_2 is analysed within the probe that is positioned between the endotracheal tube and breathing system. Mainstream analysers tend to be more bulky - because the gas analysis is taking place within the actual probe itself – which creates drag on the endotracheal tube. There have been reports of burns occurring in human patients (mainstream analysers heat are heated to prevent the build up of condensation), although this appears much less problematic with newer machines. The large sensor within the airway increases apparatus dead space, and these types of monitors cannot measure other gases at the same time, such as anaesthetic vapour concentration. However, mainstream analysis is cheaper and the response time is faster. Additionally, as gas is not being removed from the patient there is no requirement for scavenging. Mainstream analysers cannot generally be used in non-intubated patients, although there is one manufacturer that produces an analyser that can be attached to nasal prongs.

2. Diverting or sidestream analysers - the gas sample is automatically drawn out of the connector and analysed at the main body of the capnograph at a fixed rate (usually 150 ml/min), which sits distant from the patient. Sidestream analysers do not have the problem of a bulky probe, as they utilise a simple connector to divert the gas from the airway to the main body of the capnograph; however, they have a slower response time (due to delay) than the mainstream analysers, because of the time taken to transport the gas from the airway to the analyser. Sidestream analysers, however, can be used in non-intubated patients (e.g. sampling *via* nasal prongs) Gas diverted to sidestream analysers should be scavenged or returned to the breathing system, otherwise environmental contamination will occur (assuming the patient is on an inhaled anaesthetic agent). Sidestream analysers usually incorporate polychromatic infrared technology which allows the unit to determine the concentration of several different gases (not oxygen) e.g. anaesthetic vapour and nitrous oxide, within the inhaled and exhaled gas mixture. However, these units may be prone to leaks in the sampling line and moisture must be collected using a water trap which should be emptied daily. Sidestream analysers must be calibrated regularly – usually at the 12 month service – using a calibration gas with a known concentration of CO_2.

A variation on the standard sidestream unit is 'Microstream' technology. These capnographs sample at a much lower flow (50 ml/min) and are generally more accurate in small patients or those with fast respiratory rates. However, the consumables for these monitors are relatively expensive, and as a water trap is incorporated into the sampling line itself, the line must be changed at regular intervals (recommended that lines are changed after 8 hours of continuous measurement).

All sidestream analysers can be used remotely e.g. in an MRI scanner, because the sampling line does not contain any magnetic parts.

The Capnogram

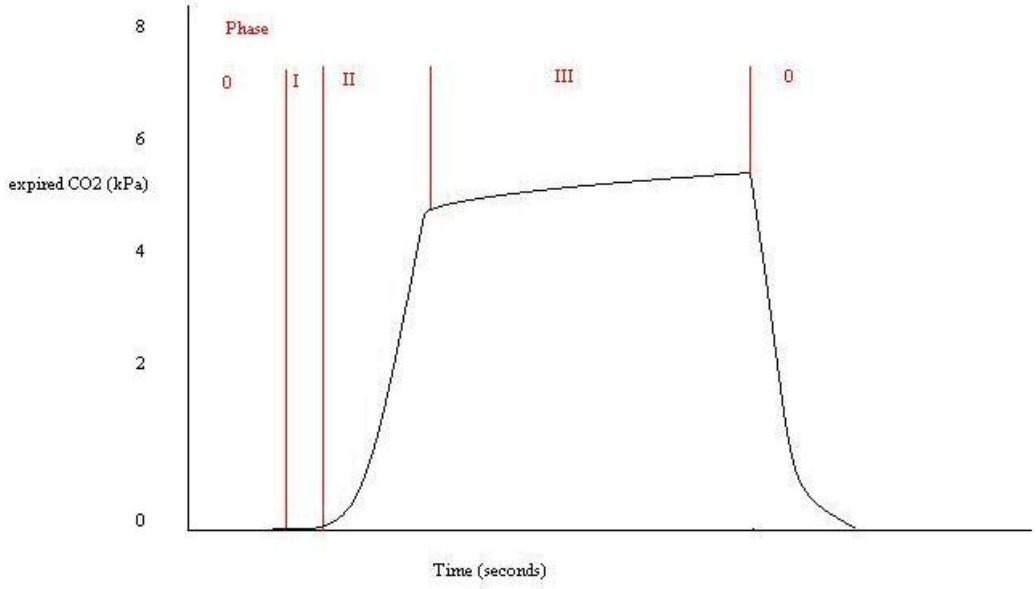


Figure 1 – a normal single breath capnogram waveform

There are 4 phases to the capnogram (indicated by I, II, III and 0 in Fig. 1):

i) Phase I is the start of expiration. The first gas to leave the lungs comes from the conducting airways (dead space gas) and has not, therefore, taken part in gas exchange so contains no CO_2. As a consequence of this, you can't actually tell where expiration commences by looking at the capnogram.

ii) Phase II indicates the sudden increase in CO_2 as carbon dioxide-rich gas leaves the lungs. This gas comprises a mixture of dead space gas and alveolar gas. Phase II should have an almost vertical upstroke.

iii) Phase III is termed the alveolar plateau, and represents exhalation of CO_2-rich gas from the alveoli. 'Alveolar plateau' is actually a misnomer, as the slope usually continues to rise slightly upwards during this phase, due to continued excretion of CO_2 into the alveoli during exhalation combined with differential emptying of alveoli at varying rates.

iv) Phase 0 is the inspiratory segment of the capnogram, and indicates the rapid return of the trace to baseline as the patient breathes in CO_2-free gas from the breathing system.

In addition to producing a capnogram trace, capnographs display both the respiratory rate and the end-tidal CO_2 ($ETCO_2$) value. The $ETCO_2$ value is taken as the highest point of phase III, just before the beginning of phase 0 (Fig. 1). This value is the means by which adequacy of ventilation is assessed (in the absence of arterial blood gas analysis): high $ETCO_2$ implies hypoventilation, while low $ETCO_2$ values may imply hyperventilation, or may be an indication that blood flow to the lungs is inadequate (i.e. there is insufficient blood flow to carry CO_2 from tissues to the lungs) – this may occur with profound hypovolaemia/hypotension, and may also be seen in conjunction with pulmonary emboli. Normal $ETCO_2$ values are generally given as 35-45mmHg. However, these are human figures, and while they correlate fairly closely with canine values, they are higher than would be expected in cats, where $ETCO_2$ is more commonly in the low to mid 30mmHg range. It is important to emphasise that these are the normal values in **conscious** patients; since all anaesthetic agents cause respiratory depression, it is usual to have higher values during general anaesthesia: $ETCO_2$ values in the dog are commonly in the low 50's mmHg at surgical planes of anaesthesia with isoflurane or sevoflurane. While this implies that the animal has a degree of respiratory depression, this kind of level is not generally detrimental in healthy patients.

Since respiratory depression during anaesthesia is dose dependent, it follows that the capnograph can give a rough indication of anaesthetic depth. For example, if you have a dog anaesthetised with isoflurane or sevoflurane and the $ETCO_2$ is 65mmHg, this implies that there is a greater degree of respiratory depression than one might expect at surgical planes of anaesthesia with these two agents, and should prompt an assessment, and possibly reduction, of anaesthetic depth. By far the commonest cause of high $ETCO_2$ is excessive anaesthetic depth (but remember, it will always go up a bit under anaesthesia). Unfortunately, not all animals have read the textbooks, and it is not that uncommon to get animals with higher-than-expected $ETCO_2$ values that do not appear excessively 'deep'. When this arises, it is a simple matter of ventilating the patient, and this will lower $ETCO_2$.

$ETCO_2$ values may be displayed in different units (mmHg, kPa, %) depending on the machine, although most will allow the user to alter the display to the units they wish to use. (1 kPa ≈ 1% ≈ 7.5 mmHg)

Several processes must be occurring for a capnogram to be generated:

1. The cells must be producing CO_2
2. Blood must be circulating to carry CO_2 from the tissues to the lungs
3. The patient must be breathing in order for the CO_2 to leave the lungs and be detected by the capnograph.
4. The breathing system must be working correctly to purge or recirculate exhaled gases

Thus, generation of a capnogram trace implies that blood is flowing around the body, and the patient is ventilating.

$ETCO_2$ versus $PaCO_2$

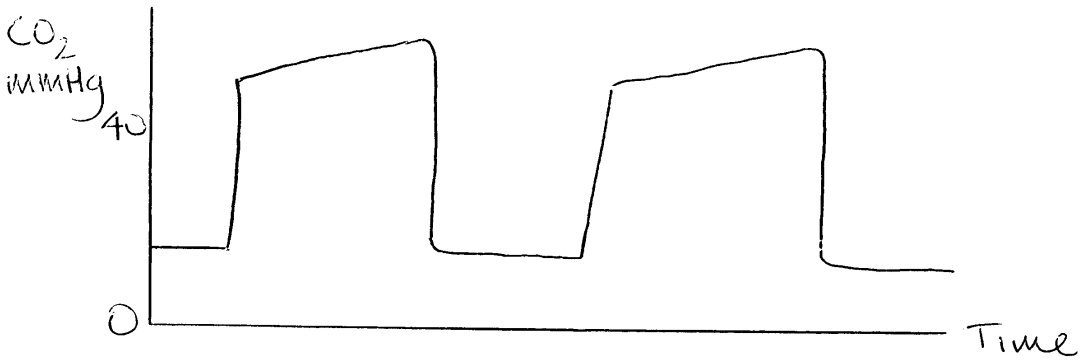
We have already seen that $ETCO_2$ should reflect $PaCO_2$ i.e. complete gas exchange is occurring inn the alveoli. However, there will always be a small difference between the 2 values with $PaCO_2$ being 2 – 5 mmHg greater. When ventilation perfusion mismatching occurs, the difference can increase markedly and the value can be used as an index of the amount of alveolar deadspace i.e. areas of lung which are not participating in gas exchange. Gas exhaled from these non-perfused alveoli will have no carbon dioxide in them and therefore will dilute gas from alveoli in which gas exchanged has occurred, thus lowering the ET CO_2.

From this, in most patients it is adequate to measure $ETCO_2$ as a marker of ventilation. However, in a critical care setting, Pa CO_2 is preferred. The $ETCO_2$ value is still useful as it can be used to monitor trends rather than actual values.

Characteristic patterns

In addition to quantifying the adequacy of ventilatory function, the configuration of the capnogram can also provide useful information, with characteristic patterns being associated with certain events:

a) Rebreathing capnogram

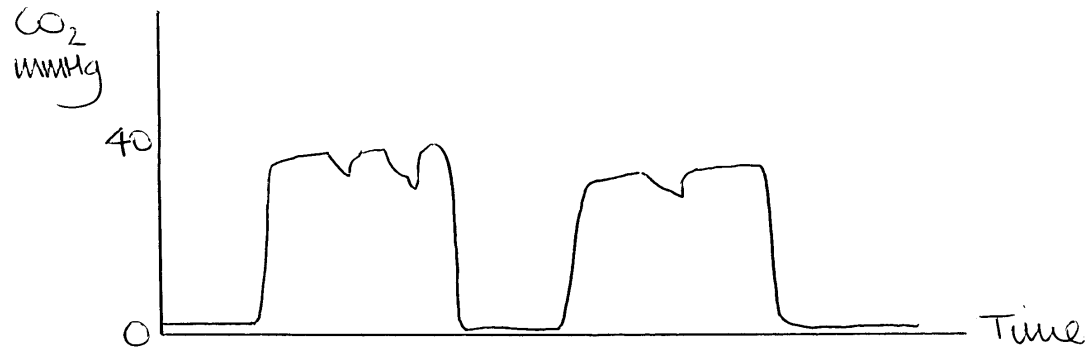


In this diagram, it can be seen that the trace does not reach the baseline during inspiration, i.e. there is CO_2 in the inspired gas. This may be due to a number of things:

- inadequate fresh gas flow in a non-rebreathing system
- disconnected inner tube in a coaxial breathing system (Bain, Lack)
- exhausted soda lime in a rebreathing system
- faulty unidirectional valve in a Circle system
- excessive apparatus dead space
- 'channelling' of gases over the soda lime in an improperly packed To & Fro

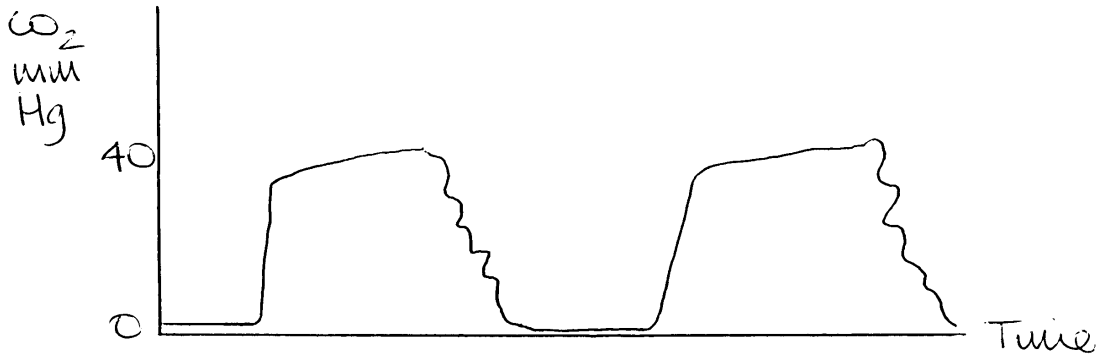
It is not quite so straightforward as this, and faulty unidirectional valves in a Circle system can illicit 'signature' capnograms. It is enough to know however, that if the trace does not reach the baseline then some form of rebreathing must be occurring.

b) ‘Curare’ capnogram



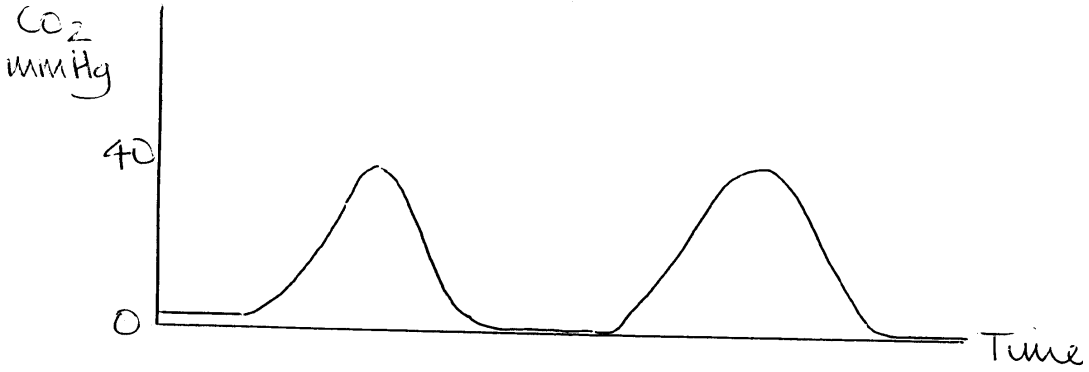
In this diagram, a number of dips, or clefts, can be seen along the alveolar plateau of each breath. This is fairly characteristic of patients attempting to take a spontaneous breath during artificial ventilation (i.e. the patient is being mechanically ventilated but still tries to breath by itself). It is commonly termed a ‘curare capnogram’, because curare is a neuromuscular blocking drug, and this pattern is often the first indication that muscle relaxation is wearing off, and an addition dose of relaxant needs to be administered.

c) Cardiogenic oscillations



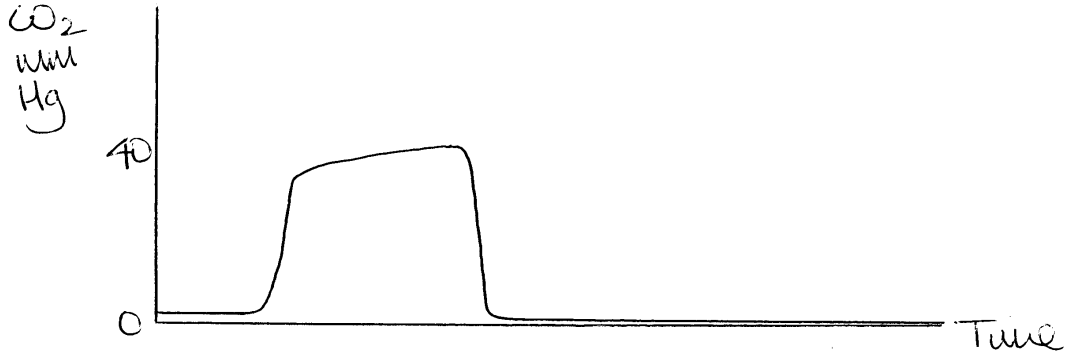
On the downstroke of this trace can be seen a number of undulations. This may be mistaken for a curare capnogram, but, if it were that, the irregularities would be seen during the alveolar plateau phase, whereas, in this trace, the undulations are all on the downstroke of the trace, not the plateau. These are called cardiogenic oscillations, and are due to the heart beating against the lung, and ‘pushing out’ small additional volumes of gas with each beat, thereby transiently increasing the CO_2 concentration on the trace. Cardiogenic oscillations are typically seen during slow spontaneous respiration, and are of no clinical consequence.

d) Expiratory resistance



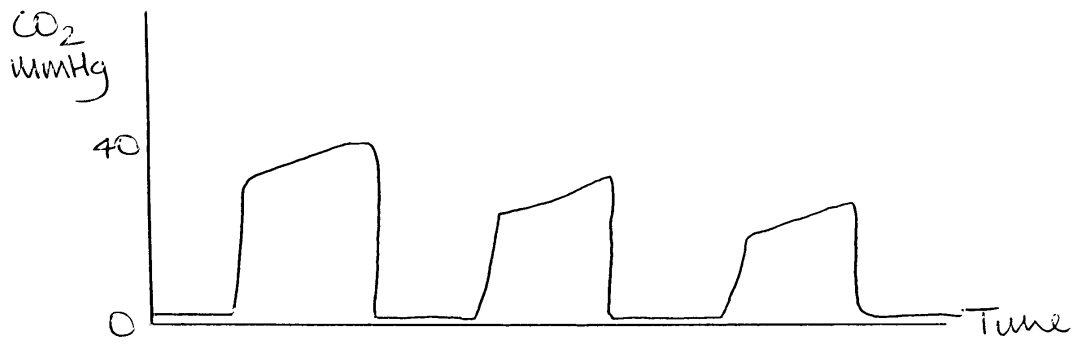
This (shark fin) trace shows a delayed upstroke (phase II) on the capnogram – instead of being the normal almost vertical line, it is slanted. This is the phase of ventilation when the patient is breathing out, and a trace such as this demonstrates a delay in expiration of gas. This is classically associated with airway obstruction, e.g. kinked or blocked endotracheal tube, asthma or other causes of bronchoconstriction. With increased expiratory resistance it is also common that an alveolar plateau is not reached.

e) Flat line capnogram



A flat line on the capnogram following a normal trace indicates either that the patient is apnoeic, or there has been a disconnection from the breathing system.

d) Progressively declining capnogram



A trace such as this showing a progressive decline in the height of adjacent capnograms may indicate hyperventilation (e.g. in response to a particularly noxious stimulus during surgery), or a gradual reduction in blood flow to the lungs (e.g. pulmonary embolus).

Capnometry

Some machines do not display a graphical trace of the CO_2 but merely report an $ETCO_2$ value. These are referred to as **capnometers**, and, although they are often cheaper than capnographs, the value of the information they supply is limited as the characteristic graph patterns cannot be seen. All capnographs are capnometers (i.e. all capnographs display an $ETCO_2$ value), but capnometers are not capnographs - i.e. they don't display a capnogram.

Anaesthetic gas monitoring

Volatile agents and nitrous oxide can also be measured by some multiparameter monitors. These monitors measure the amount of each gas in the inspired mixture and also the end tidal gas pressures – in a similar way to carbon dioxide measurement.

Inspired concentrations – should match what is dialled up on the anaesthetic machine
Expired concentrations – give an 'indication' of concentrations at the level of the brain.

These monitors be subject to some interference – methane from large animals, and propellants in some inhaled medications e.g. salbutamol

Conclusion

Capnography is likely to be the next 'big thing' to hit the veterinary anaesthesia market. To date, its use has been somewhat limited by the costs of the equipment, but second hand machines are now becoming more readily available.

Further reading

There is an excellent on-line resource for capnography at:
www.capnography.com