Keith Simpson BVSc MRCVS MIET(Electronics)

Keith Simpson is a veterinary surgeon and electronics engineer and runs a company called Vetronic Services. For 15 years after qualifying from Bristol University School of Veterinary Sciences, Keith was in mixed and small animal practice. In 2001 he left mainstream practice to concentrate on designing ventilators and monitoring equipment for the veterinary market.

Declaration of Interest

Keith Simpson is Managing Director of Vetronic Services Ltd, a company involved with the design, manufacture and sale of ventilators and monitoring equipment. All information presented in this article relating to equipment is non-specific and does not favour Vetronic Services products over any others. Any photographs in this series of articles in which the Vetronic name appears are used to illustrate a physiological principle rather than for commercial gain.

To cite this article, use either
DOI: 10.1111/vnj.12191 or Veterinary Nursing Journal VOL 29 pp358–361

Capnography for veterinary nurses – Part 1: The basics

Keith Simpson BVSc MRCVS MIET(Electronics)
Vetronic Services Ltd, 12 Henleys Business Park, Manor Road, Abbotskerswell, Newton Abbot, Devon TQ12 5NF, UK

Capnography – the measurement of CO_2 in exhaled air (also called end-tidal CO_2) – is one of the most useful anaesthetic monitoring modalities available and it can impart a lot of information about the patient's status and well-being. However, it is still shrouded in some mystery and it can take a certain amount of knowledge to interpret and use properly. This series of articles aims to look at capnography from a nurse's point of view, explaining the physiology involved so that judgements and decisions can be made based on a firm understanding of the processes.

Physiology of CO_2 production

Fundamentally, the basis of capnography is simple: cells produce CO_2 which is taken to the lungs and expelled from the body in exhaled respiration. To start, we need to revise a little basic biochemistry.

Cells respire – that is, they take in oxygen, burn sugars and release energy and CO_2 as a by-product. All living cells respire so there is a continual requirement for oxygen and a continual production of CO_2 by the body. The rate of CO_2 production is directly related to metabolic rate, so it follows that, if an animal is running, the metabolic rate will be greater than if that animal were curled up asleep. Most of the patients encountered in veterinary practice will be monitored in a fairly flat metabolic state, i.e. asleep, with no variation in exertion or effort and hence no variation in metabolic rate. There are some situations where this is not true, but we will cover those later.

For now, hold on to the first rule of capnography:

IN A RESTING ANIMAL CO_2 PRODUCTION IS CONSTANT

In making decisions at a clinical level this is probably the most important thing you need to know.

All of the CO_2 produced in the cells has to be removed, and venous blood returns to the right side of the heart rich in CO_2 (about 50 mmHg partial pressure) and goes via the pulmonary artery to the lungs. Here, CO_2 diffuses into the alveoli until the levels in the alveoli and pulmonary circulation are equal. The blood leaving the lungs is now rich in newly acquired oxygen and has CO_2 levels of around 40 mmHg partial pressure.

Blood travelling away from the lungs has not lost all of its CO_2 (50 mmHg went in, 40 mmHg came out) and the amount left in the blood that returns to the left side of the heart is at the same level as in the alveoli. So here's our second rule of capnography:

END-TIDAL CO_2 REFLECTS ARTERIAL CO_2

Most of the time it reflects it very closely (within 1–2 mmHg) so we can use this fact. The level of CO_2 in arterial blood is referred to as $PaCO_2$ and the level of CO_2 in the alveoli is referred to as $PACO_2$.

We mentioned partial pressures of CO_2 above. Partial pressures tend to be a bit confusing, but all you really need to know is that **the number represents the amount of CO_2 carried by the blood**. The higher the number, the more CO_2 there is. **Box 1** gives a clearer explanation of partial pressures.

When we run blood gases to look at various parameters, it's this $PaCO_2$ that we look at as an indicator of normo-, hyper- or hypocapnia.

From our second rule, we know that end-tidal CO_2 closely reflects arterial CO_2, so capnography allows us to assess arterial oxygen status without taking a blood sample. That's one of the reasons it's so useful.

The units used to measure CO_2 levels vary and include mmHg, % and kPa. This could be confusing so, for clarification, see **Box 2**.

Why does the body need to control CO_2 levels?

What happens if CO_2 levels get too high or too low? CO_2 levels are very closely tied in with the regulation of pH in the blood. Changes in CO_2 levels cause changes in blood pH, which has dramatic effects on stimulation or depression of respiration, perfusion of blood through organs and carriage of oxygen. For all of these reasons, many homeostatic mechanisms work to keep the level of CO_2 in the blood at a constant level. Some of these homeostatic mechanisms are lost during anaesthesia so under those conditions it is important that the anaesthetist intervenes to keep end-tidal and hence arterial levels within a normal range.

Some examples of problems arising from failure to maintain normal levels (normocapnia) are:

- **Hypercapnia (excessive CO_2)** causing:
  - central depression/narcosis
  - cerebral vasodilatation and increased cranial pressure
  - peripheral vasodilatation by direct effect on vessels
  - secondary tachycardia, sweating and peripheral vasoconstriction via the sympathetic nervous system
- **Hypocapnia (reduced CO_2)** causing:
  - loss of respiratory drive
  - depression of myocardial contractility
  - potential for cardiac arrhythmias
  - change of haemoglobin dissociation curve reducing oxygen unloading.

From a nurse's perspective, the two main points here are that, if patients become hypercapnic, they are at risk from metabolic changes and central depression. If they become hypocapnic, they are at risk from the effects on the heart and failure to breathe properly.

Box 1. Partial pressure of gases – an explanation

The partial pressure of a gas in solution is the gas pressure required on the *outside* of that solution to stop further movement of the gas *into or out of* solution. It represents how much of the total pressure is due to that gas, hence partial pressure. It doesn't mean that the gas in solution is always in equilibrium with the outside world, because most of the time it can't equilibrate simply because it can't leave the blood vessel it is in because the walls are too thick.

Here's a CO_2 analogy:

Imagine a half-full lemonade bottle with the lid on tight. The partial pressure of CO_2 in the lemonade will be very high, but the CO_2 will remain in solution because it is balanced by the partial pressure of CO_2 in the small amount of air in the bottle. In this balanced state, if the pressure above the liquid is 850 mmHg and the CO_2 content in the air is 10%, then there will be a partial pressure of 85 mmHg of CO_2 in the air and in the lemonade.

When the lid is undone, the pressure at the surface changes to atmospheric pressure (760 mmHg) and the partial pressure of CO_2 in free air is only 0.04% or 0.3 mmHg so CO_2 begins to escape – we see all those bubbles rapidly rising to the surface because the pressure difference is massive (85 mmHg in the lemonade and only 0.3 mmHg in the air). If we leave the lid off, the lemonade will go completely flat because CO_2 will continue to leave until the partial pressure of CO_2 in the lemonade is the same as it is in air, only 0.3 mmHg. But, if we put the lid back on before that happens, the air between the lemonade and the top of the bottle will fill with CO_2 until the partial pressure of CO_2 in the air above the lemonade is the same as the partial pressure of CO_2 in the lemonade. It will remain perfectly in this state until the pressure changes again, which is why the lemonade doesn't go flat if you put the top back on.

Removing the lid in our analogy is the same as blood reaching the alveoli. The impenetrable walls of the artery (lid on) change to the freely permeable walls of the alveoli (lid off). Now there is a clear and easy pathway through the capillary endothelium, so CO_2 starts to leave the blood. But the CO_2 is diffusing into a closed space (like our closed bottle), so it stops when the pressure is equal. Blood then leaves the alveoli and the complete blood vessel walls (closed endothelium, lid on) prevent further CO_2 escape.

Box 2. CO_2 units – mmHg, % or kPa?

In the UK there seems to be no preferred CO_2 unit, although many training centres and veterinary schools seem to use mmHg. In the UK it doesn't matter which unit you prefer and most capnographs have the option to switch units if required. But to aid your understanding of mmHg versus %, here's how it works.

The average atmospheric pressure in the UK is 760 mmHg. If the reported CO_2 value is 40 mmHg, that represents $40/760 \times 100\% = 5.3\%$. In places such as Denver, Colorado, where the atmospheric pressure is much lower at around 625 mmHg, the same partial pressure of 40 mmHg would represent a percentage value of $40/625 \times 100\% = 6.4\%$. Denver is a bit of a special case, so for UK practices just use 760 mmHg as your standard atmospheric pressure reference. As a rough guide, conversion from mmHg to % is a division by 8 (the actual value should be division by 7.6 but 8 will get you close enough for making clinical decisions), e.g. 45 mmHg = 45/8 or approximately 5.5%.

In Scandinavia there seems to be a preference for using kPa as the unit of measure for capnography. This sounds even more confusing but in fact it isn't. Because atmospheric pressure in kPa is around 100 kPa (actually it is typically 101.3), it means that the partial pressure in kPa is practically the same as the number in per cent, i.e. $5.1\text{ kPa} = 5.1/101.3 \times 100\% = 5.03\%$.

For the level of measurement we are using, this error of less than 0.1% isn't worth worrying about, so (unless you live in Denver) we can take kPa as being the same as %.

In patients with a history of head injury, hypercapnia should be avoided to prevent increases in cranial pressure due to cerebral vasodilatation. It is for these reasons that CO_2 levels should be closely monitored.

The story so far

Now that we've cleared some early hurdles, let's recap what we know:

- In a resting animal, CO_2 production is constant.
- End-tidal CO_2 reflects arterial CO_2 therefore we can use end-tidal CO_2 as a good measure of arterial CO_2.
- It is important to keep arterial CO_2 within certain limits.
- CO_2 levels in mmHg and % are the same thing presented in different ways.
- The values of CO_2 in kPa and % are virtually the same.

Types of capnograph

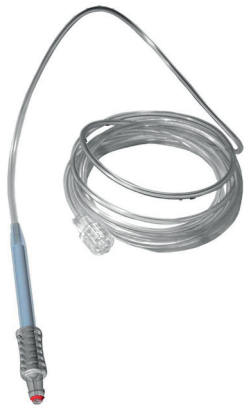
Capnographs are used to measure the expired CO_2 from the animal and come in two types – sidestream and mainstream. We should take a moment here to explore the difference between the two because knowing which one you are using is important, especially when your patients are really small.

The difference relates to the position of the CO_2 sensor. In a mainstream device it's placed at the head of the ET tube so that all the gas from the patient passes through it (**Figure 1**). In a sidestream device a small sampling tube continually extracts a small sample of the breath and analyses it using a sensor situated some way away (typically a metre or so) (**Figure 2**).

There are pros and cons associated with both mainstream and sidestream devices (**Table 1**) but, on balance, in most small animal practices a sidestream device is preferred because of its versatility and reduced vulnerability.

Photograph © Keith Simpson

Figure 1. A mainstream capnograph



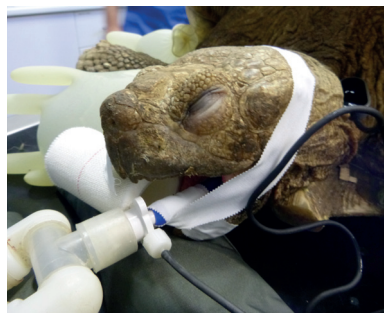
Photograph © Keith Simpson

Figure 2. A sidestream capnograph

Versatility

A sidestream device will generally support a lower patient weight limit, depending on its sampling rate, but probably no upper weight limit, so it can be used on all animals from kittens up to horses (**Figure 3**).

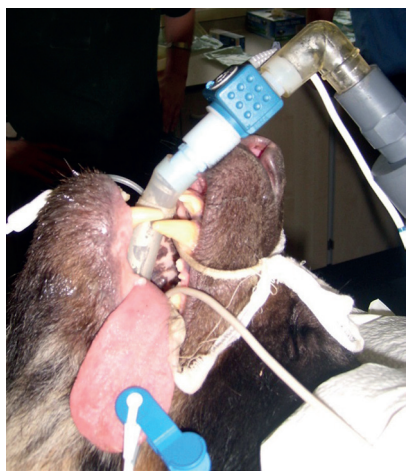
A mainstream unit will have a fixed dead-space volume and a fixed lumen size, so you cannot normally use it on something really big like a horse.



Photograph © Craig Hunt MRFCVS, Chine House

Figure 3. A sidestream capnograph in use

As these devices are usually designed for use with human patients, there are two sizes, adult and paediatric, so you can usually manage to monitor kittens and larger animals up to about 50 kg (**Figure 4**).



Photograph © Keith Simpson

Figure 4. A mainstream capnograph in use

Table 1. Mainstream and sidestream capnographs compared

	Mainstream	Sidestream
Sensor location	At end of ET tube	Remote from patient
Weight range	Limited Usually 1–5 kg (5 mm diameter) and 5–80 kg (15 mm diameter) Not easy to use with larger patients	150 g upwards No upper limit
Vulnerability	Very vulnerable to physical damage Relatively immune to water damage	Remote location means physical damage unlikely Very susceptible to water/fluid damage
Response time	Immediate – analysis is done at end of ET tube	Slight delay as gas needs to travel down sampling line
Cost	Typically £1,200–2,000	Typically £1,200–2,000

Vulnerability

It doesn't matter too much if an animal chews through the sidestream sampling tube – you just fit a new one. But, if an animal chews through a mainstream unit, that will mean a new unit and typically at least a £1,000 bill!

Sampling rate

As mentioned above, there is a lower weight limit on sidestream devices. What that lower weight limit is will depend on the actual sampling rate of the sidestream device. The sampling rate is the rate at which the unit sucks off gas, and, in most machines on the market, it is between 200 and 50 ml/minute. Why does this matter?

Most of the machines with a sampling rate of 200 or even 150 ml/minute are designed to monitor human patients, where removing 2–3 ml/second has no effect on the result. But imagine removing 2 ml/second from an animal with only a 1.5 ml tidal volume, e.g. a small lizard or small bird. The sampling flow will literally suck up all of the expired breath and draw in some additional gas, so what you will see will be very small pathetic waveforms. This is caused by a dilution effect and we will revisit this later. Capnograph manufacturers refer to the term 'micro-sampling', which is an industry standard and represents a sampling rate of 50 ml/minute. With careful use of low-dead-space ET connectors, this will allow correct monitoring of animals down to about 150 g.

Positioning

When using sidestream capnographs, it is important to think about the position of the sampling port. In fact, there are two main considerations here: *where* to connect the sampling line and *how* to connect the sampling line.

The sampling line should always be connected in the common gas flow portion of the circuit, i.e. in a part of the circuit where there is both inspired and expired gas flowing. Usually this is at the end of the ET tube, before it connects to the Y-piece connector. ET connectors with sidestream ports make this very easy (**Figure 5**).

For larger patients (over about 10 kg), an in-line adaptor should be used to connect the sampling line (**Figure 6**).

Now, here's the really important bit: **all sidestream capnographs hate fluid.** That's why they have complicated filters or water traps or special Nafion® tubing – anything to stop fluid getting into

Photograph © Keith Simpson

Figure 5. An ET connector with a sidestream port

Photograph © Keith Simpson

Figure 6. For larger patients, use an in-line adaptor to connect the sampling line

Photograph © Keith Simpson

Figure 7. Water doesn't flow uphill, so position your sampling take-off point high

the sensor. One of the early things we all learn about water is that it doesn't flow uphill. So position your sidestream sampling take-off point so it is always at the highest vertical point (**Figure 7**). That way, if any condensation or fluid should accumulate in the airway, it will not run down the side and into the sampling line. This simple fact could prolong your filter life by many months and protect your sidestream sensor against damage.

Summary

In this article we have looked at:

- the origin of CO_2 in the blood
- the relationship between CO_2, the blood and levels in end-tidal gas
- obtaining a capnogram.

In Part 2 we will explore the phases of the capnogram and what they represent. vnj

NEWS REVIEW

by Jean Turner

Shropshire vet becomes BVA President

John Blackwell, new BVA President

Farm animal and equine veterinary surgeon John Blackwell has been elected President of the British Veterinary Association (BVA) for 2014/2015. The ceremony took place during the Association's Members' Day, held in Manchester. Also elected were Sean Wensley as Junior Vice President and Robin Hargreaves as Senior Vice President.

Mr Blackwell graduated from the University of Liverpool Veterinary School in 1985. He is currently a director of Brownlow Veterinary Centre, a three-centre mixed practice in Ellesmere, Shropshire.

The theme for his Presidency at the BVA will be 'Delivering Change and Shaping the Future'.

Petplan Veterinary Awards 2015

Pet insurance provider Petplan is delighted to announce that nominations for the prestigious Petplan Veterinary Awards are now open.

Last year Petplan received more than 12,000 nominations, and every nominee was sent a certificate of recognition for their hard work. Nominations can be made at www.petplanvet.co.uk/vetawards until the closing date of 16 January 2015.

The awards ceremony will take place on 9 April 2015.