



Capnography

What does it mean and how can it help us?

Capnography is the study of a capnogram (trace information) produced from a Capnograph (instrument used to detect CO₂).

Capnographs measure the content of CO₂ in air and are typically used to monitor the inspired and expired CO₂ content of a patient's breath.

Why should the value of CO₂ be helpful in the monitoring of anaesthetised animals?

To answer this we need to look at the origin of CO₂ and its path in reaching the lungs and eventual expulsion during expiration.

All cells respire, meaning that they use oxygen to convert simple sugars to water, energy and carbon dioxide. So CO₂ or carbon dioxide is the waste product of all cells and so the whole body is constantly producing carbon dioxide as a waste product. This waste product must be removed at a constant rate otherwise it will accumulate and have detrimental effects. CO₂ is removed from the site of cellular respiration by the blood stream and carried in the venous return to the right side of the heart and then to the lungs. Here there is a large diffusion gradient so that CO₂ diffuses passively out of the blood stream and in to the alveoli. Once the concentration in the alveoli equilibrates with the concentration in the pulmonary artery there is no further loss of CO₂ and so blood returning from the lungs is at the same level as the concentration in the alveoli of the lungs. There is no further addition or loss of CO₂ as the blood passes into the left side of the heart and then out through the aorta and on to the arterial circulation. For this reason arterial blood CO₂ concentration will very closely match the end-expired CO₂ concentration. This is the main reason why end-tidal CO₂ values are so useful because they provide a close insight into the production and elimination of CO₂. Excepting lung pathology the end-tidal CO₂ closely follows the arterial CO₂ levels. So capnography provides a simple non-invasive method of assessing the arterial CO₂ concentration.

Good, but why bother assessing the arterial CO₂ concentration?

Because the level is closely controlled and normal mechanisms work to keep it at a level of around 35-40mm Hg (4.5-5%).

Consider the situation where an animal stops breathing temporarily. Cellular respiration is unaffected so CO₂ production continues at the normal rate. Circulation is unaffected so removal from the tissues continues at the normal rate. Removal in the lungs is stopped so arterial CO₂ levels will steadily rise. The same is true if an anaesthetised animal has reduced breathing or apnoea.



Some points on CO₂ production:

As far as everyday situations are concerned, consider the production of CO₂ to be at a constant rate. This is especially true for anaesthetised patients.
Only a true Hypothermia will lead to a reduction in CO₂ production
Only a true hyperthermia will lead to an increase in CO₂ production.
For most situations forget any influence changes in production might have. If your patient has a high end-tidal CO₂ this is due to a decreased breathing rate and NOT an increase in CO₂ production.

Use the end-tidal CO₂ value as a means of assessing the efficiency of the breathing process.

If the CO₂ value goes up (hypercapnia) then the animal is not breathing sufficiently.

If the CO₂ value goes down (hypocapnia) then the animal is over-breathing.

Insufficient breathing and over-breathing are general terms and need some means of being quantified. For this reason we need to think in terms of Minute Volume ventilation rather than just about Tidal Volume?

Why Minute Volume and what is it?

Minute Volume

This is not a term that many people use daily but it is the basis for controlling CO₂ and adjusting ventilation parameters during anaesthesia. Minute Volume is the product of Tidal Volume and Respiratory rate.

Minute Volume (L) = Tidal Volume (L) x Respiratory Rate (BPM)

So an animal breathing in 1.2L, 10 times a minute will have a minute volume of 12L. If the tidal volume does not change but the respiration rate increases to 14 then the Minute Volume will have increased to 16.8L.

It is the Minute Volume that determines whether the animal is breathing sufficiently. It is important that you know the Minute Volume requirement of your patients, not just their Tidal Volume. This will become apparent with an example later on.

So now we have some idea why we are measuring expired CO₂ and we have some idea of how it relates to the breathing of our patients, but how do we actually measure the CO₂ value?

Sidestream versus Mainstream

There are 2 basic technologies for measuring the content of CO₂ in a patients breath. Most of the time they are anaesthetised and they have an ET tube in place so we can connect our device at the end of the ET tube and measure the levels here. To do this we have 2 options:



1) Place the measurement device at the end of the ET tube and measure the amount of CO₂ in real time as the gas passes to and fro through our sensor. This is **mainstream** sampling and gives a very rapid result because there is no delay in the measurement. The sensor needs a minimum amount of gas to work with and this will limit how small the adaptor can be that fits on to the end of the ET tube. Because the volume of this measuring device is effectively stuck on the end of the ET tube it will increase the dead space volume. The typical increase in dead space volume of a standard main stream adaptor is about 10mls so this is not a problem for animals of 10kg or more. Those animals have a tidal volume of 100mls+ so the dead space is less than 10% of the TV which is OK. Below 10kg though a smaller adaptor is needed. The dead space of the infant adaptors of most mainstream units is 1.5mls, which means they are OK for animals down to about 1kg. Below this weight the dead space will have a marked impact on rebreathing with an increase in inspired CO₂. There will also be a marked diluting effect on the sampling if the dead space is too large.

At the other end of the scale the 15mm diameter limitation of the large airway adaptor may become a limiting factor. It would not be suitable for a horse or a camel because the small lumen would cause a resistance to inspiration and expiration making breathing very difficult. Thus our mainstream devices are really suited for animals in the range 2kg to 75kg.

2) Place the measurement device well away from the animal and connect a small sampling tube to the top of the ET tube. Use this sampling tube to draw off a continuous stream of gas and measure the CO₂ content of that gas as a representation of the airway gas. In practice this works well and the expensive part of the equipment is kept well away from the mouth of the patient. This method is called **sidestream** sampling and sidestream units vary in the rate at which they suck gas away from the ET tube. For sidestream units it is this withdrawal or sampling rate that is the limiting factor. There is no upper animal weight limit but there will always be a lower animal weight limit. How low this lower limit is will depend on the sampling or withdrawal rate of the device. Most medical systems and some veterinary systems that use medical parts sample at 200mls/minute. That's a little over 3mls per second, so imagine what will happen to any animal exhaling at less than 3mls per second. The sampling system will exceed the gas coming from the animal and so must drag in air from the breathing circuit as well. This causes dilution and leads to an under-estimation of the end-tidal CO₂ value. Also, if there is any increase in size of the airway this will affect the sampling as well and lead to rounding of the waveform and low end-tidal values.

The lower the sampling rate for any given set up then the lower the size of animal that can be monitored using the sidestream method. Systems designed for veterinary use have sampling rates of 50ml/minute or less. This is often referred to as micro-sampling. Since 50mls/min is a quarter of 200mls/min, micro-sampling devices can monitor animals a quarter of the size of a unit with 200mls/min sampling. In practice the lower limit of animal weights that can be monitored using a sidestream device running at



50ml/minute is of the order of 100g. To achieve this you must use Low Dead Space ET connectors and a minimum bore (0.8mm) diameter tubing for the sampling line.

Limitations of sidestream capnography will manifest themselves as changes in the capnogram. Most notably the capnogram will become distorted by dilution effects.

Therefore dilution effects are seen in both sidestream and mainstream systems and it is important to understand what these effects look like and what they do to the results obtained.

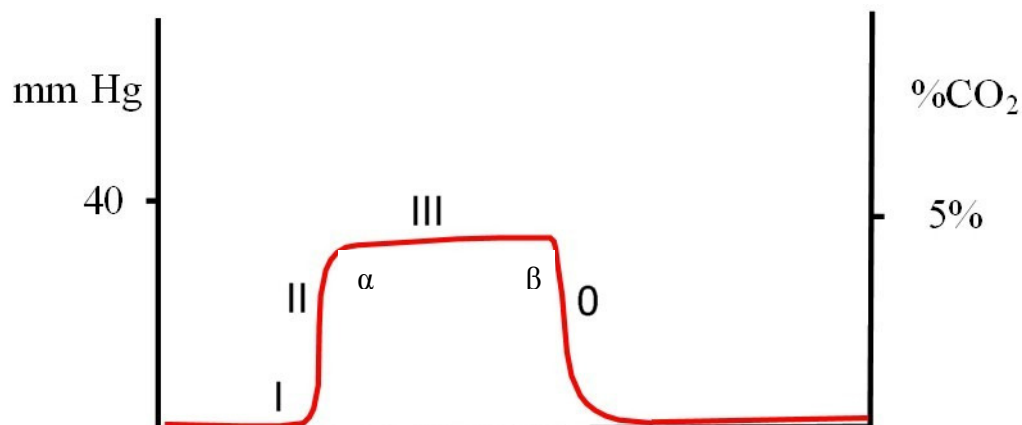
For a full explanation of the effects in sidestream sampling (the most complex to understand), see the document "**Explanation of how the sidestream sampling rate has an effect on the accuracy of the sample**"

The two take-home messages from this document are that the initial changes are to the rise and fall phases (II and 0) of the capnogram followed by loss of the plateau phase.

A rapid respiratory rate in some exotic species may be so fast that it is difficult to tell if there is a true plateau phase, so how can you spot a poorly sampled side-stream capnogram?

Before we can answer that question we need to know what a normal capnogram should look like.

A capnogram trace is divided into 4 phases. The following picture shows how a normal trace should look:



Phase 0 is inspiration – low level/atmospheric levels of CO₂ ~ 0.04 %

Phase I is beginning of expiration – removal of gas from anatomical dead space

Phase II is mixing of expired gas and dead space gas



Phase III - expired gas consists entirely of alveolar gas. Gentle slope to this phase

The alpha angle (α) is the angle between phase II and phase III

The beta angle (β) is the angle between phase III and phase 0.

This is what a typical capnogram should look like.

Note the very square appearance of the trace with a rapid rise in phase II and a rapid fall in phase 0. Note how sharp the alpha and beta angles are - there is a very obvious change in concentration at these points.

The presence of phase III indicates that the alveolar CO₂ has been expired and is a good feature to look for when assessing the validity of a trace.

When a Capnograph reports CO₂ values from a patient there are usually 2 values reported. One is referred to as the end-tidal CO₂ value and the other is referred to as the inspired CO₂ value.

As described earlier the end-tidal CO₂ value represents the amount of CO₂ at the end of expiration and follows closely the patient's arterial value. When patients are referred to as Hypocapnic or Hypercapnic it is this value that is being used for that assessment.

The inspired value of CO₂ should be zero or very close to zero. Air contains 0.04% CO₂, so this will not be measured by a standard capnograph and will be read as zero. Any value above zero indicates a degree of re-breathing of the patient's own gas. Depending on the setup, values of 1-3 mmHg are typical in most small animal circuits. Values above 4mmHg should be investigated.

The reporting of the end-tidal value can vary with different machines. Some machines will simply report the maximum value of CO₂ measured during the expiratory phase, whilst others will report the level of CO₂ at the turning point of phase III to phase 0. The latter is typically the most accurate as it ignores spurious values during expiration.

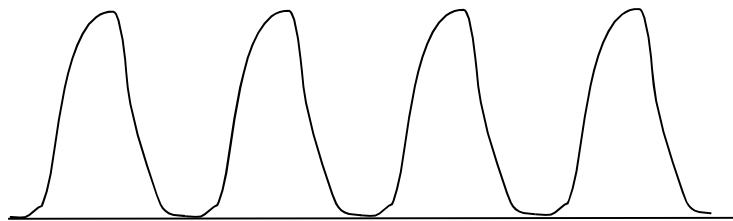
Normal end-tidal CO₂ values for most mammals and birds is a level of 35-40mmHg or 4.5-5.0%. Values in reptiles will be approximately similar particularly if the animal is at room temperature. Be aware though that being cold-blooded, reptiles metabolic rate and therefore CO₂ production will be lower at lower temperatures and that an end-tidal CO₂ of 5% in a reptile with a core temperature of 26°C may indicate hypercapnia.

The duration of phase II is limited by the rate at which the patient can expire. Similarly the duration of phase 0 is limited by the rate at which the patient can inspire. Typically these phases will not change very much in their profile unless there are large changes in respiratory rate. The phase that shows the biggest variation in duration is phase III since this includes the period of rest between end of expiration and beginning of inspiration. As the respiratory rate



increases phase III will get shorter until, in very rapidly breathing animals it can be hard to distinguish.

Here is a capnogram trace from a rapidly breathing animal:



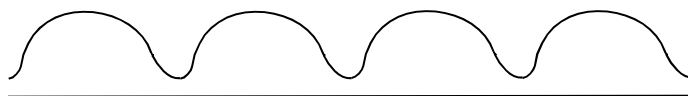
ET CO₂ = 4.0%

Because of the fast breathing rate there is no obvious plateau phase but the curve has the following characteristics:

- A rapid rise to phase II
- A distinct alpha angle at the end of phase II.
- A rapid fall in phase 0
- A return to baseline
- A normal end-tidal value

The effect of having too large a sampling rate or too large an aperture will lead to averaging of the data and will turn the nice sharp rise and fall profiles to rounded-off mole-hills:

Here is the same animal sampled inappropriately using a sidestream device:



ET = 2.3%

Notice the following:

- A slow rising phase II which has an indistinct change to phase III
- Loss of a clear alpha angle
- A slow fall in phase 0
- A non-return to baseline
- A reduced end-tidal value



The above example is an extreme case but you should always look for:

- A plateau phase
- A sharp rise in phase II
- A clear alpha angle
- A sharp fall in phase 0

Here are the cardinal rules:

Have you got a plateau phase to the capnogram?

Yes - then the end-tidal value is OK

No - the end-tidal value may be wrong so look at phases II and 0

Are phases II and 0 normal, with rapid rise times and a recognisable alpha and beta angle?

Yes- the end-tidal value is OK

No - the sample is diluted and the end-tidal value is wrong (too low)

How do you optimise the sampling process using a sidestream capnograph?

Use the lowest sidestream sampling rate possible

Sample as close to the end of the ET tube as possible. Use ET connectors with side-ports:



If possible use low dead-space ET connectors. This reduces turbulence and dilution and effectively moves the sampling point down into the ET tube.

Now we understand the origin of the capnogram and what can affect the suitability of the trace that we obtain, we can look at abnormalities of the capnogram and work out what is going wrong based on the principles we have learned.



Capnograms - deviation from the normal and how to respond

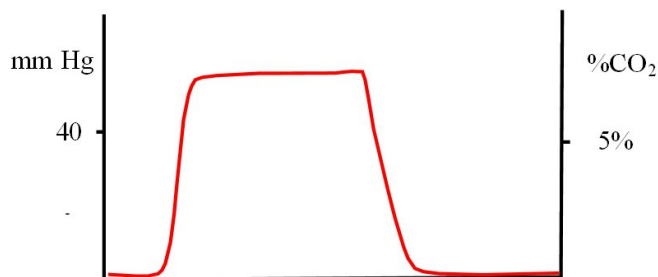
There are a number of ways that capnograms can deviate from the expected trace. They can change in terms of their height, indicating either Hypercapnia or Hypocapnia and they can change in terms of their profile, whilst still maintaining a normocapnic value.

1 Hypercapnia

This means an increase in the expired CO₂ levels above normal.

This is probably the most commonly encountered change when monitoring an animal's CO₂ level.

The capnogram looks like this:



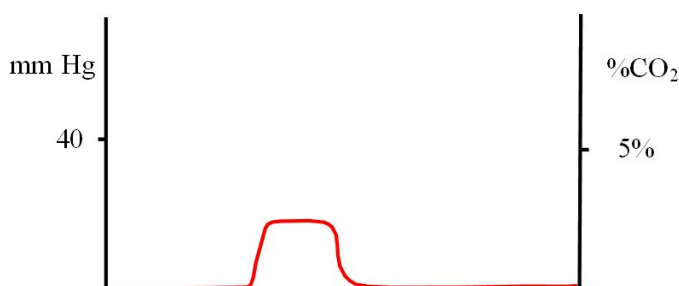
The capnogram has a normal profile but the value of the expired CO₂ is too high.

Since production of CO₂ in the body is constant this must represent a failure to remove CO₂ fast enough. Since CO₂ is removed by breathing it follows that the minute volume of the patient is too low. If an animal is spontaneously breathing then there are no adjustments you can make to alter either the Tidal Volume or Respiratory rate. For this reason if you see this change in a patient that is spontaneously breathing, give a few extra breaths by squeezing the bag. This will increase the minute volume ventilation of the patient and reduce the end-tidal CO₂. If the hypercapnia is persistent then repeated manual or mechanical IPPV is indicated.

2 Hypocapnia

This means a fall in the expired CO₂ levels below normal.

This is less common in spontaneously breathing patients and occurs most commonly in ventilated patients.



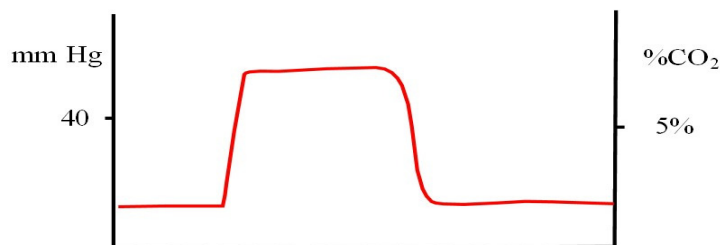


The capnogram has a normal profile but the value of the expired CO₂ is too low. Since production of CO₂ is constant, this must represent an excessive rate of removal of CO₂ from the patient and it follows that the minute volume of the patient is too high. This could be the response to a tachypnoea but is most commonly seen in excessive minute volume ventilation by manual IPPV or mechanical ventilators.

The response should be to reduce the minute volume. The best way to do this is to reduce the frequency of ventilation, i.e reduce the respiratory rate.

Be aware of other possible causes of abrupt falls in CO₂ values - see later

3 An increase in Inspired CO₂



Here the shape and size of the capnogram are normal but the baseline of the capnogram does not return to zero. This means that during the inspiratory phase the patient is inhaling gas with a CO₂ content of about 2%. This has an additive effect on the end-tidal CO₂ value which is now reading about 7%. Whilst this is a true hypercapnia, it can be seen that by reducing the inspired CO₂ to zero, the end-tidal value would then fall within normal limits at around 5%. Attention must be made to the anaesthetic circuit to look for causes of this re-breathing. The approach is different depending on whether the circuit is rebreathing or non-rebreathing.

Non-rebreathing anaesthetic circuit (non-circle)

- Fresh Gas Flow (FGF) rate too low
- Excessive dead space volume

Remember that the FGF rate is determined by the minute volume requirement of the animal and **not the weight** of the animal. A simple example will illustrate this.

Take a 5kg cat on a simple T-Piece system.

The tidal volume can be estimated as 50mls.

The respiratory rate for the cat is typically 20 breaths per minute

The minute volume is therefore $50 \times 20 = 1000\text{mls} = 1\text{L}$. Taking into account the circuit factor for a T-piece system as 3, you would set your FGF on the anaesthetic machine to 3L.min



Take a 5kg rabbit on a simple T-Piece system
The tidal volume can be estimated as 50mls.
The respiratory rate for the rabbit is typically 40 breaths per minute
The minute volume is therefore $50 \times 40 = 2000\text{mls} = 2\text{L}$. Taking into account the circuit factor for a T-piece system as 3, you would set your FGF on the anaesthetic machine to 6L.min

So, to avoid rebreathing on a T-piece system a patient with a spontaneous respiratory rate of 40 bpm needs a 6L/min FGF rate. Whereas a patient with a spontaneous respiratory rate of 20 bpm needs only 3L/min even though both patients WEIGH THE SAME.

Circle system (re-breathing anaesthetic circuit)

- Exhausted soda-lime
- Excessive dead-space volume

4 An increase in the duration of phases II & III of the capnogram



Here the increased duration of phases II and III make it look as if the capnogram has been skewed to the right. It has taken longer for the patient to exhale because there is resistance in the expiratory circuit. This can be due to many possible factors

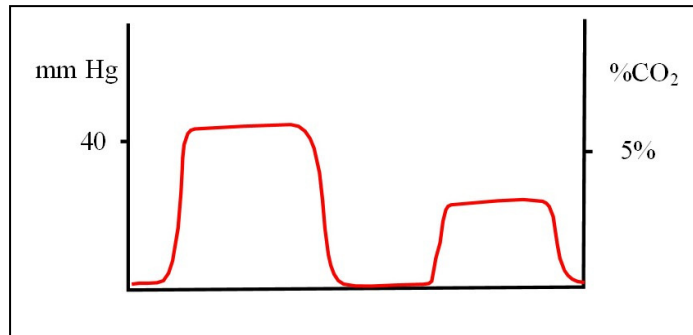
Mucous in the ET tube

Kink in the ET tube

Faulty valve in the expiratory circuit - circle or ADE system

Functional blockage in the upper airways

5 Abrupt fall in end-tidal CO₂ level

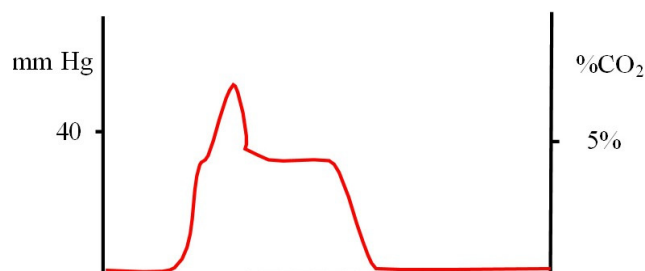


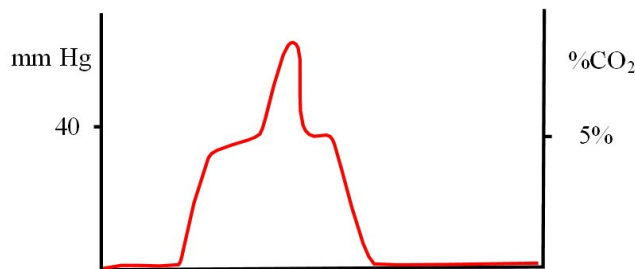
Here the fall in end-tidal CO₂ has been sudden - from one breath to another. This is not the same as seen with Hypocapnia, even though what is shown is a reduced end-tidal CO₂ value. How can this occur?

Since CO₂ production in the body is constant this cannot be a fall in production. Also, since there has been good CO₂ exchange (the shape of the smaller capnogram is normal) it cannot be due to changes in respiration. So there must be less CO₂ reaching the lungs. The cause of such an abrupt change in CO₂ levels is seen with a sudden fall in cardiac output.

- Pulmonary artery compression by thoracic surgeon
- Pulmonary artery embolism
- Sudden haemorrhage
- Acute cardiac tamponade
- Cardiac compression by surgeon/posture

6 Differential Emptying

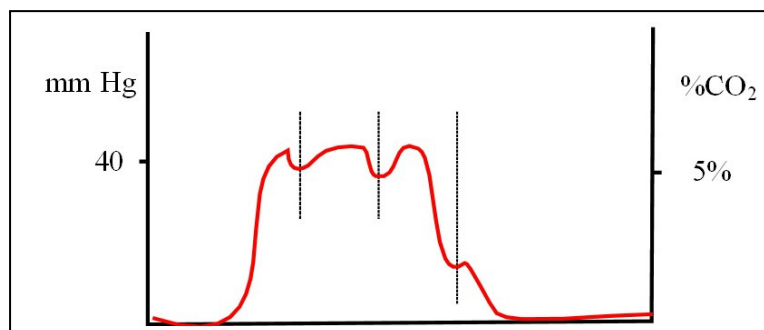




The two pictures represent the same thing - a basically normal capnogram with a large CO₂ spike superimposed on it. This is caused when a pocket of gas is trapped in a region of the lungs and is then released. The trapping leads to increased CO₂ levels which are then seen as a spike. This can happen when a blob of mucous or a foreign body blocks a small bronchus, or any airway below the carina. The same effect can also be seen with single-bronchus intubation because the non-intubated lung will have a much higher content of CO₂ which is entrained into the ET tube during expiration.

7 Cardiogenic oscillations

These can be seen in any animal where the beating of the heart causes areas of lungs to be compressed and thereby emptied and filled. The guide to the fact that this is happening is that the intervals between the oscillations are regular and in time with the heart beat. Typically seen in large dogs.



The vertical lines show the timings of the dips in CO₂. Note their regularity. Large single dips in the waveform often occur with ventilated animals that are making inspiratory efforts during the ventilator expiratory period.



Summary

The field of capnography is huge and there is much information to be gained from a standard trace. The information imparted by that trace and the action to be taken can be arrived at by applying sound basic principles coupled with an understanding of standard anaesthetic circuits.

Useful conversions:

760mmHg = 101.3kPa

5% CO₂ = 38mmHg = 5.1kPa