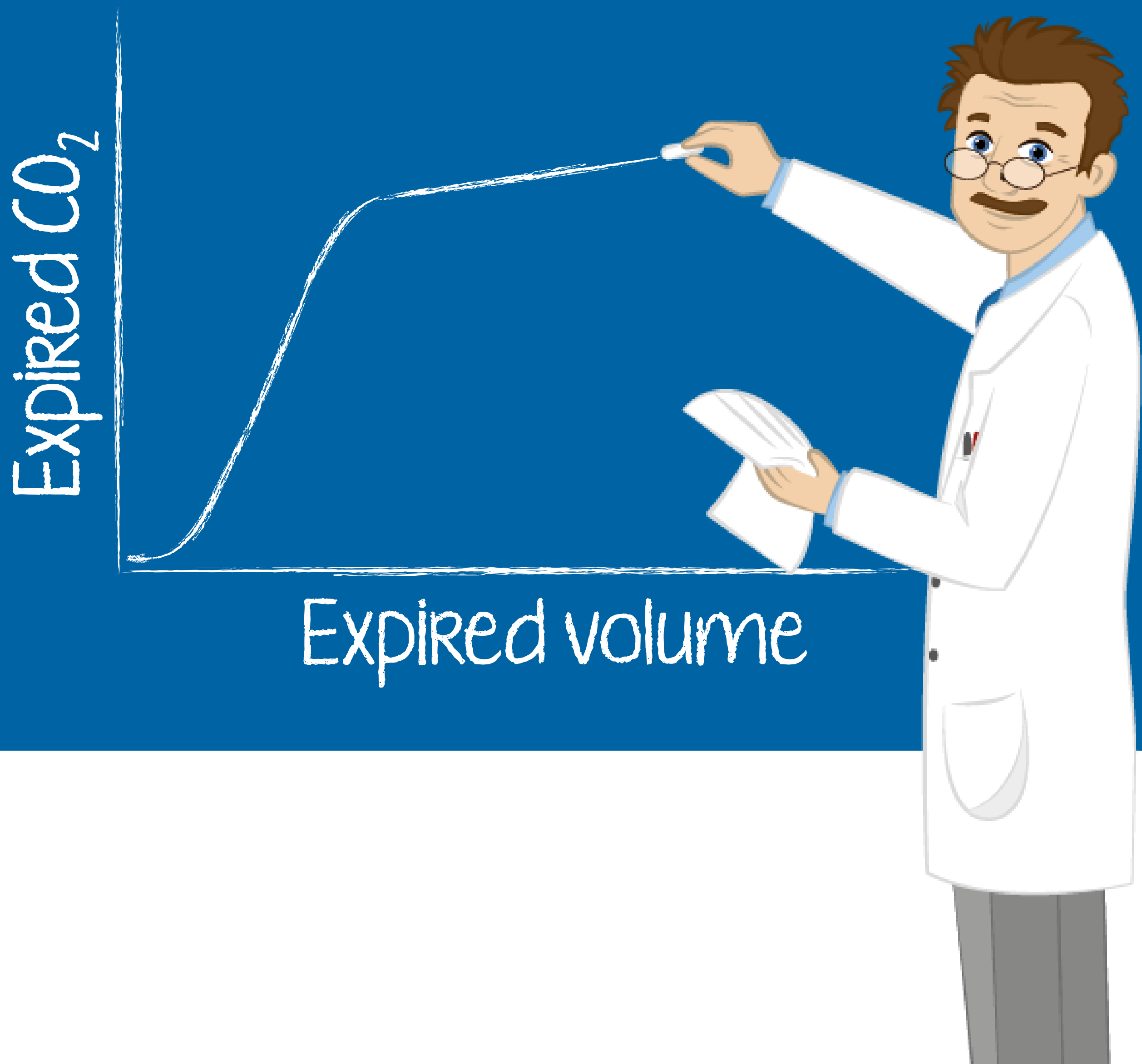
Volumetric Capnography



HAMILTON MEDICAL

Intelligent Ventilation since 1983

Content overview – 1/2

Content overview – 2/2

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Introduction

Carbon dioxide (CO_2) is the most abundant gas produced by the human body. CO_2 is the primary drive to breathe and a primary motivation for mechanically ventilating a patient. Monitoring the CO_2 level during respiration (capnography) is noninvasive, easy to do, relatively inexpensive, and has been studied extensively.

Capnography has improved over the last few decades thanks to the developement of faster infrared sensors that can measure CO_2 at the airway opening in realtime. By knowing how CO_2 behaves on its way from the bloodstream through the alveoli to the ambient air, physicians can obtain useful information about ventilation and perfusion.

There are two distinct types of capnography: Conventional, **time-based capnography** allows only qualitative and semi-quantitative, and sometimes misleading, measurements, so **volumetric capnography** has emerged as the preferred method to assess the quality and quantity of ventilation.

This ebook concentrates on the use of **volumetric capnography** for mechanically ventilated patients.

Benefits of volumetric capnography

- Improves, simplifies, and complements patient monitoring in relation to metabolism, circulation, and ventilation (V/Q)
- Provides information about the homogeneity or heterogeneity of the lungs
- Trend functions and reference loops allow for more comprehensive analysis of the patient condition
- Multiple clinical applications, such as detection of early signs of pulmonary emboli, COPD, ARDS, etc.
- Helps you optimize your ventilator settings
- Is easy to do and is relatively inexpensive

In short, volumetric capnography is a valuable tool to improve the ventilation quality and efficiency for your ventilated patients.

The volumetric capnogram

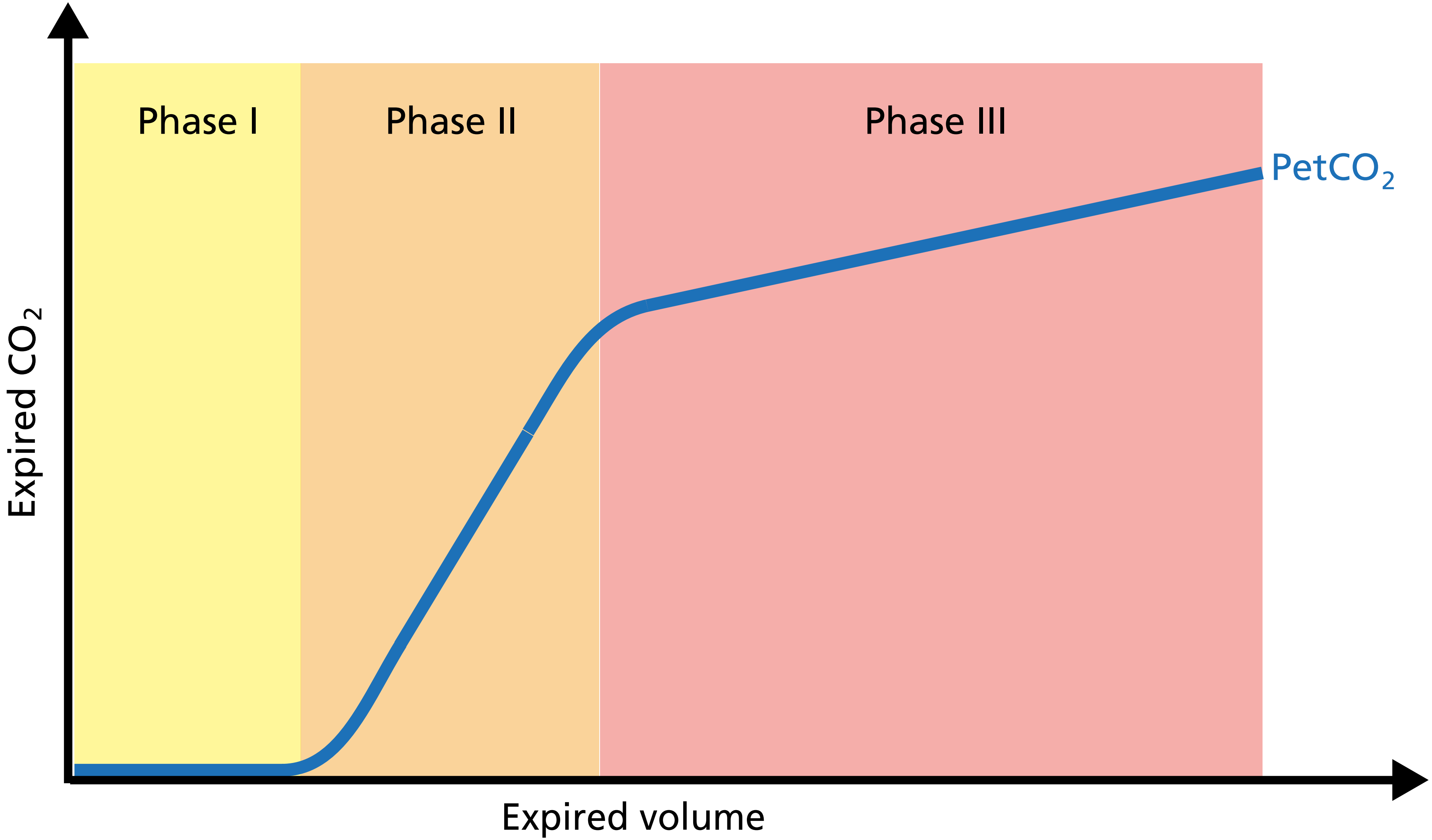
The three phases

The alveolar concentration of carbon dioxide (CO_2) is the result of metabolism, cardiac output, lung perfusion, and ventilation. Change in the concentration of CO_2 reflects perturbations in any or a combination of these factors. Volumetric capnography provides continuous monitoring of CO_2 production, ventilation/perfusion (V/Q) status, and airway patency, as well as function of the ventilator breathing circuit itself.

Expired gas receives CO_2 from three sequential compartments of the airways, forming three recognizable phases on the expired capnogram. A single breath curve in volumetric capnography exhibits these three characteristic phases of changing gas mixtures - they refer to the airway region in which they originate:

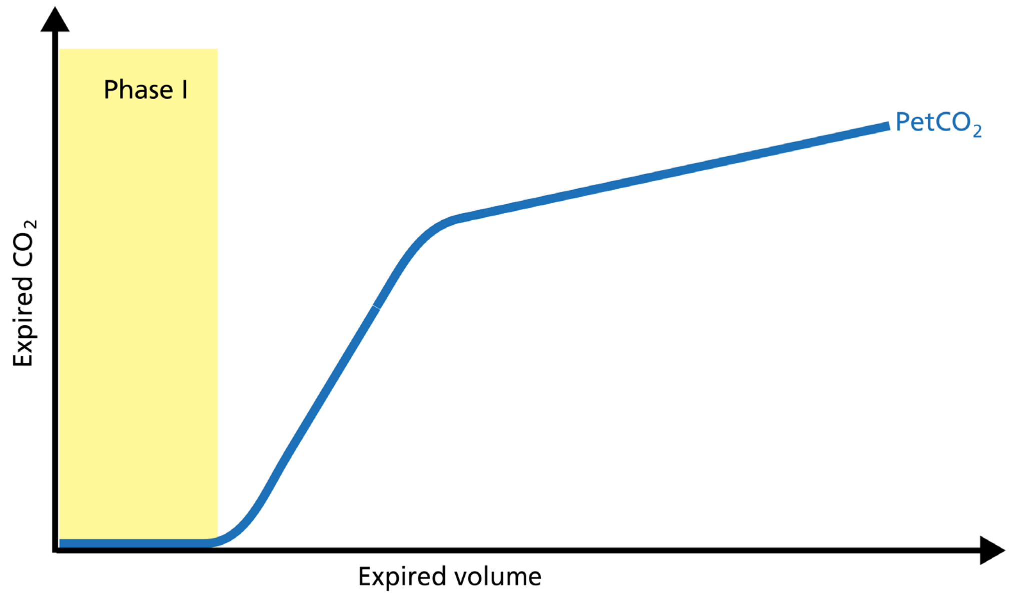
- Phase I - Anatomical dead space
- Phase II - Transition phase: gas from proximal lung areas and fast emptying lung areas
- Phase III - Plateau phase: gas from alveoli and slow emptying areas

Using features from each phase, physiologic measurements can be calculated.


Phase I
Phase II
Phase III
PetCO2
Expired CO2
Expired volume

Phase I – Anatomical dead space

The first gas that passes the sensor at the onset of expiration comes from the airways and the breathing circuit where no gas exchange has taken place = anatomical + artificial dead space. This gas usually does not contain any CO_2. Hence the graph shows movement along the X-axis (expired volume), but no gain in CO_2 on the Y-axis.

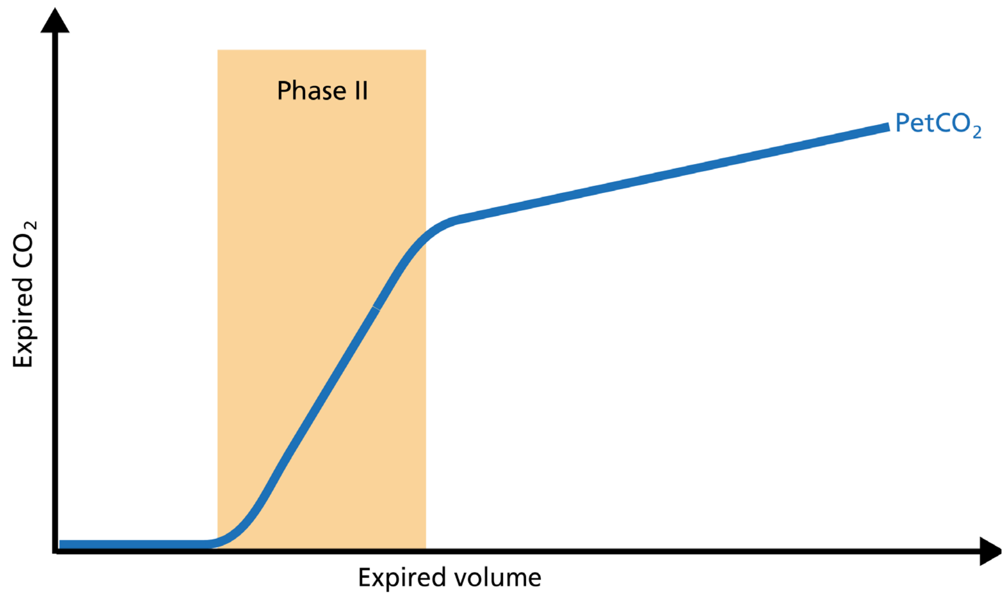


A prolonged Phase I indicates an increase in anatomical dead space ventilation (VD_{aw}).

Presence of CO_2 during Phase I indicates rebreathing or that the sensor needs to be recalibrated.

Phase II – Transition phase

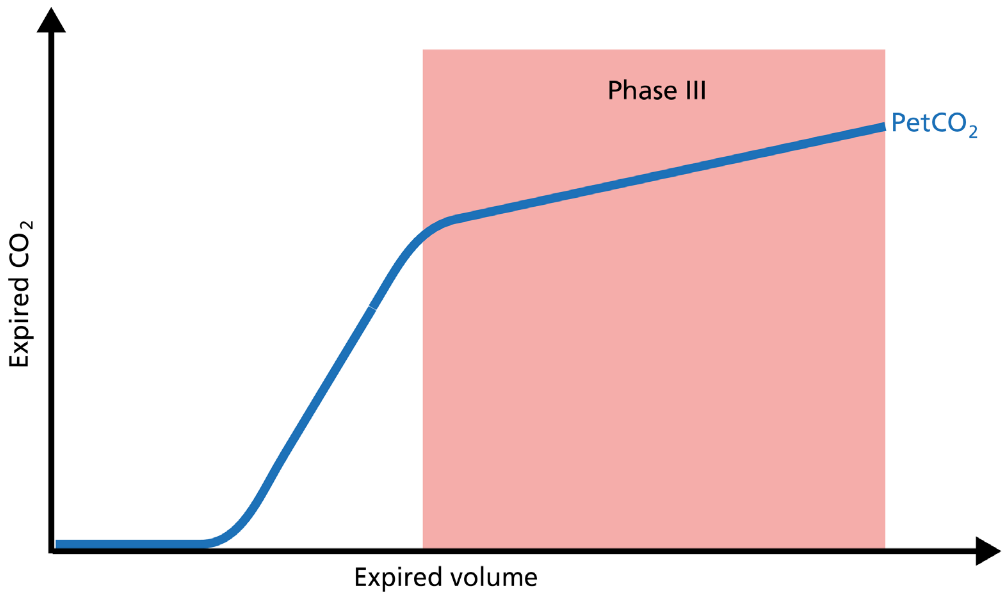
Phase II represents gas that is composed partially of distal airway volume and mixed with gas from fast emptying alveoli. The curve slope represents transition velocity between distal airway and alveolar gas – providing information about perfusion changes and also about airway resistances.



A prolonged Phase II can indicate an increase in airway resistance and/or a Ventilation/Perfusion (V/P) mismatch.

Phase III – Plateau phase

Phase III gas is entirely from the alveoli where gas exchange takes place. This phase is representative of gas distribution. The final CO_2 value in Phase III is called end-tidal CO_2 ($PetCO_2$).



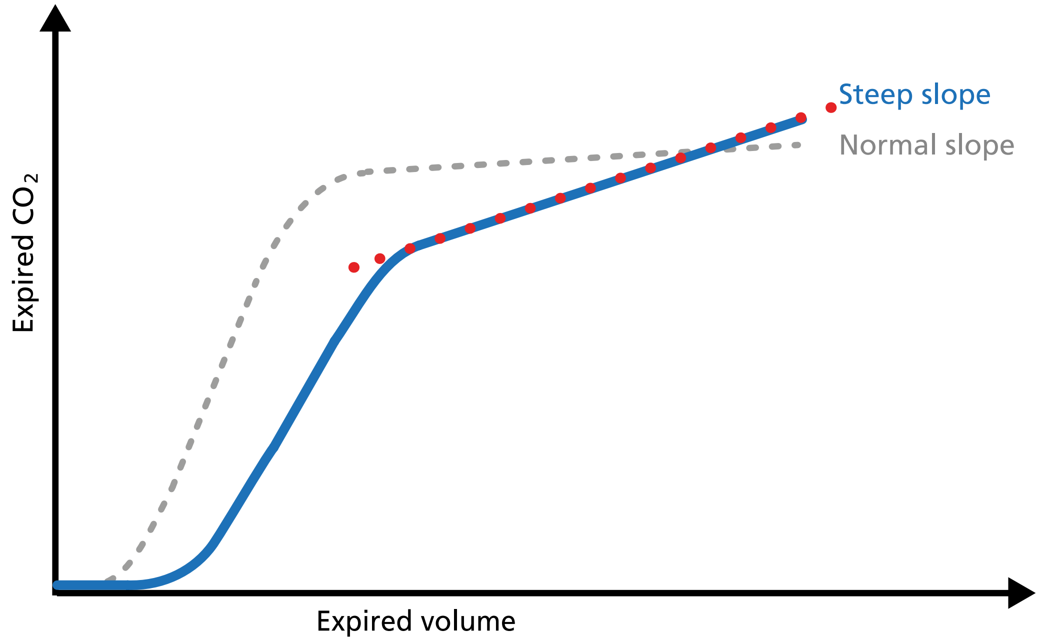
A steep slope in Phase III provides information about lung heterogeneity with some fast and some slow emptying lung areas.

For example, obstructed airway results in insufficiently ventilated alveoli, inducing high CO_2 values and increased time constants in this region.

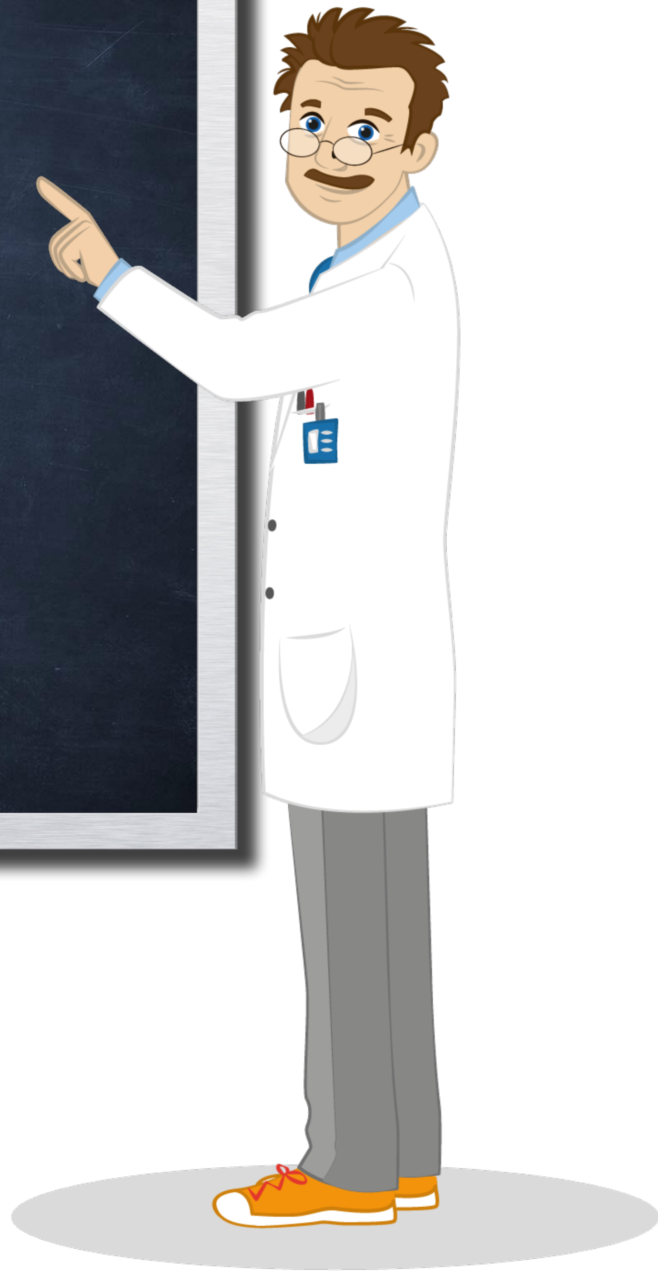
Slope of Phase III

The slope of Phase III is a characteristic of the volumetric capnogram shape. This slope is measured in the geometric center of the curve, which is defined as the middle two quarters lying between VD_{aw} and the end of exhalation.

A steep slope can be seen, for example, in COPD and ARDS patients.



Single breath CO_2 analysis



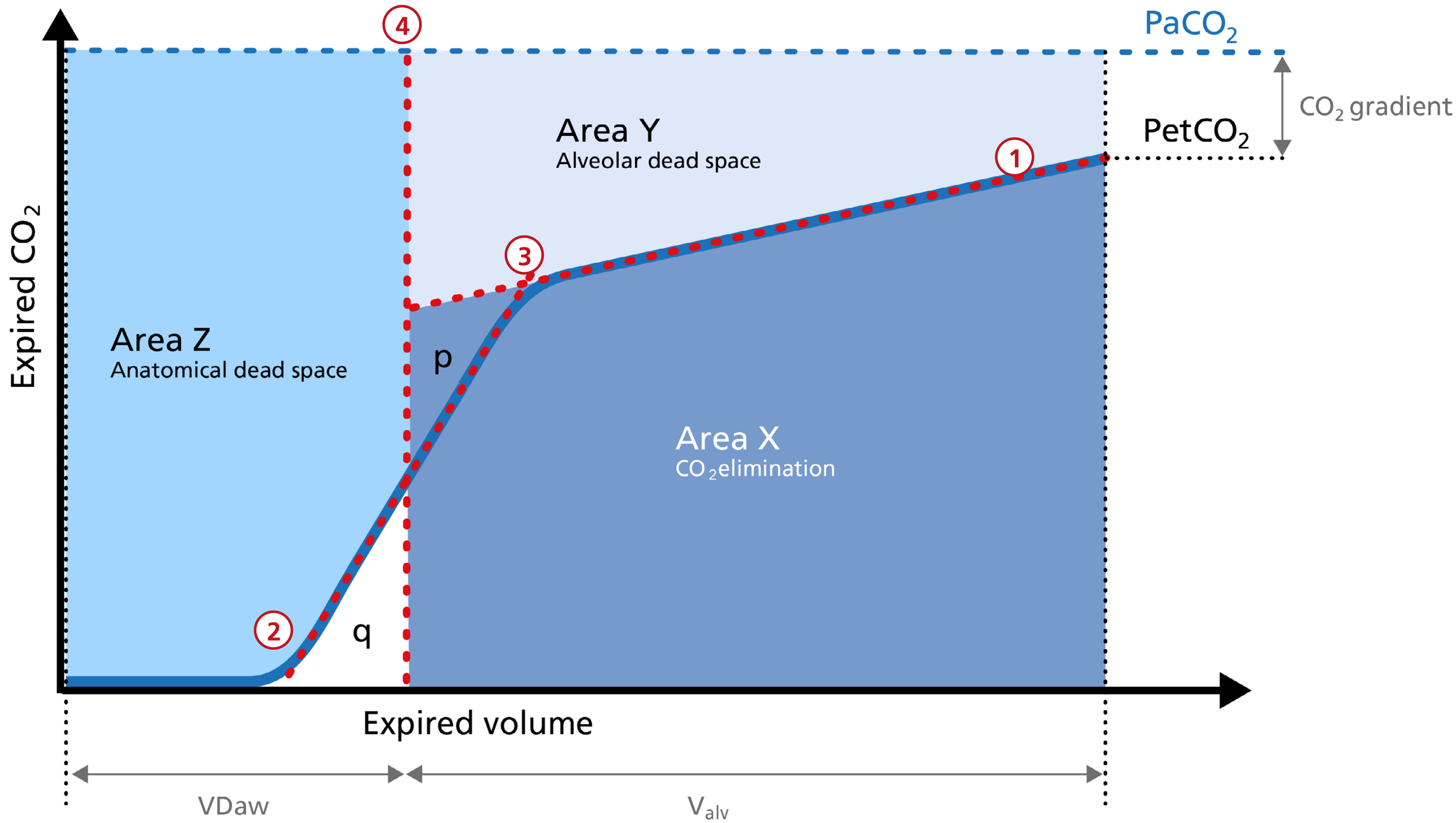
Insight into the patient's lung condition

The volumetric capnogram can also be divided into three areas:

- Area X - CO_2 elimination
- Area Y - Alveolar dead space
- Area Z - Anatomical dead space

The size of the areas, as well as the form of the curve, can give you more insight into the patient's lung condition regarding:

- Dead space fraction – VD_{aw}/VTE
- Alveolar minute ventilation – V'alv



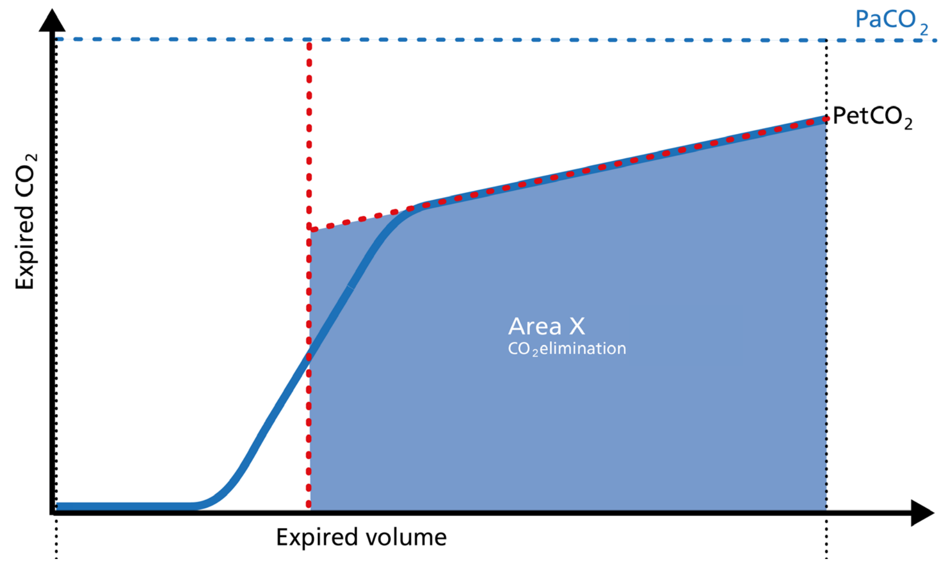
1. Slope of Phase III
2. Slope of Phase II
3. The intersection of lines 1 and 2 defines the limit between Phases II and III.
4. A perpendicular line is projected onto the x-axis and its position is adjusted until the areas ***p*** and ***q*** on both sides become equal.

Area X – CO_2 elimination ($V'CO_2$) – 1/2

Area X represents the actual volume of CO_2 exhaled in one breath ($VeCO_2$). Adding up all of the single breaths in one minute gives you the total elimination of CO_2 per minute ($V'CO_2$). If cardiac output, lung perfusion, and ventilation are stable, this is an assessment of the production of CO_2 called $V'CO_2$. The $V'CO_2$ value displayed on the ventilator can be affected by any change in CO_2 production, cardiac output, lung perfusion, and ventilation. It indicates instantly how the patient's gas exchange responds to a change in ventilator settings. Monitoring trends allows for detection of sudden and rapid changes in $V'CO_2$.

Decreasing $V'CO_2$

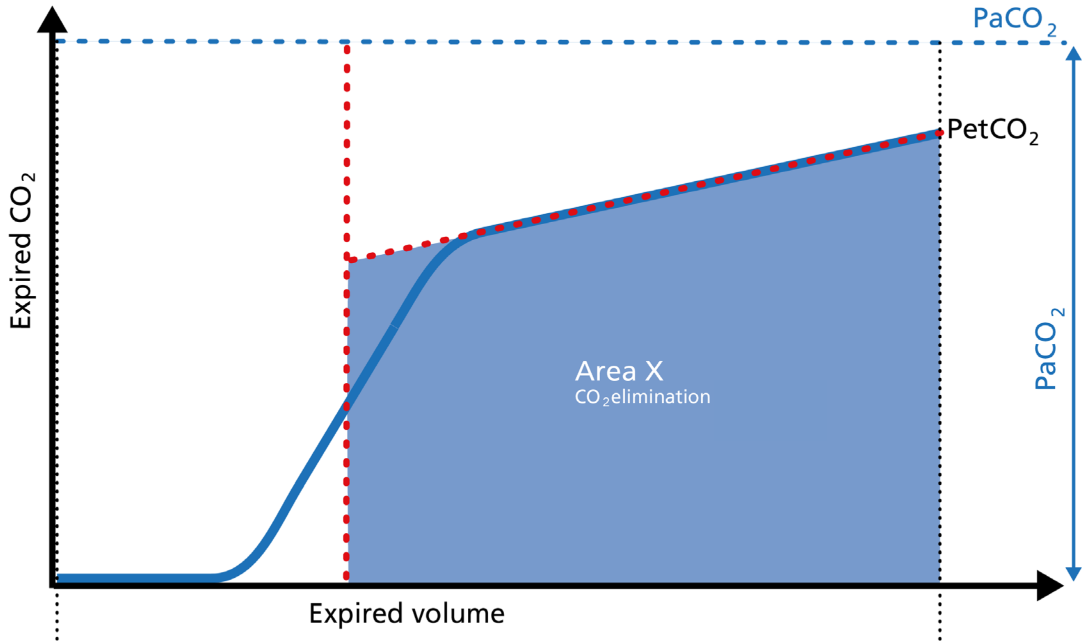
Hypothermia, deep sedation, hypothyroidism, paralysis, and brain death decrease CO_2 production and induce a decrease in $V'CO_2$.
Decreasing $V'CO_2$ can also be due to a decrease in cardiac output or blood loss, and may also suggest a change in blood flow to the lung areas. Pulmonary embolism, for example, exhibits $V'CO_2$ reduction and a slope reduction in Phase II.



Area X – CO_2 elimination (V'CO_2) – 2/2

Increase in V'CO_2
is usually due to bicarbonate infusion or an increase in CO_2 production that can be caused by:

- Fever
- Sepsis
- Seizures
- Hyperthyroidism
- Insulin therapy

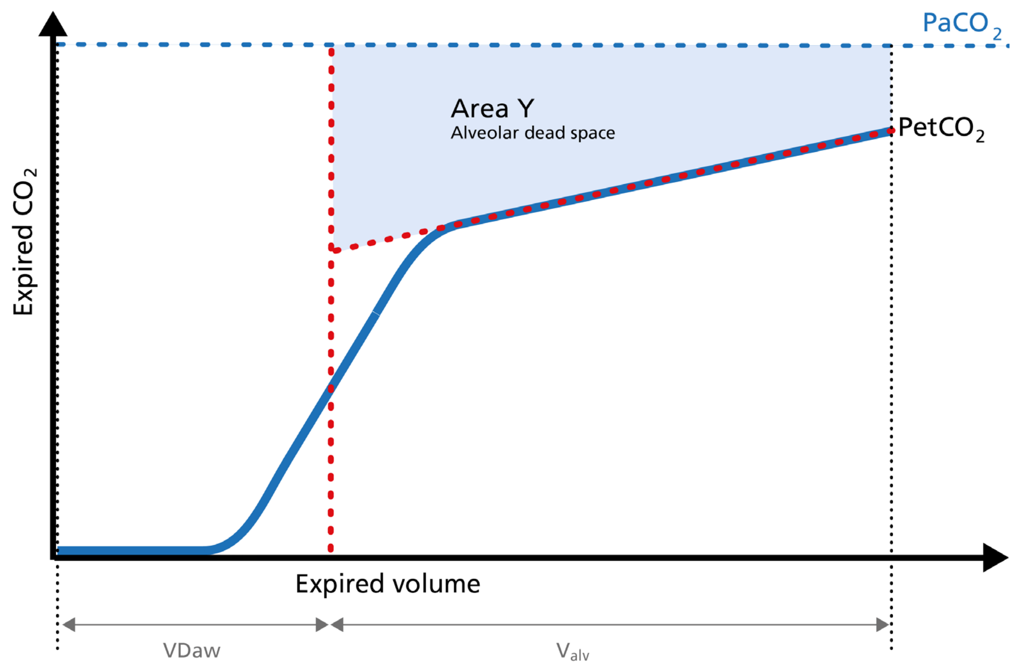


Area Y - Alveolar dead space

Area Y represents the amount of CO_2 that is not eliminated due to alveolar dead space.

Increase
Alveolar dead space is increased in cases of lung emphysema, lung overdistension, pulmonary embolism, pulmonary hypertension, and cardiac output compromise.

Decrease
If the above mentioned conditions improve due to successful therapy, the alveolar dead space decreases.

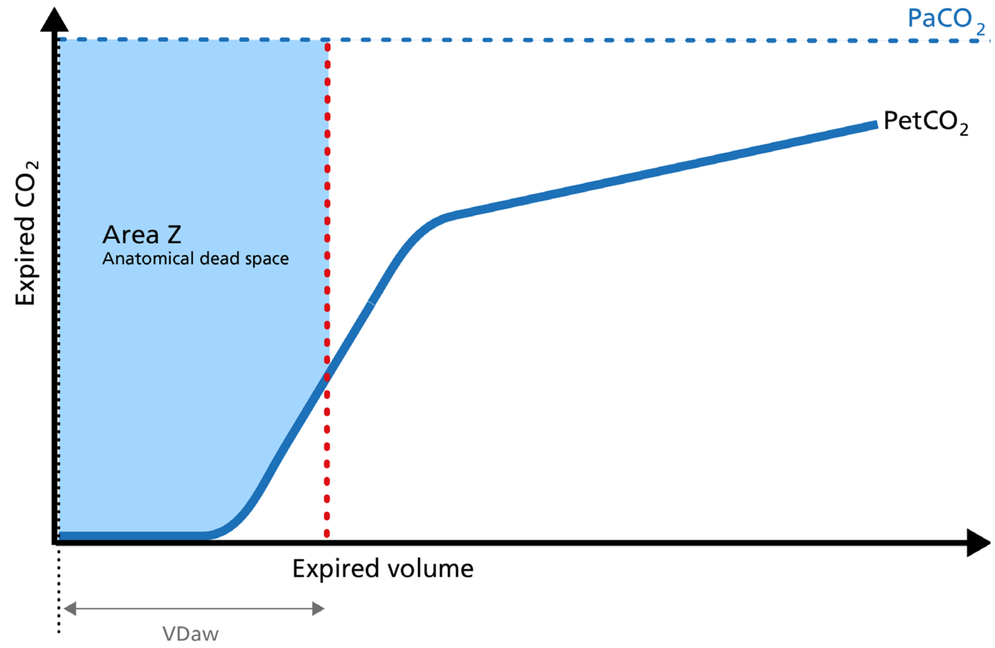


Area Z - Anatomical dead space

Anatomical dead space measurement using a volumetric capnogram gives an effective, in-vivo measure of volume lost in the conducting airway. This area represents a volume without CO_2. It does not take part in the gas exchange and consists of the airway, endotracheal tube, and artificial accessories, such as a flextube positioned between the CO_2 sensor and the patient.

An expansion of Area Z can indicate an increase in anatomical dead space ventilation (VD_{aw}). Consider a reduction of your artificial dead space volume.

A **diminution of Area Z** is seen when artificial dead space volume is decreased and when excessive PEEP is decreased.



Alveolar minute ventilation – V'alv

Phase III of the waveform represents the quantity of gas that comes from the alveoli and actively participates in gas exchange. V'alv is calculated by subtracting the anatomical dead space (VD_{aw}) from the tidal volume (VTE) multiplied by the respiratory rate from the minute volume (MinVol):

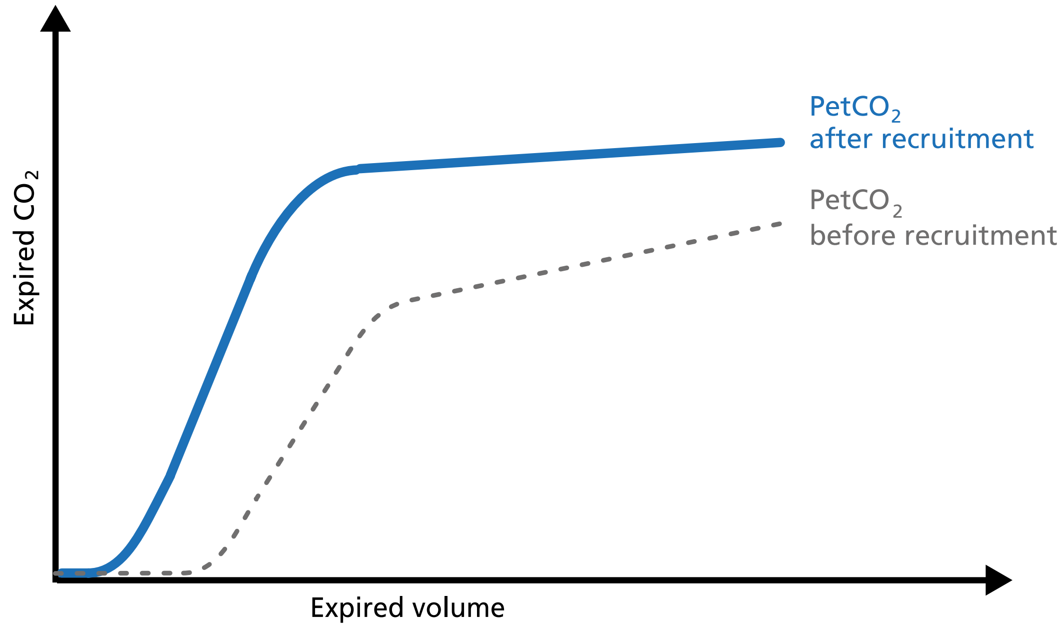
$V'alv = RR*Vt_{alv} = RR*(VTE-VD_{aw})$

Increase

An increase in V'alv is seen after an efficient recruitment maneuver and induces a transient increase in $V'CO_2$.

Decrease

A decrease in V'alv can indicate that fewer alveoli are participating in the gas exchange, for example, due to pulmonary edema.



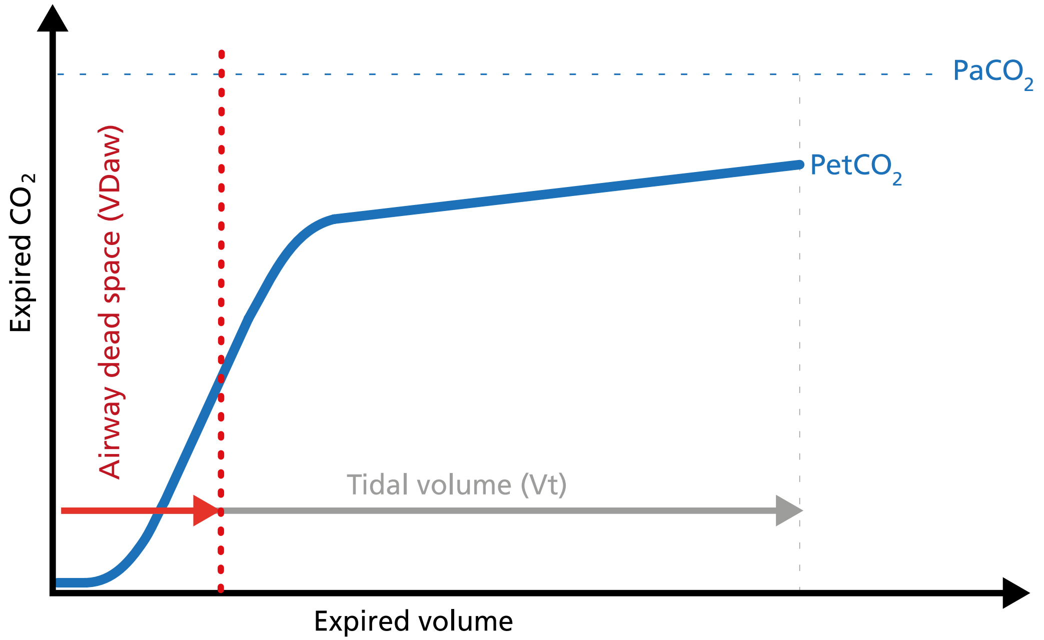
Dead space ventilation - VD_{aw}/VTE ratio

The ratio of airway dead space (VD_{aw}) to tidal volume (VTE) – the VD_{aw}/VTE ratio – gives you an insight into the effectiveness of ventilation.

A rising VD_{aw}/VTE ratio can be a sign of ARDS.

In a normal lung, the VD_{aw}/VTE ratio is between 25% and 30%.

In early ARDS, it is between 58% and up to 83%.



What is the clinical relevance?

Improve ventilation quality and efficiency

You can use the insights from the CO_2 curve to improve ventilation quality and efficiency for your patients. On the following pages, you will find examples for the use of the CO_2 curve in the clinical scenarios listed below:

- Signs of ARDS
- PEEP management
- Recruitment maneuver
- Expiratory resistance
- Obstructive lung disease
- Pulmonary embolism
- Hemorrhagic shock
- Optimize management of the weaning process
- Monitor perfusion during patient transport
- Detection of rebreathing

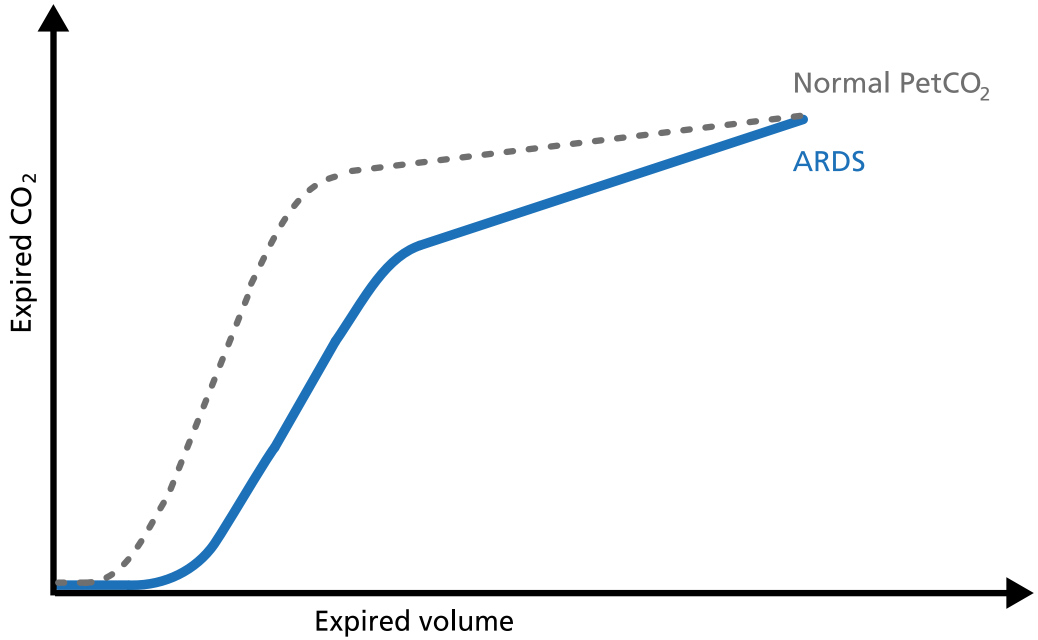
Signs of ARDS - Acute respiratory distress syndrome

In ARDS, the ventilation/perfusion ratio is disturbed and changes in the slope of the volumetric capnogram curve can be observed.

Phase I is larger due to increased anatomical dead space caused by PEEP.

The slope of Phase II is decreased due to lung perfusion abnormalities.

The slope of Phase III is increased due to lung heterogeneity.



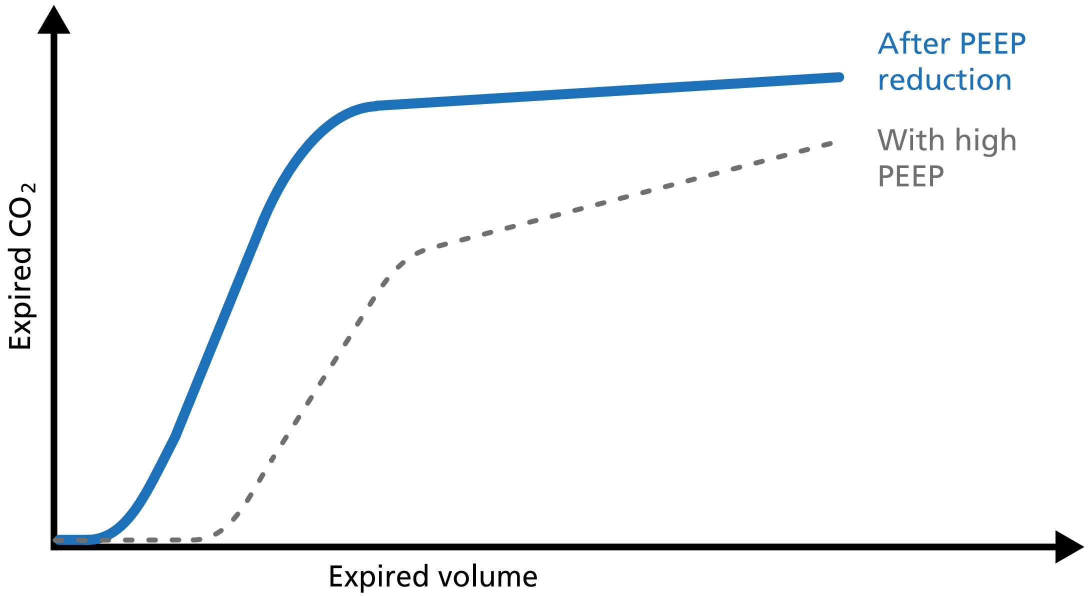
PEEP management

If PEEP is too high, the intrathoracic pressure rises, the venous return decreases, and pulmonal vascular resistance (PVR) increases. These changes can be easily observed on the volumetric capnogram.

An increase in Phase I shows an increase in anatomical dead space.

A decrease in the Phase II slope indicates a decrease in perfusion.

An increase in the Phase III slope depicts a maldistribution of gas, which can be caused by an inappropriately low PEEP setting or an inappropriately high PEEP setting causing lung overdistension.

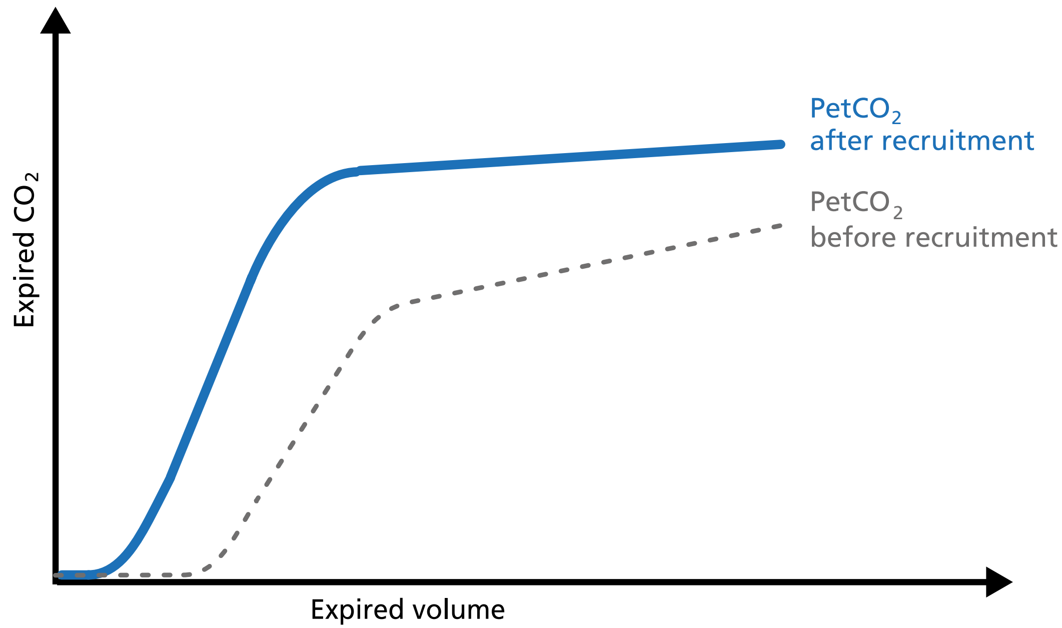


Recruitment maneuver

The volumetric capnogram can be used to assess the effectiveness of recruitment maneuvers and might give you an insight into the recruited lung volume.

After a sucessful recruitment maneuver, you should see a transient increase in $V'CO_2$.

Phase I may decrease a little. The slope of Phase II becomes steeper with improved lung perfusion. The slope of Phase III improves as a result of more homogeneous lung emptying.



Expiratory resistance

Concave Phase-III volumetric capnograms have been seen with obese patients and patients with increased expiratory resistance. Obese patients (Fig. 1) can have biphasic emptying and higher $PetCO_2$ than $PaCO_2$. That difference suggests varying mechanical and ventilation/perfusion properties. The increase in expiratory resistance (Fig. 2) may reflect a slow expiratory phase with a slow accumulation of alveolar CO_2. The alveoli that empty last may have more time for CO_2 diffusion.

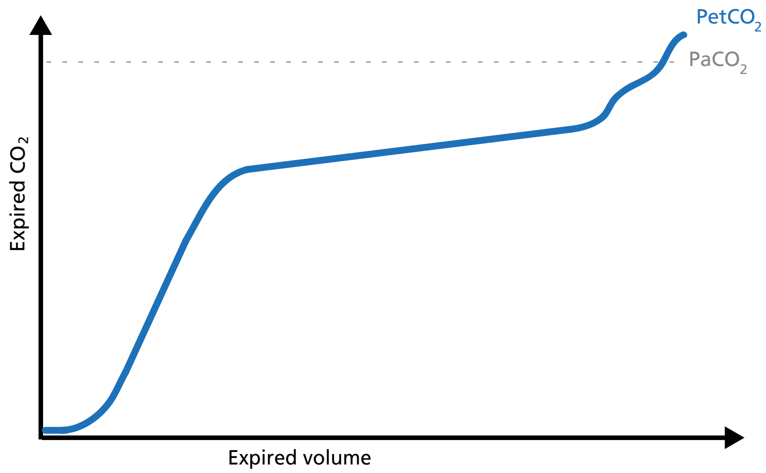


Fig 1: Concave volumetric capnogram associated with obesity

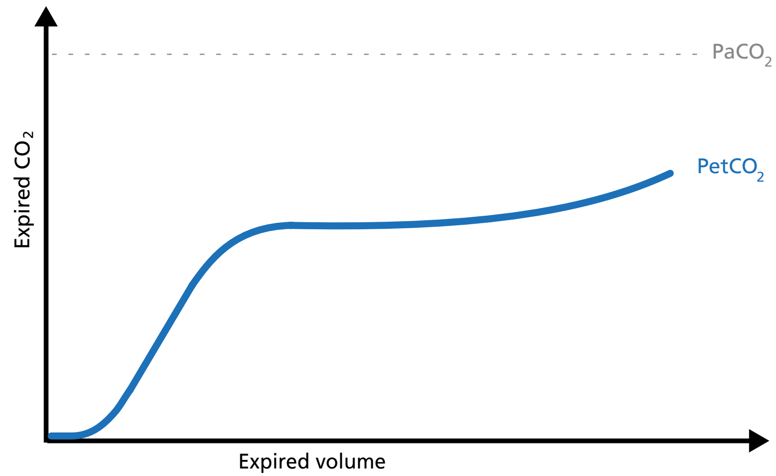
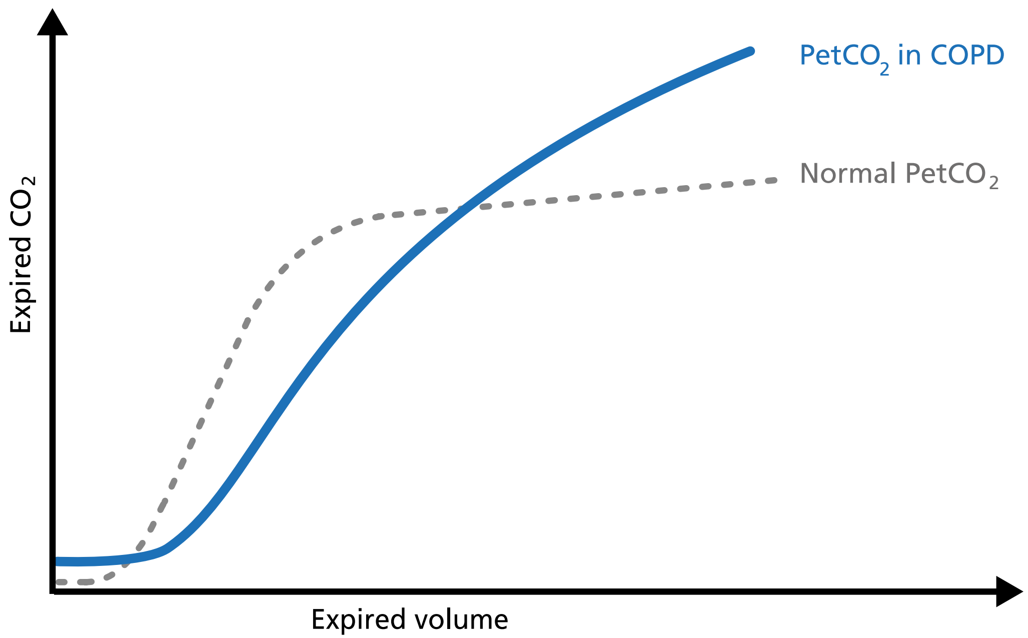


Fig 2: Concave volumetric capnogram associated with increased airway resistance

Obstructive lung disease – 1/2

When spirometry cannot be reliably performed, volumetric capnography can be used as an alternative test to evaluate the degree of functional involvement in obstructive lung disease patients (COPD, asthma, cystic fibrosis, etc.). Obstructive lung disease is characterized by asynchronous emptying of compartments with different ventilation/perfusion ratios.

The volumetric capnogram in COPD patients shows a prolonged Phase II, an increase in $PetCO_2$, and a continuously ascending slope without plateau in Phase III.

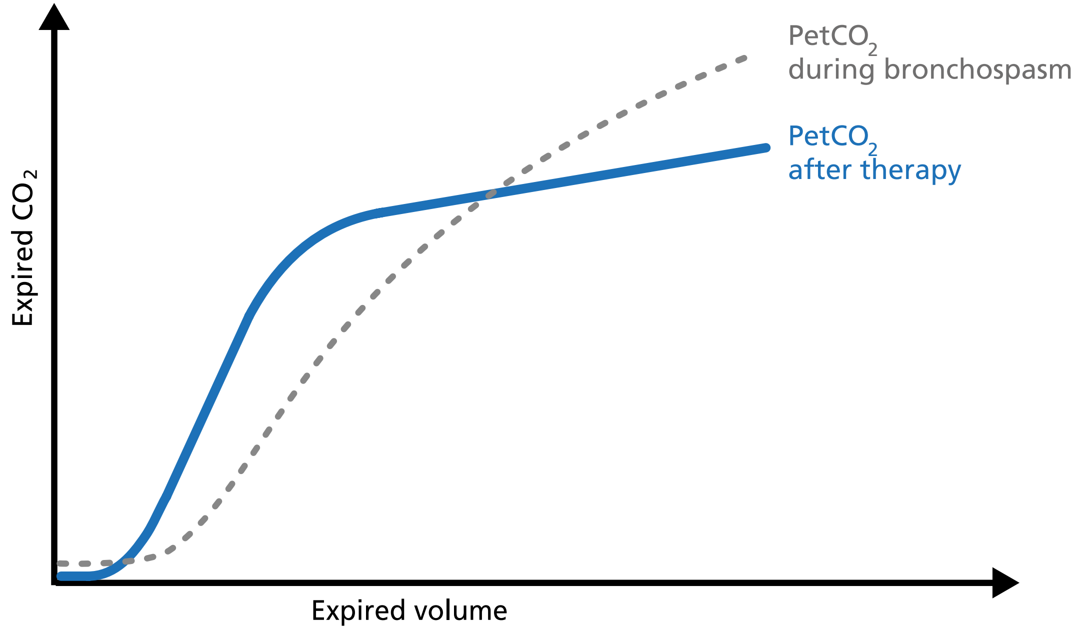


Obstructive lung disease – 2/2

Patients with high airway resistance demonstrate a a decrease in the Phase II slope and a steep slope in Phase III. The volumetric capnogram can give you insights into therapy efficiency.

A Phase II shift to the left indicates reduced resistance.

Phase III slope shows a decrease in steepness indicating better gas distribution and reduced alveolar dead space (VD_{alv}).

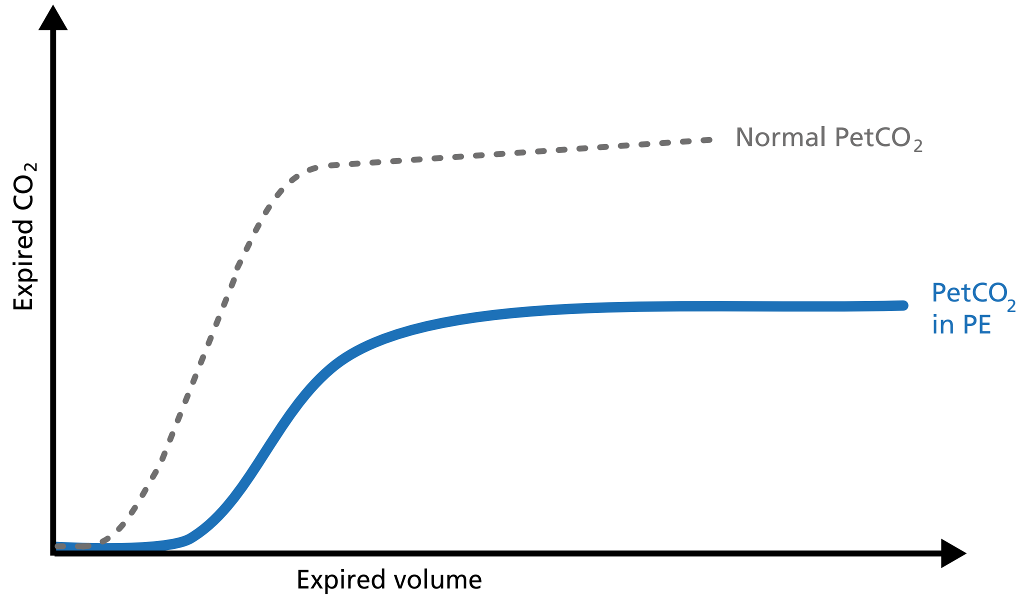


Signs of pulmonary embolism

Pulmonary embolism (PE) leads to an abnormal alveolar dead space that is expired in synchrony with gas from normally perfused alveoli. This feature of PE separates it from pulmonary diseases affecting the airway, which are characterized by nonsynchronous emptying of compartments with an uneven ventilation/perfusion relationship. In case of sudden pulmonary embolism, volumetric capnography has a typical unique shape.

In patients with sudden pulmonary vascular occlusion due to pulmonary embolism, Phase I is increased due to increased anatomical dead space.

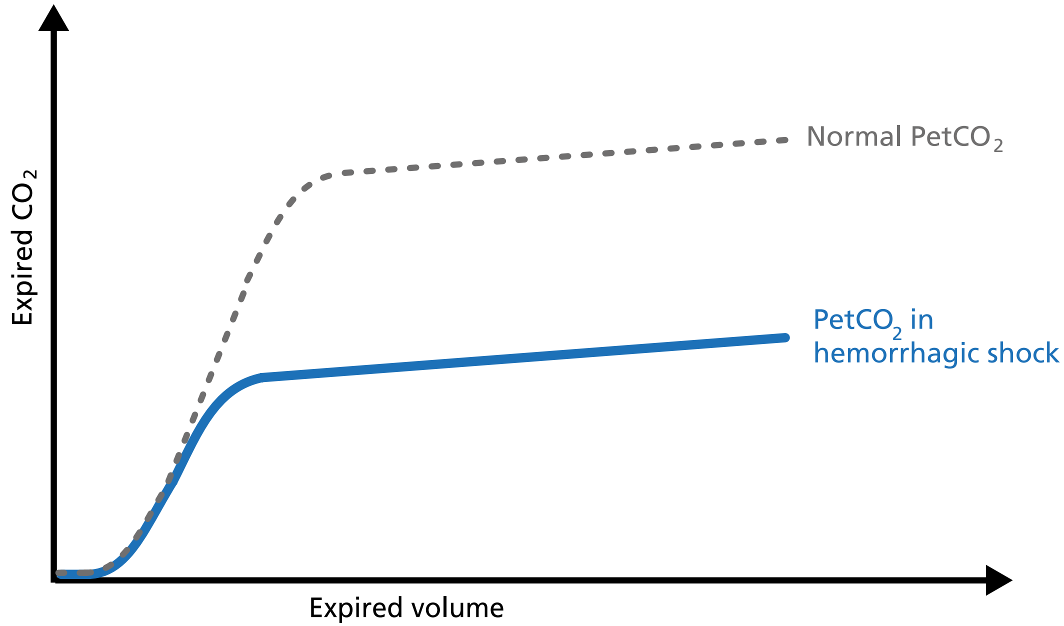
The slope of Phase II is decreased due to poor lung perfusion. Phase III has a normal plateau with low $PetCO_2$ because the number of functional alveoli is reduced. In this case, $V'CO_2$ drops suddenly.



Hemorrhagic shock

Hemorrhagic shock is a condition of reduced tissue perfusion, resulting in the inadequate delivery of oxygen and nutrients that are necessary for cellular function.

The expired CO_2 drops drastically. Phase I is unchanged and the slopes of Phase II and III are unchanged, but $PetCO_2$ is decreased due to the increase in alveolar dead space.



Optimize management of the weaning process – 1/2

The volumetric capnogram and trends show the patient's response to the weaning trial and allow for better management of the weaning process.

Indications for a successful weaning trial are:

- **Stable V'alv and constant tidal volumes**
  As ventilatory support is being weaned, the patient assumes the additional work of breathing while V'alv remains stable and spontaneous tidal volumes remain constant.

- **V'CO_2 remains stable and then slightly increases**
  The slight increase in V'CO_2 represents an increase in CO_2 production as patient work of breathing increases in association with the decrease in ventilatory support. This suggests an increase in metabolic activity due to the additional task of breathing by the patient.

Optimize management of the weaning process – 2/2

Indications for an unsuccessful weaning trial are:

- **Dramatic increase in V'CO_2**
  A more dramatic increase in V'CO_2 would suggest excessive work of breathing and the potential for impending respiratory decompensation. This scenario would be consistent with a visual assessment of increasing respiratory distress (for example, retraction, tachypnea, and agitation). The V'CO_2 will eventually decrease if the patient gets exhausted.

- **Decrease in V'CO_2**
  As the ventilator settings are decreased, the patient is no longer able to maintain an adequate degree of spontaneous ventilation, and total minute ventilation falls with a decrease in CO_2 elimination.

- **Increased VD_{aw}/VTE ratio**
  If reducing ventilatory support is followed by a decrease in tidal volume, the VD_{aw}/VTE ratio increases. This reduces ventilatory efficiency and the patient's ability to remove CO_2.

Monitor perfusion during patient transport

If arterial access is not something you routinely perform when you transport a ventilated patient, $PetCO_2$ can be used for monitoring perfusion and ventilation during transport.

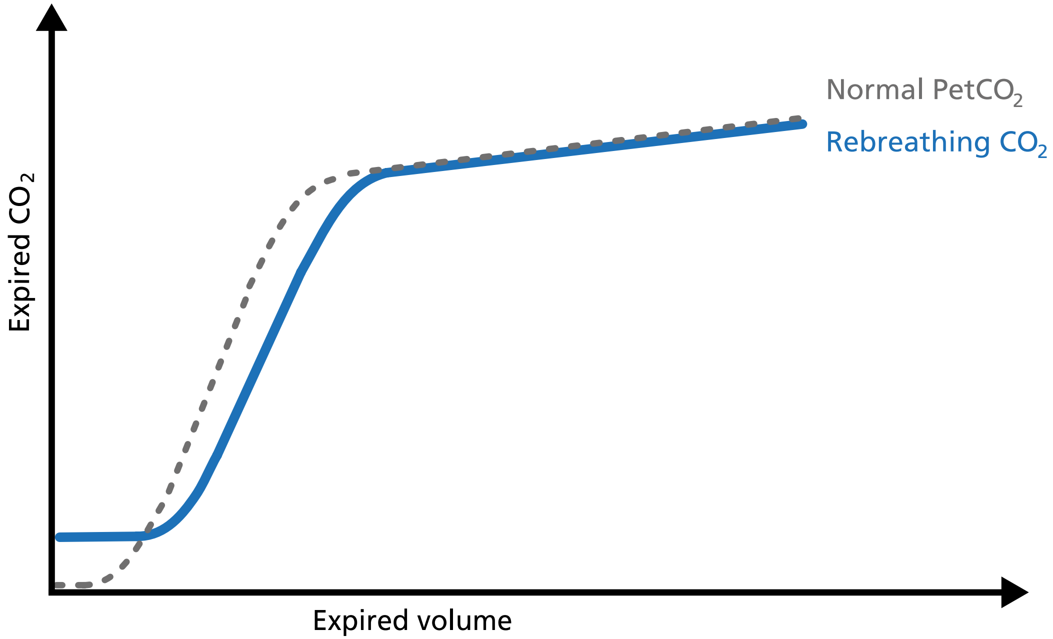
A **decrease in $PetCO_2$ accompanied by a decrease of VCO_2** can signify:

- ET tube displacement
- Decreased cardiac output
- Pulmonary embolism
- Atelectasis
- Overdistension of alveoli (for example, excessive PEEP)

Detection of rebreathing

An elevation of the baseline during Phase I indicates rebreathing of CO_2, which may be due to mechanical problems or therapeutic use of mechanical dead space.

Consider recalibration of the CO_2 sensor or reduction of the airway accessories.

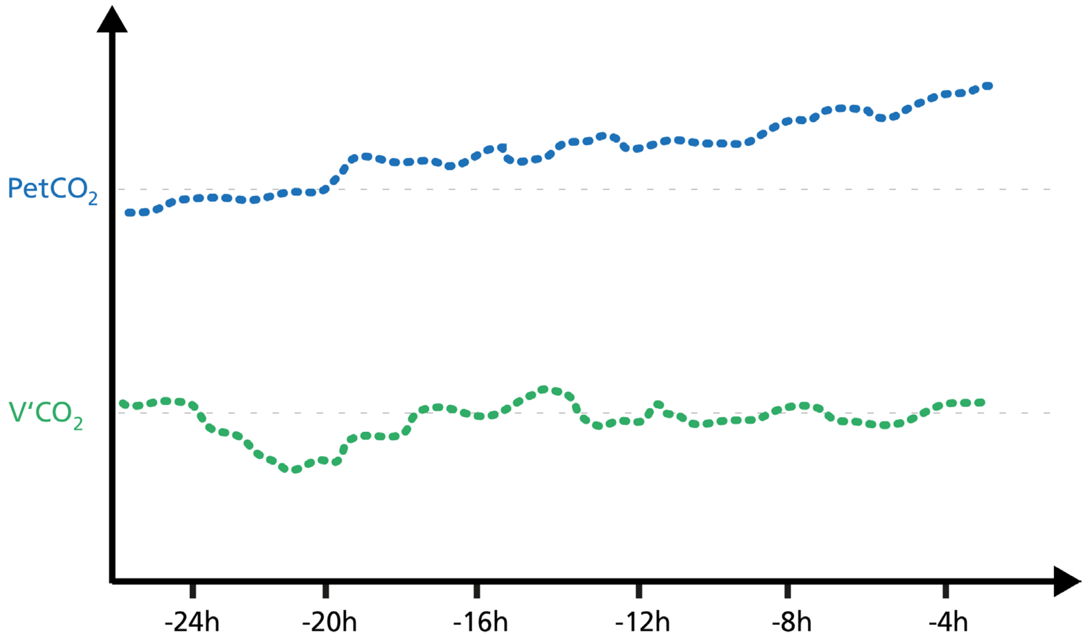



Clincial applications of trends

$PetCO_2$ versus $V'CO_2$ - Opposing, asynchronous trends

If the $PetCO_2$ trend moves up while the $V'CO_2$ trend decreases for a while and then returns to baseline, this indicates a worsening of ventilation.

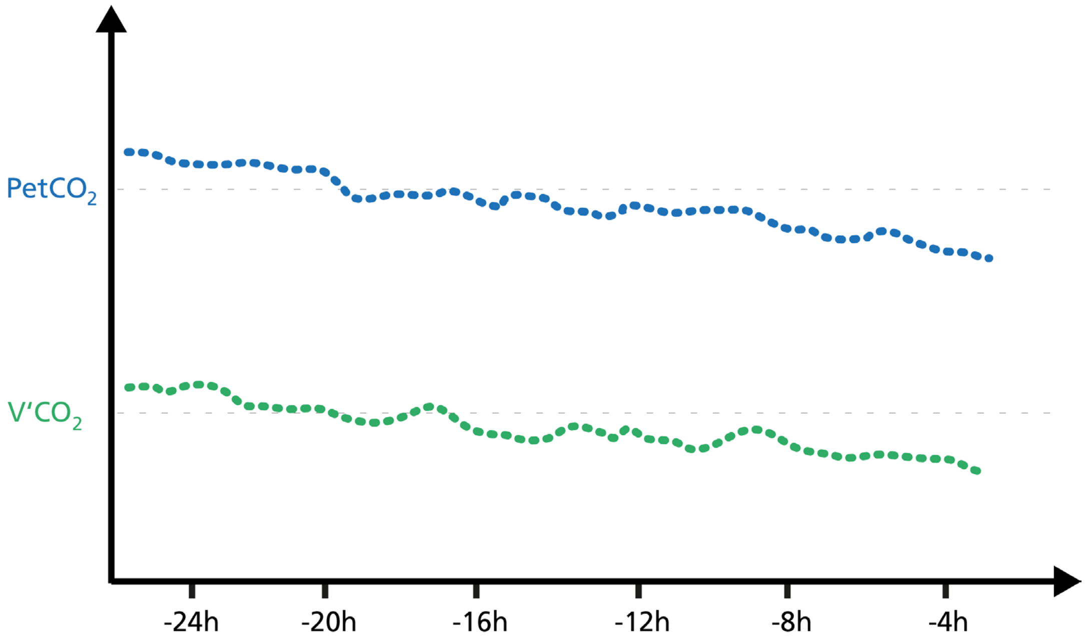
If the $PetCO_2$ trend moves down while the $V'CO_2$ trend increases for a while and then returns to baseline, this indicates an improvment of ventilation.



$PetCO_2$ versus $V'CO_2$ - Synchronous trends

Rising $PetCO_2$ and $V'CO_2$ trends indicate increasing CO_2 production (agitation, pain, fever).

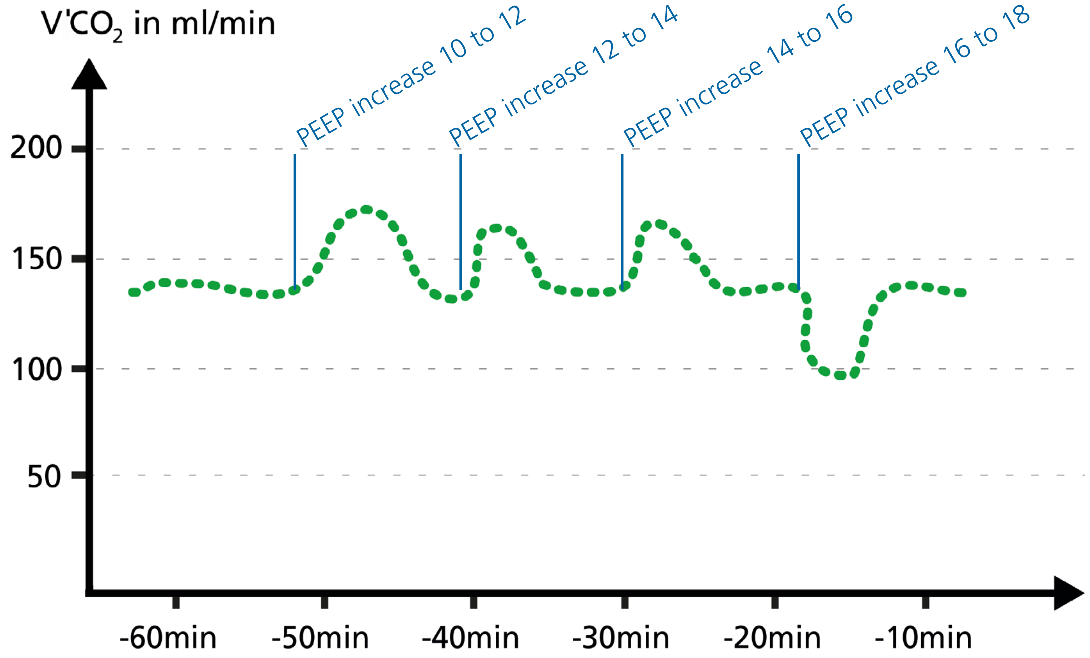
Falling $PetCO_2$ and $V'CO_2$ trends indicate a decrease in CO_2 production.



Optimizing PEEP by trends

When PEEP change is associated with an improving ventilation/perfusion ratio, V'CO_2 shows a transient increase for a couple of minutes and then returns back to baseline, that is, in equilibrium with CO_2 production.

When PEEP change is associated with a worsening of the ventilation/ perfusion ratio, V'CO_2 transiently decreases for a few minutes and then returns to baseline.

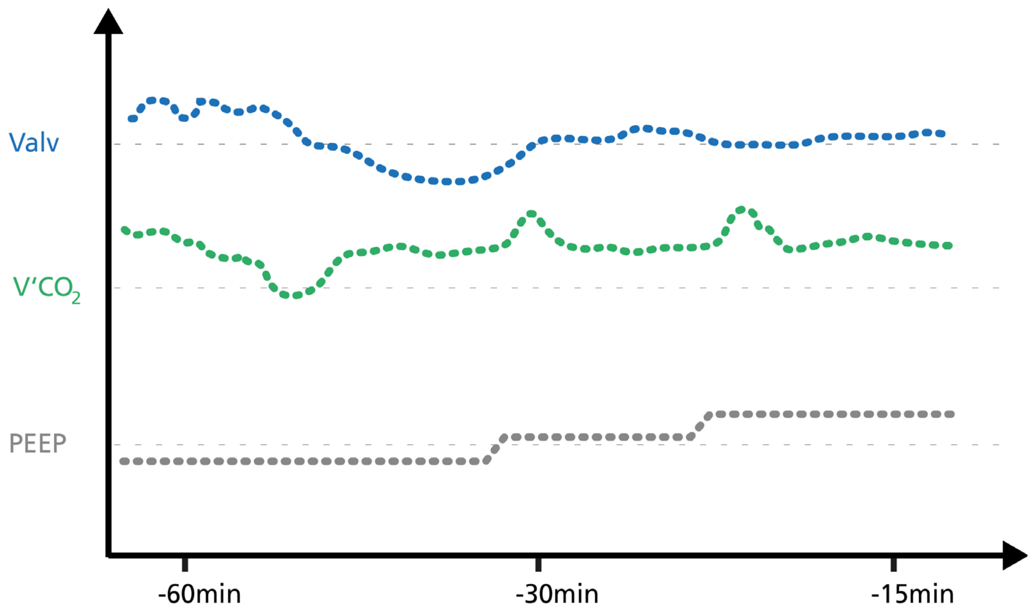


Detecting alveolar derecruitment

Volumetric CO_2 provides continuous monitoring to detect derecruitment and recruitment of alveoli.

Alveolar ventilation and $V'CO_2$ will first decrease if the lung derecruits, and will then stabilize again at equilibrium.

Recruitment, during, for example, a PEEP increase, can be detected by short $V'CO_2$ peaks before $V'CO_2$ returns to equilibrium.



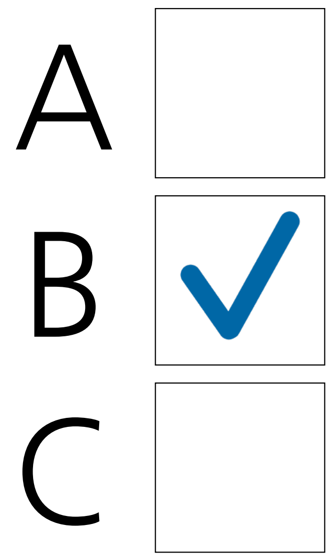

Test yourself

Multiple choice test

Now it is time to put your newly learned knowledge to the test. On the following pages you will find clinical cases of intubated ICU patients, including three typical symptoms for each case. Your task is to figure out the patient's condition by interpreting the volumetric capnogram.

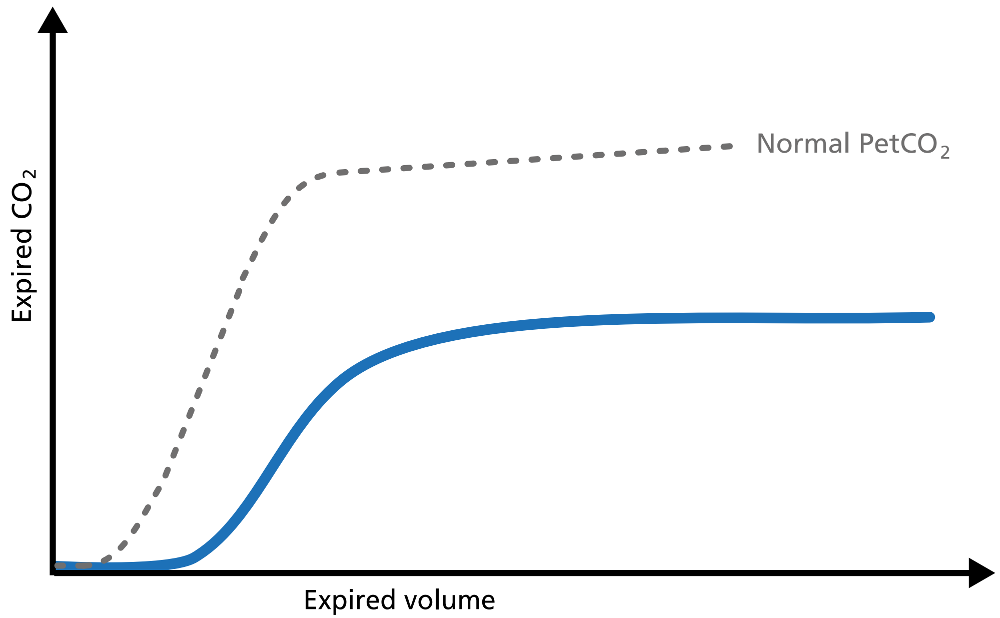
You are presented with three possible answers of which only one is correct.
The solutions are on page 48.

Good luck!



Patient A

Adult female intubated patient presents with a respiratory rate of 35 breaths/min (tachypnea) and swollen calves. What does the volumetric capnogram indicate?



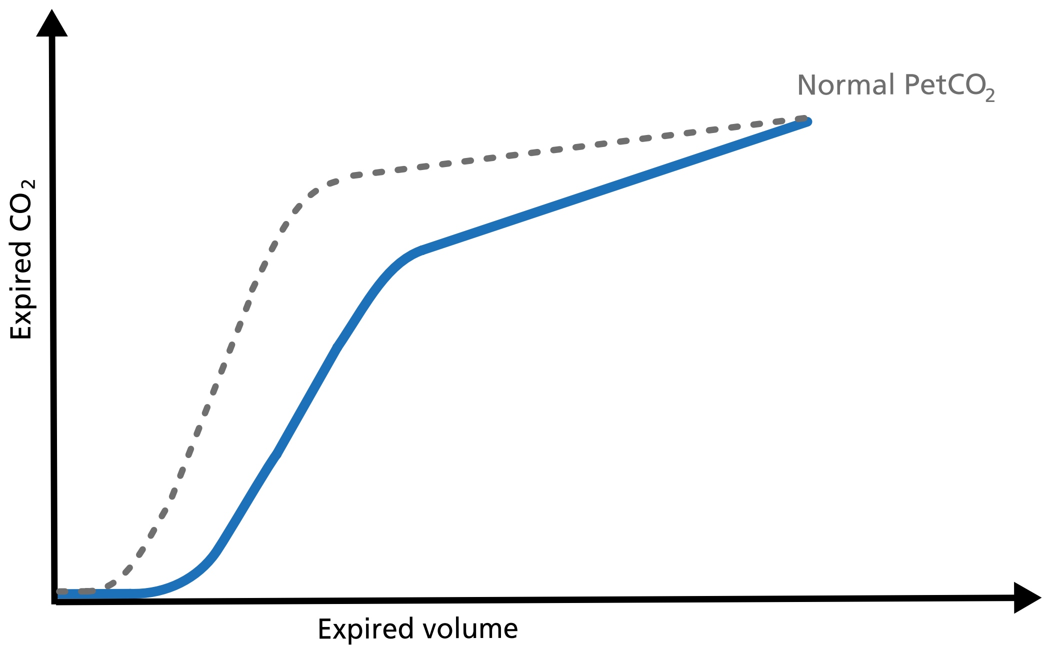
a) Pulmonary embolism

b) ARDS

c) Sepsis

Patient B

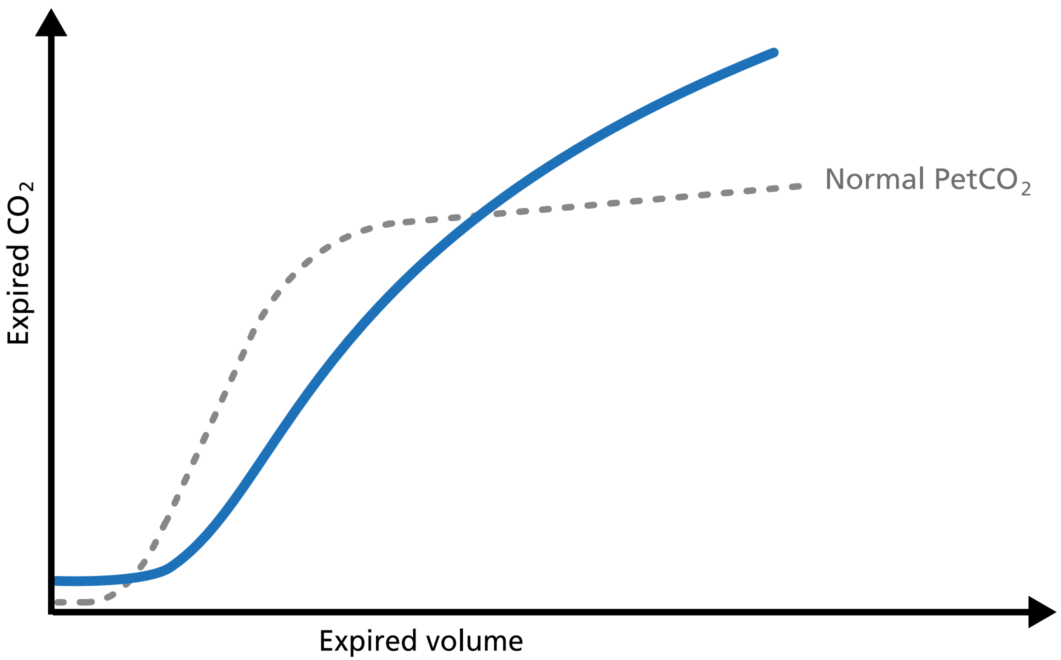
Adult male intubated patient presents with a dry, nonproductive cough, crackling noises in the lungs, and a heart rate of 110 beats/min (tachycardia). What does the volumetric capnogram indicate?



- **a) Cardiac arrest**
- **b) ARDS**
- **c) Sepsis**

Patient C

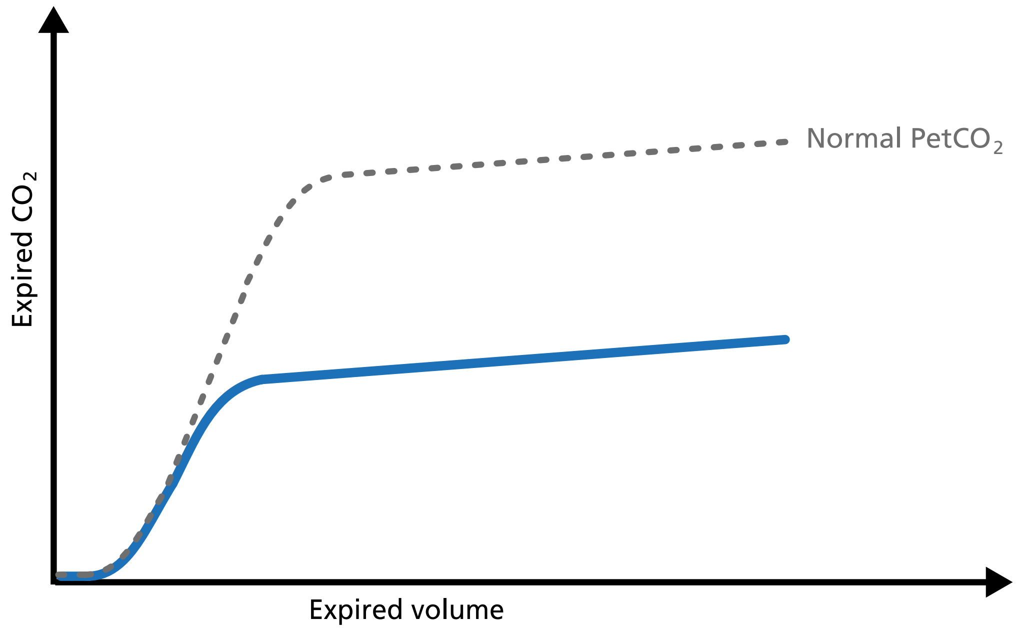
Adult male intubated patient presents with blueness of the lips and fingernail beds (cyanosis), oxygen saturation (SaO_2) of 89%, and the x-ray shows overexpanded lungs. What does the volumetric capnogram indicate?



- **a) PEEP is too high**
- **b) Pulmonary embolism**
- **c) Severe COPD**

Patient D

Adult female patient, hospitalized comatose after car accident with no visible injuries, presents after intubation with low blood pressure, hyperglycemia, and a heart rate of 118 beats/min (tachycardia). What does the volumetric capnogram indicate?



a) Pneumothorax

b) ARDS

c) Hemorrhagic shock

Solutions

Patient A	a) Pulmonary embolism
Patient B	b) ARDS
Patient C	c) Severe COPD
Patient D	c) Hemorrhagic shock

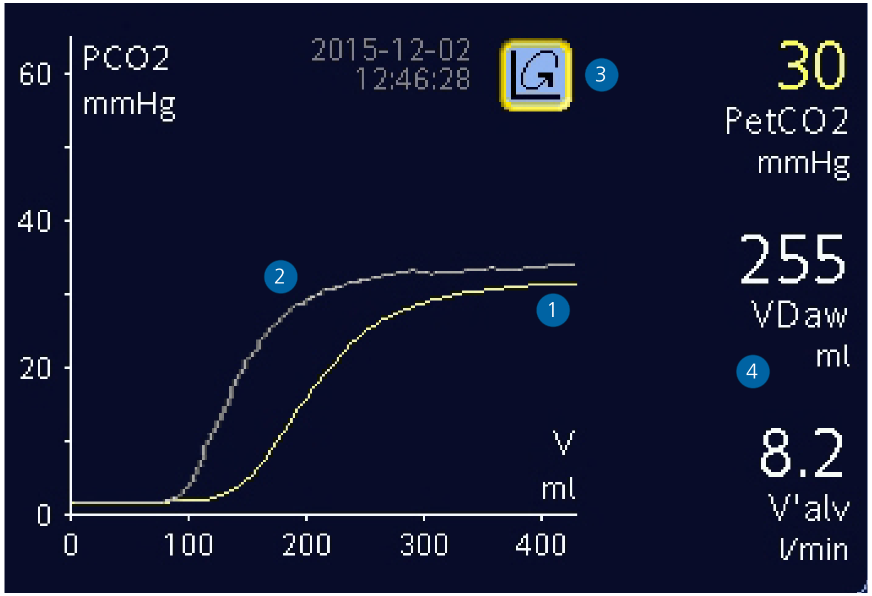

Appendix

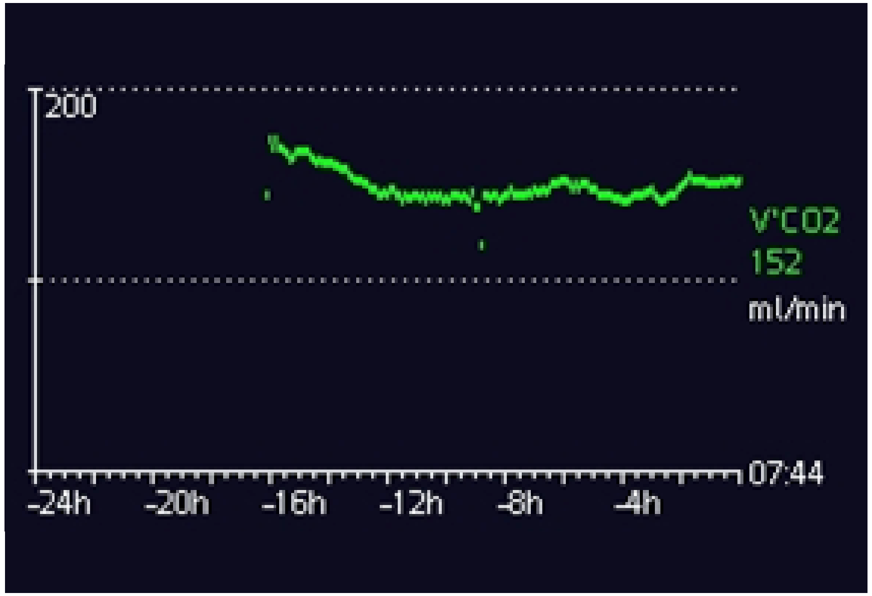
Volumetric capnography in Hamilton Medical ventilators

All Hamilton Medical ventilators offer volumetric capnography either included standard or as an optional feature.

The CO_2 measurement is performed using a CAPNOSTAT® 5 mainstream CO_2 sensor at the patient's airway opening. The CAPNOSTAT® 5 sensor provides technologically advanced measurement of end-tidal carbon dioxide ($PetCO_2$), respiratory rate, and a clear, accurate capnogram at all respiratory rates up to 150 breaths per minute.

Loops and trends on the display





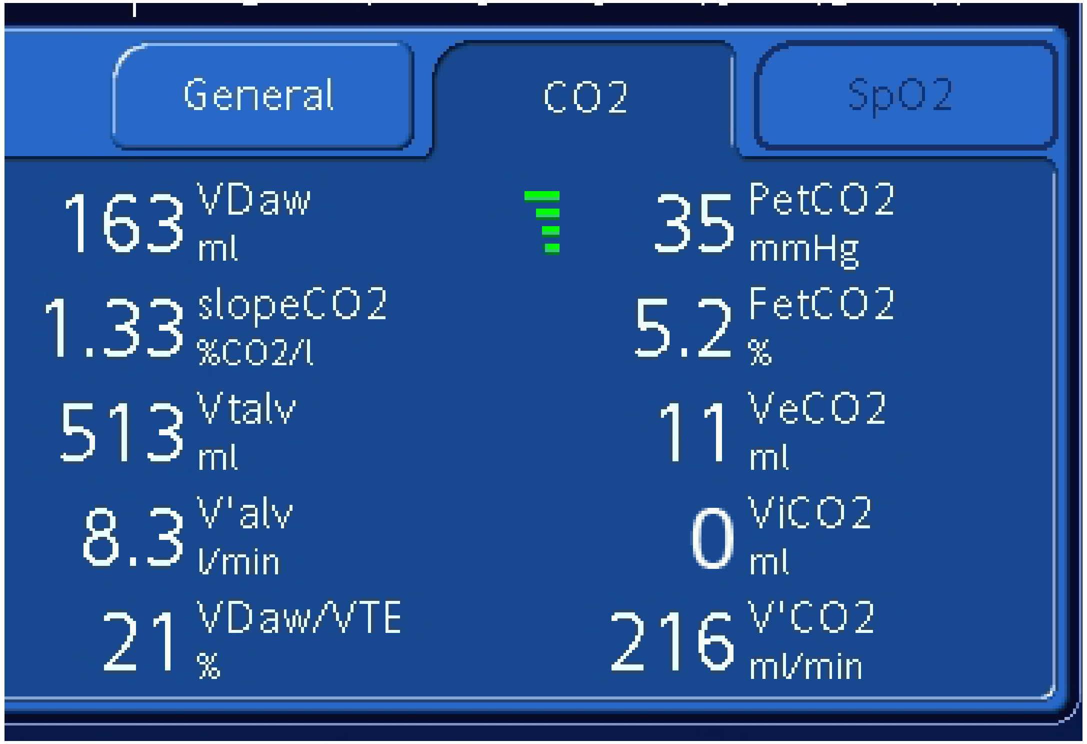
1. Current volumetric capnogram loop
2. Volumetric capnogram reference loop
3. Reference loop button with time and date of reference loop
4. Most relevant CO_2 values, breath by breath

A 72-hour trend (or 96-hour with HAMILTON-S1/G5) is available for:

- $PetCO_2$
- $V'CO_2$
- $FetCO_2$
- $VeCO_2$
- $ViCO_2$
- VD_{aw}
- VD_{aw}/VTE
- Slope CO_2

Volumetric capnography in monitoring

To make your life easier, the Hamilton Medical ventilators offer an overview of all relevant CO_2-related values in the monitoring window.



Calculation formulas

Vt_{alv}	Alveolar tidal volume	$Vt_{alv} = Vt - VD_{aw}$
V'alv	Alveolar minute ventilation	$V'alv = RR*Vt_{alv}$
VCO_2	Volume of CO_2 eliminated/breath	$VCO_2 = VeCO_2 - ViCO_2$
$V'CO_2$	Volume of CO_2 eliminated/minute	VCO_2*Number of breaths/min
$FetCO_2$	Fractional concentration of CO_2 in exhaled gas	$FetCO_2 = V'CO_2/MinVol$
$PetCO_2$	Partial pressure of CO_2 in exhaled gas	$PetCO_2 = FetCO_2*(Pb-PH_2O)$
VD_{aw}/VTE	Anatomical dead space fraction	$VD_{aw}/VTE = 1 - (PetCO_2/PaCO_2)$

Examples of normal values for ventilated patients[1]

Description	Unit[2]	Normal	Reference
VD_{aw}	ml	2.2 ml/kg IBW	Radford 1954
$slopeCO_2$	$\%CO_2/l$	31324 * Vt-1.535	Aström 2000
$V'CO_2$	ml/min	2.6 to 2.9 ml/min/kg	Weissmann 1986 / Wolff 1986
$FetCO_2$	%	5.1% to 6.1%	Wolff 1986
V'alv	l/min	0.052 to 0.070 l/min/kg	($V'CO_2$ / $FetCO_2$)

1. These values are for illustration purposes and do not replace physician-directed treatment.
2. Bulk gas volumes, such as minute ventilation and tidal volumes, are usually measured in BTPS. Specific gas volumes are expressed in STPD. Conversion factors can be found in physics textbooks.

References A – Z

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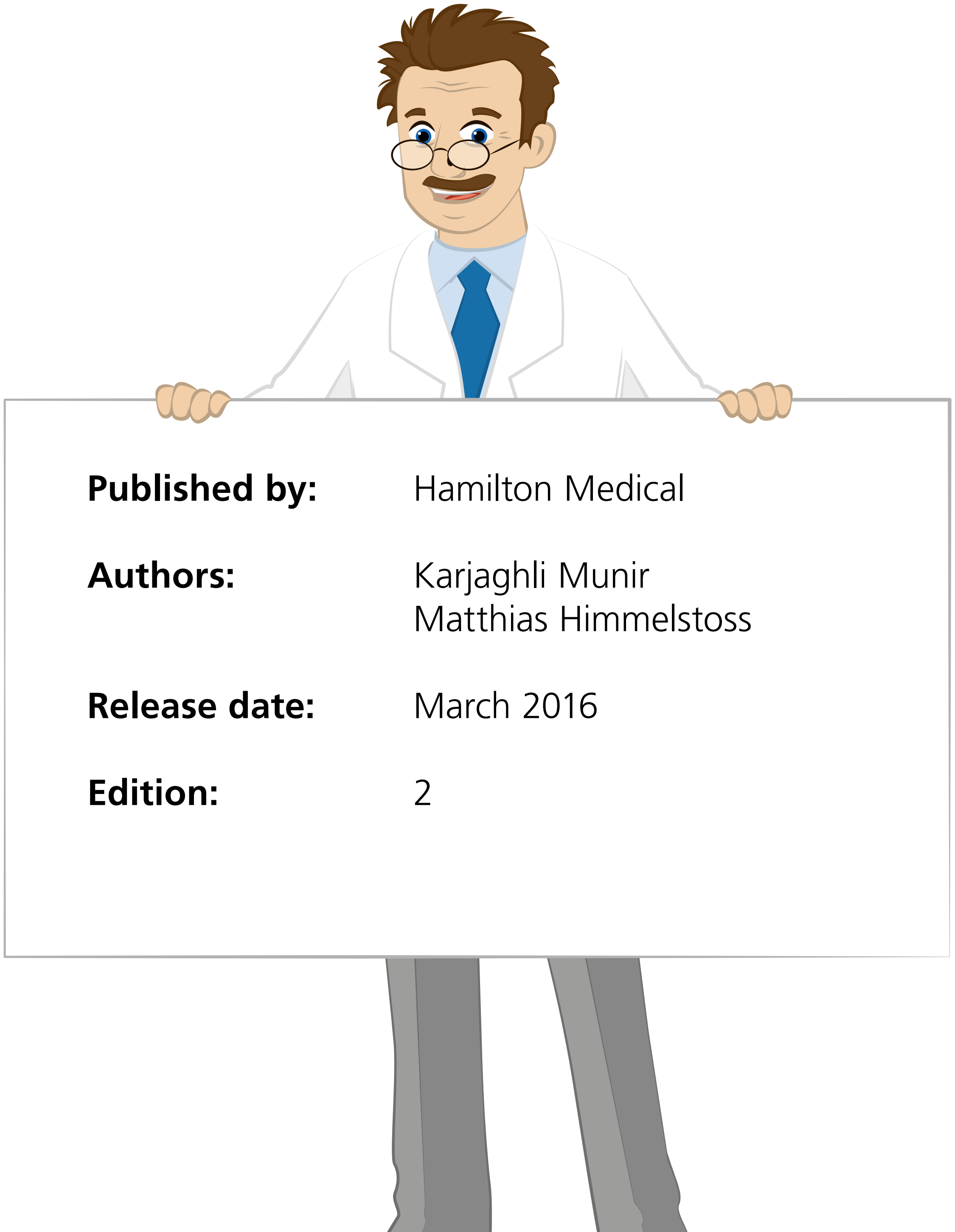
Glossary A – Z

f	Frequency or resipratory rate = The number of breaths per minute
$PaCO_2$	Partial pressure of carbon dioxide in the arterial blood; arterial carbon dioxide concentration or tension It is either expressed in mmHg or in kPa
PCO_2	Partial pressure of carbon dioxide
$PetCO_2$	End-tidal carbon dioxide
$SBCO_2$	Single breath carbon dioxide
V'alv	Alveolar minute ventilation The amount of minute ventilation volume that is actually participating in gas exchange
$V'CO_2$	Volume of CO_2 eliminated per minute
VD	Physiological dead space
VD_{aw}	Anatomical dead space ventilation
VD_{aw}/VTE	Anatomical dead space to tidal volume ratio
Ve	Minute ventilation = Tidal volume multiplied by respiratory rate (Vt x f = Ve)
$VeCO_2$	Expired CO_2 volume
$ViCO_2$	Inspired CO_2 volume
VTE	Tidal volume is the lung volume representing the normal volume of gas displaced between inhalation and exhalation

Imprint



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www.hamilton-medical.com/volumetric-capnography

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